MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

GAMMA KNIFE: TREATMENT PLATFORM, QA, AND TREATMENT UNCERTAINTY

Dan McDonald, MS
Assistant Professor, Medical University of South Carolina

DISCLOSURES

- No conflicts of interest to disclose

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

OUTLINE

- Calibration and commissioning
- Treatment prep and image acquisition
  - How do I determine imaging modality?
  - What potential sources of error arise due to imaging?
- Treatment planning and delivery
- QA
- Sources of uncertainty
- Gamma Knife ICON
- SAMS

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

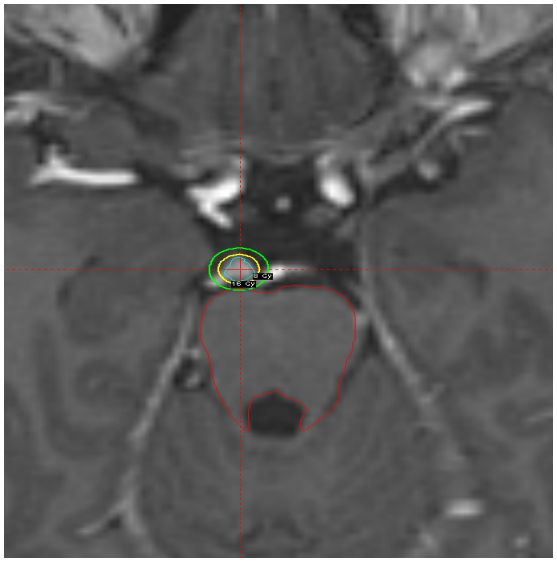
GAMMA KNIFE PROGRAM

- 1st GK patient treated January 2010
- 2 physicists, 2 neurosurgeons (1 primary), 4 radiation oncologists (1 primary)
- Source reload August 2014

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

Gamma Knife Program

- Over 1500 treatments provided to date
- 273 in 2016
- Wide range of indications
  - Metastatic disease
  - Surgical cavity
  - Primary malignant brain tumor
  - Acoustic neuroma
  - Meningioma
  - Trigeminal neuralgia
  - AVM
  - Glomus tumor
  - Essential tremor



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

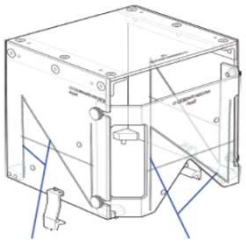
Calibration and Commissioning

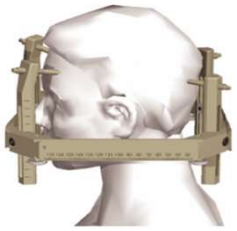
- Single output measurement required for commissioning!
- No clear guidelines on calibration methodology
- McDonald et al in Med Phys: *Calibration of the Gamma Knife Perfexion using TG-21 and the Solid Water Leksell Dosimetry Phantom*
  - TG-21 using solid water phantom + A14SL ionization chamber
- Verify Monte-Carlo-based output factors

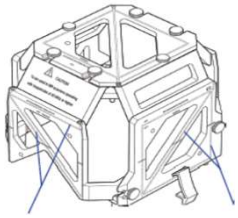
MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

Treatment Preparation

- Stereotactic frame-based system
- Neurosurgeon positions frame on morning of treatment
- Patient receives:
  - MRI and/or
  - CT and/or
  - Angiogram (AVM only)
- Each imaging modality has dedicated localizer
- At MUSC 90% of patients receive MRI only
- Typical sequences
  - T1 volume scan w/ gado (1mm slice)
  - T2 Drive (0.7mm slice)
  - Time-of-flight (0.7mm slice)



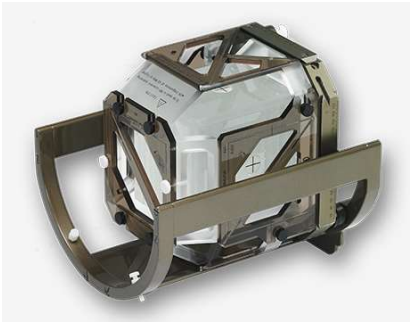




MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

Imaging and Localization

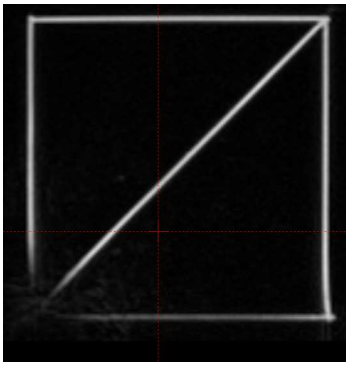
- Consider inherent MR distortion
  - Gradient non-linearity largest cause
  - Increases with distance from imaging center
  - Ensure vendor distortion correction is activated
    - Beware of outside MRs
  - Standard diagnostic QA/PMs may not be sufficient
    - **ACR requires ± 2mm**
  - Dedicated phantoms available to help quantify MR distortion
    - Pictured – *Modus Medical Quasar Grid3D™*



