Building a Dose Verification Model for M6™ Cyberknife® System using Monte Carlo Simulation

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INTRODUCTION

M6™ CyberKnife®

- The M6™ CyberKnife® (M6CK) is a Stereotactic Robotic Radiosurgery System (Accuray Inc., Sunnyvale. CA), equipped with Incise™ 2 Multi-Leaf Collimator (IMLC) system (26 pairs of Tungsten leaf, each leaf of width 3.85mm at 800mm SAD) for cancer treatments[1].
- It enables the delivery of 6MV Flattening Filter Free (FFF) photon beam from multiple directions with stereotactic precision provided by image guidance, thereby providing a few mm accuracy for both static, as well as dynamic targets.
- It has a potential to improve the Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT) cancer treatments.

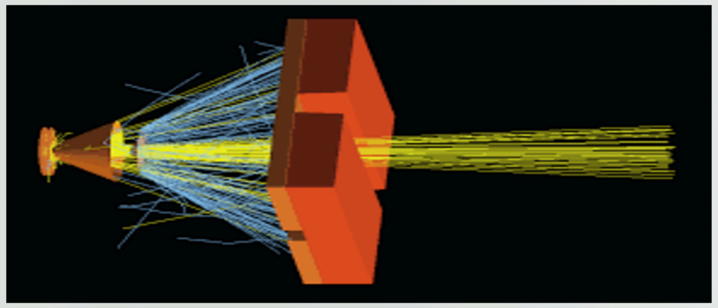


FIG 1: Sample MC Beam Simulation

Monte Carlo Simulation

- Monte Carlo (MC) simulation in radiation therapy uses the probability distributions governing the interactions of electrons/photons in materials to simulate the random trajectories of particles for a large number of histories to provide the required information on the average physical quantities[2].
- The MC simulation efficiency is given by $\varepsilon = \frac{1}{S^2 * T}$ where s^2 is sample variance (uncertainty), T (time) is proportional to N (# of particles)
- MC dose prediction model is proven to be the most accurate dose calculation method. It is recommended as an independent tool to validate the existing dose calculation modalities, specifically in heterogeneous media and complex geometries.
- Energy Gamma Shower (EGSnrc) is a user-friendly and widely accepted MC program/code in Radiation Therapy.

PURPOSE

- To build an efficient MC model for the dose calculations in heterogeneous media and the complex geometry of the M6CK for SRS/SBRT treatments.
- To validate the MC model within the treatment planning system using different dose measurements methodologies.
- To calculate the field specific-correction factors/output factors in small fields and investigate the implementation in patient specific quality assurance[3,4].

MATERIALS AND METHODS

BEAMnrc: BEAM Modeling

- The M6CK head including an IMLC was modeled, based on detailed diagrams provided by Accuray Inc. (Sunnyvale, CA) using the BEAMnrc simulation with millions of primary charged particles (histories) striking the target[5].
- The linac head was modeled using a mono-energetic electron beam with 2D Gaussian beam profile as a primary source and optimized with measurements at 800 mm SAD in water phantom.
- A new module (input file) for the IMLC was created upon the pre-existing regular MLC modules.

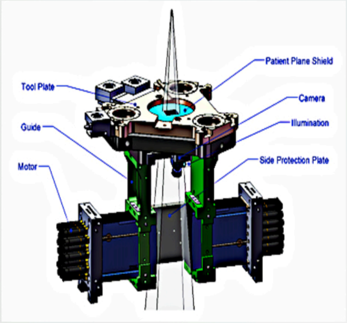
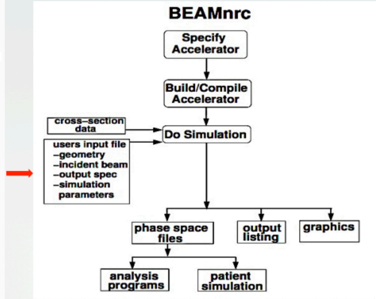


FIG 2: M6CK Robotic Radiosurgery Linac (Accuray Inc., Sunnyvale, CA)



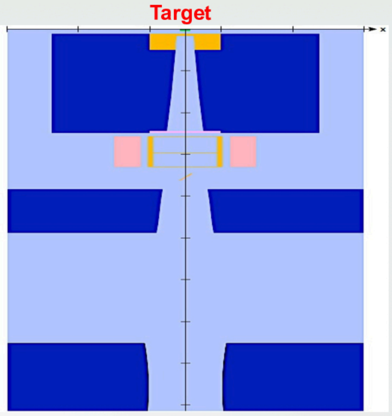
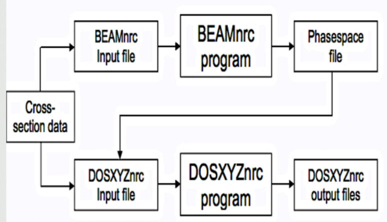


FIG 3: M6CK BEAM model

DOSXYZnrc: MC Dose



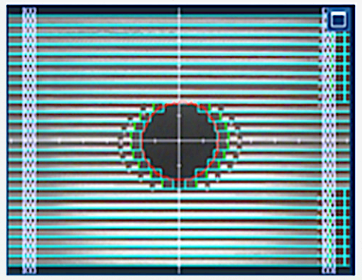


FIG 4: processed view of IMLC in M6CK

TMR Method

- Set up 1
  - SAD - 80cm
  - SSD - 78.5 cm
  - Depth - 1.5 cm
- Set up 2 (MapCheck QA)
  - SAD - 80 cm
  - SSD - 73 cm
  - Depth - 7 cm
- TMR= D(d=7)/D(d=1.5)

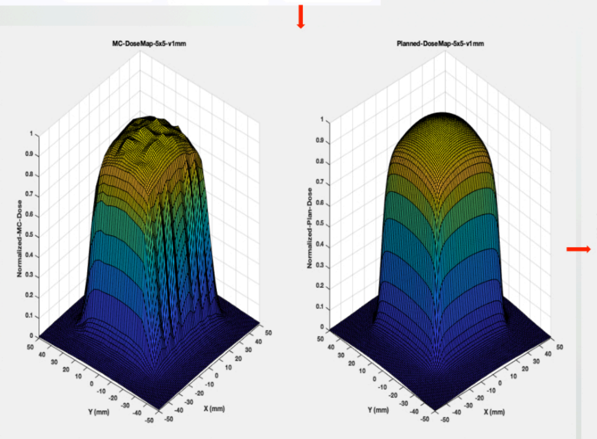


FIG 5: MC vs treatment planned dose profiles

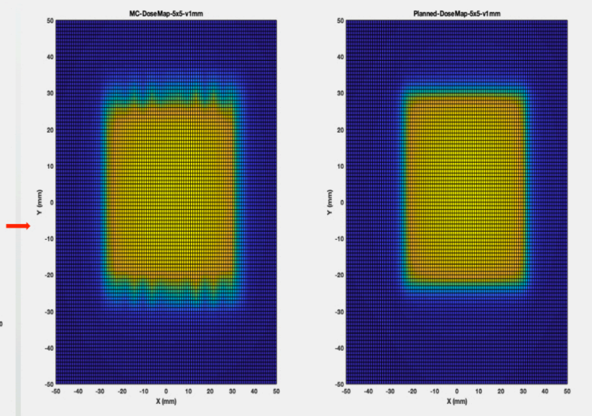


FIG 6: MC vs treatment planned 2D dose-maps

MC Simulation Process