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

IMAGING AND LOCALIZATION

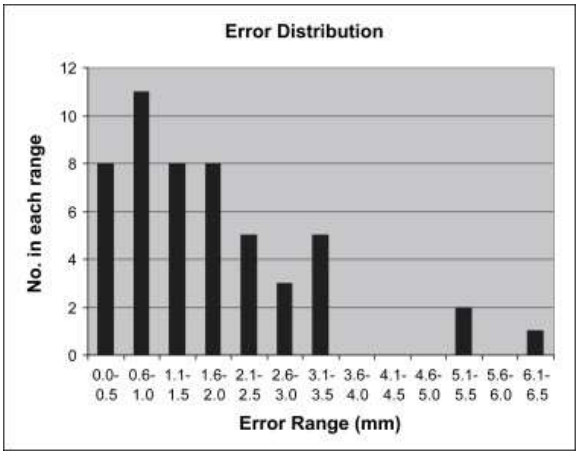
- MR distortion due to Leksell frame
  - E P Pappas in Physics in Med and Bio: *Characterization of system-related geometric distortions in MR images employed in Gamma Knife radiosurgery applications*
    - GK frame base can introduce additional MR distortion
    - Up to 5mm adjacent to frame base
    - Distortion decreases with distance from frame base
    - Frame related distortion eliminated 9cm superior to base
    - Distortion reduced at center of coordinate space



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

IMAGING AND LOCALIZATION

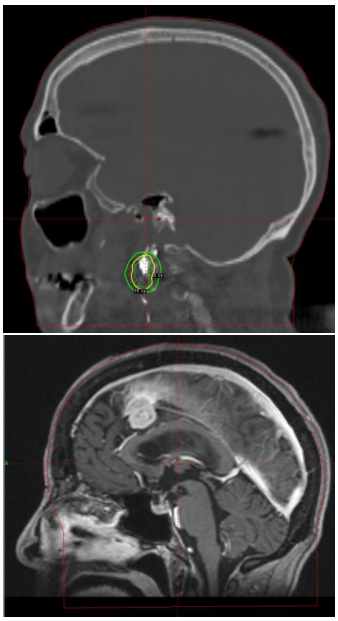
- Consider registration accuracy
  - Kenneth Ulin in Int. Journal of Rad Onc Bio Phys: *Results of a Multi-Institutional Benchmark Test for Cranial CT/MR Image Registration*
    - Graph result of benchmark study of CT/MRI cranial rigid registration
    - Average error found to be 1.8mm
    - Manual registration found to be more accurate than automatic
  - MR distortion affects registration accuracy



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

IMAGING AND LOCALIZATION

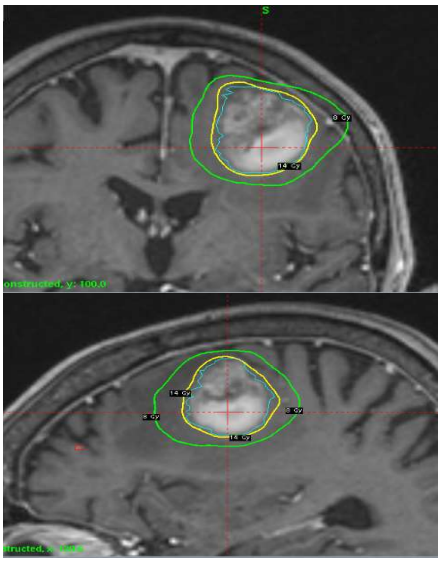
- Consider GK skull measurement
  - "Bubble measurement" external contour
    - Generated by model
    - Fails to capture extreme/unusual head shapes
    - Fails to accurately represent surface below the cerebellum
    - Historically sufficient for older-model GKs
  - CT-based external contour
    - More accurate
    - Requires day-of-tx CT
    - Can represent surface below the cerebellum
  - Patient anatomy and target location dictate need for CT-based contour



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

TREATMENT PLANNING

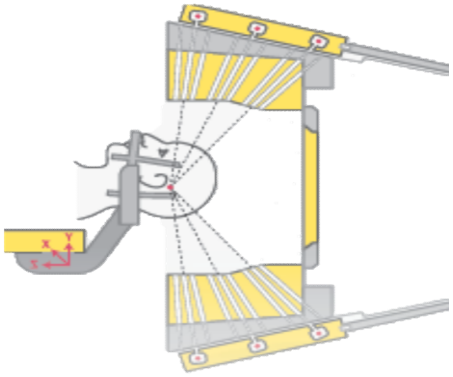
- MUSC procedure
  - Physicist imports and prepares images for planning
    - Definition of in-frame images
    - Registration of out-of-frame images
    - Creation of external ("skull") contour
  - Neurosurgeon reviews registrations, contours tumor volumes and OARs
  - Physicist creates treatment plan
  - Radiation Oncologist determines prescription, reviews and approves plan

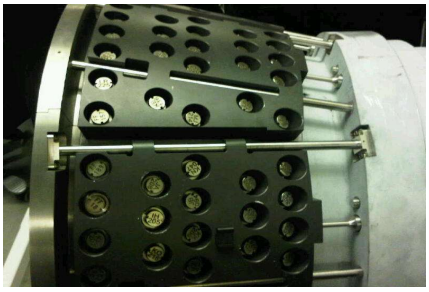


MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

TREATMENT PLANNING

- Plans created by placing "shots"
- Each "shot" consists of:
  - **Table position**
  - **Collimator selection**
  - **Weighting (time)**
- 192 sources divided onto 8 movable plates
- Each plate can be positioned over the **4, 8, or 16mm** collimator, or blocked completely
- Plates positioned independently (4^8 possible patterns per shot!)
- 3 head tilt positions (Gamma Angles) available
  - 70 (chin back), 90 (neutral), 110 (chin down)





MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

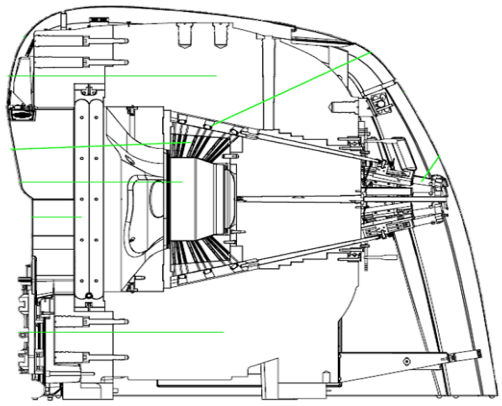
TREATMENT DELIVERY

- Patient docked to treatment couch
- Treatment couch moves patient around fixed isocenter to create desired dose distribution
- Source plates simultaneously move 192 Co-60 sources over desired collimators

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

MACHINE SPECIFICATIONS

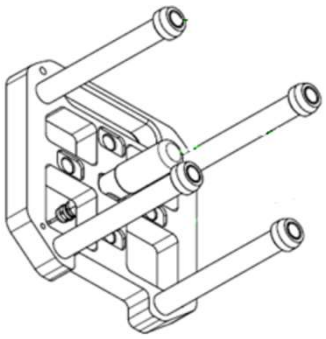
- Available collimator sizes
  - **4, 8, 16mm – 8 independent source plates**
- Radiological accuracy
  - **<0.25mm**
- Positioning accuracy
  - **<0.20mm**
- Number of radiation sources
  - **192**
- Total activity at loading
  - **5100-6300Ci**
- Max dose rate (16mm coll) at loading
  - **>3Gy/min**
- Treatment timer accuracy
  - **<0.2%**
- Couch weight limit
  - **500lbs**



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

QUALITY ASSURANCE

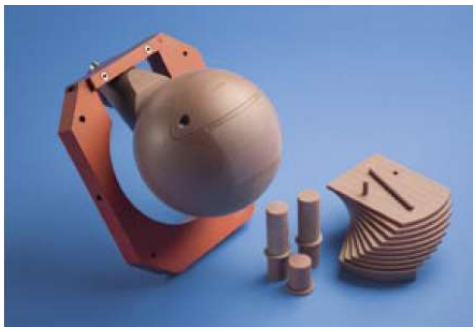
- Daily QA
  - Focus precision
    - Verification of radiation isocenter vs couch position
    - Automatic routine
    - Diode detector mounted to couch using clinical frame adapter
    - 4mm collimator used
    - **0.1mm** tolerance
  - Emergency alarm
  - AV
  - Gamma angle sensor
  - Radiation survey
  - Interlocks (Door, Lt and Rt patient protection, frame docked)
  - Pause, emergency stop, door open
  - Radiation monitor and warning lights



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

QUALITY ASSURANCE

- Monthly QA
  - All daily checks +
  - Ion-chamber output check
    - GK solid water phantom
    - A14SL ion-chamber
  - Timer check



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

QUALITY ASSURANCE

- Annual QA
  - All daily and monthly checks +
  - Output factor verification
  - Radiation isocenter centricity
    - X, Y, and Z directions
  - Radiation profile vs baseline for each collimator
  - All tests utilize Gafchromic film

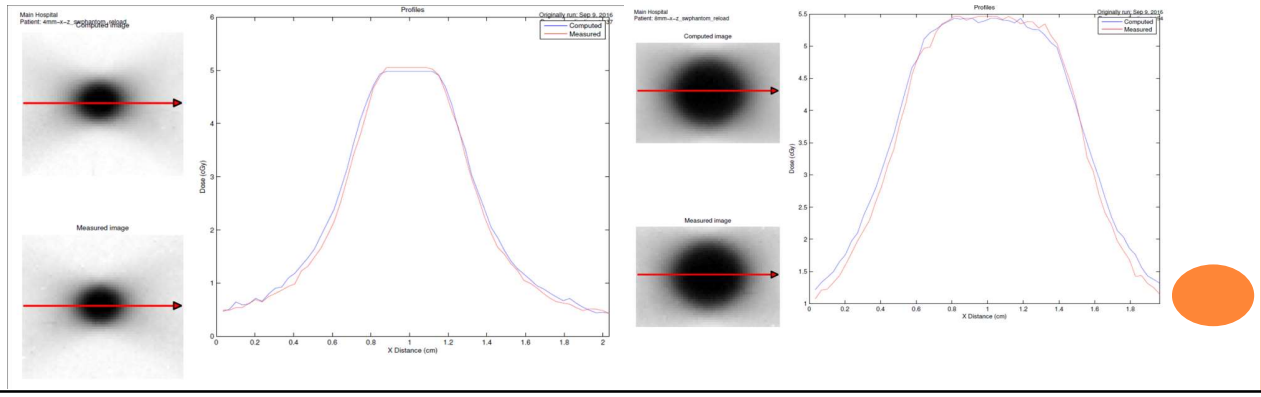
Isocenter Centricity Check 16mm

X	
Approximate In-Field Intensity Value:	5800
Use curser to determine approximate intensity value in the flat portion of the delivered field. Exact value is not important.	
Pin-Prick Position:	1.626
Use curser to determine the position of the center of the pin prick	
50% Intensity Value:	2900
Left 50% Intensity Position:	0.3048
Left 50% Intensity Value:	2885
Distance to Pin-Prick - Left:	1.32
Use curser to determine position and intensity value on the left side of the profile. Choose the position closest to the calculated 50% intensity value.	
Right 50% Intensity Position:	2.946
Right 50% Intensity Value:	2862
Distance to Pin-Prick - Right:	1.32
Use curser to determine position and intensity value on the left side of the profile. Choose the position closest to the calculated 50% intensity value.	
Distance Difference:	0.00
Tolerance (cm):	0.05
Pass?:	PASS

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

PROFILE COMPARISON

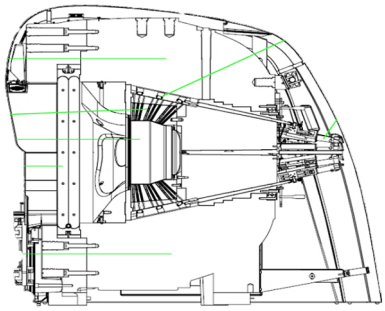
- Annual vs Baseline



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

TREATMENT UNCERTAINTIES

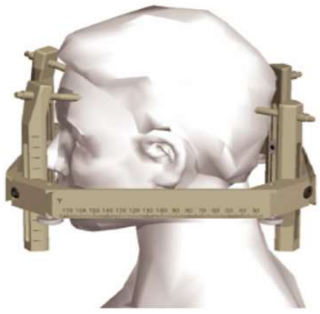
- **Mechanical performance of treatment unit**
  - Daily verification of radiation iso vs couch position
  - Couch position sensors stop tx at >0.1mm deviation
  - Plate motion and collimator design minimize opportunity for wear and error
  - Positioning accuracy guaranteed through service contract and verified during bi-annual PM
  - Novotny et al in Med Phys: *Long-term stability of the Leksell Gamma Knife® Perfexion™ patient positioning system (PPS).*
    - Measurements collected over 4 years
    - Average deviations 0.1mm or less



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

TREATMENT UNCERTAINTIES

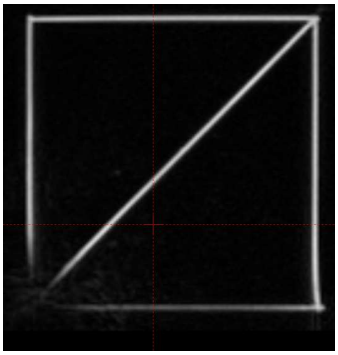
- **Frame integrity**
  - Once images are obtained, frame placement is assumed to be invariant
  - Improper frame placement could lead to frame shift which may not be caught prior to treatment
  - **Experienced neurosurgeon extremely important**
    - Frame assembly
    - Frame position
    - Pin entry angle
    - Pin pressure
    - Patient history
  - If in doubt – re-image!



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

TREATMENT UNCERTAINTIES

- **Uncertainty due to image distortion or registration**
  - MR distortion always present
    - Increases with distance from imaging isocenter
    - Increased near GK frame
  - CT/MR registration introduces error
    - Carefully verify automatic registration results
    - Consider MR distortion during registration
      - Avoid focusing on areas of known MR distortion



MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

GAMMA KNIFE ICON

- Newest Gamma Knife platform
- Perfexion body with added CBCT
- Includes infrared tracking for frameless treatment
- May:
  - Expand GK use to include more fractionated treatments due to frameless tracking
  - Allow for quick verification of frame integrity prior to treatment for traditional patients
  - Track frame integrity throughout treatment with infrared system

MUSC Health
MEDICAL UNIVERSITY of SOUTH CAROLINA

REFERENCES

- McDonald, D., Yount, C., Koch, N., Ashenafi, M., Peng, J., & Vanek, K. (2011). **Calibration of the Gamma Knife Perfexion using TG-21 and the solid water Leksell dosimetry phantom.** *Medical Physics, 38*(3), 1685-1693. doi:101118/13557884
- Ulin, K., Urie, M. M., & Cherlow, J. M. (2010). **Results of a multi-institutional benchmark test for cranial CT/MR image registration.** *International Journal of Radiation Oncology* Biology* Physics*, *77*(5), 1584-1589.
- Pappas, E. P., Seimenis, I., Moutsatsos, A., Georgiou, E., Nomikos, P., & Karaiskos, P. (2016). **Characterization of system-related geometric distortions in MR images employed in Gamma Knife radiosurgery applications**. *Physics in Medicine and Biology*, *61*(19), 6993.
- Novotny Jr, J., Bhatnagar, J. P., Xu, Y., & Huq, M. S. (2014). **Long-term stability of the Leksell Gamma Knife® Perfexion™ patient positioning system (PPS).** *Medical physics*, *41*(3), 031711.

SAM Question 1

- Uncertainty during treatment on the Gamma Knife Perfexion is predominantly due to:
  - Mechanical performance of the treatment machine
  - MLC positioning error
  - Frame integrity and planning image registrations and distortions
  - Machine output fluctuation

SAM Question 1

- Uncertainty during treatment on the Gamma Knife Perfexion is predominantly due to:
  - Frame integrity and planning image registrations and distortions

- References

  - Ulin, K., Urie, M. M., & Cherlow, J. M. (2010). **Results of a multi-institutional benchmark test for cranial CT/MR image registration.** *International Journal of Radiation Oncology* Biology* Physics*, *77*(5), 1584-1589.
  - Pappas, E. P., Seimenis, I., Moutsatsos, A., Georgiou, E., Nomikos, P., & Karaiskos, P. (2016). **Characterization of system-related geometric distortions in MR images employed in Gamma Knife radiosurgery applications**. *Physics in Medicine and Biology*, *61*(19), 6993.
  - Novotny Jr, J., Bhatnagar, J. P., Xu, Y., & Huq, M. S. (2014). **Long-term stability of the Leksell Gamma Knife® Perfexion™ patient positioning system (PPS).** *Medical physics*, *41*(3), 031711.

SAM Question 2

- MR Distortion Due to the GK Frame Base is:
  - Minimal compared to distortion already inherent in MR imaging
  - Significant adjacent to the frame base, decreasing as distance from the frame base increases
  - Corrected during the localization process
  - Minimal compared to mechanical uncertainty of the treatment unit

SAM Question 2

- MR Distortion Due to the GK Frame Base is:
  - Significant adjacent to the frame base, decreasing as distance from the frame base increases

- References
  - Pappas, E. P., Seimenis, I., Moutsatsos, A., Georgiou, E., Nomikos, P., & Karaiskos, P. (2016). **Characterization of system-related geometric distortions in MR images employed in Gamma Knife radiosurgery applications**. *Physics in Medicine and Biology*, *61*(19), 6993.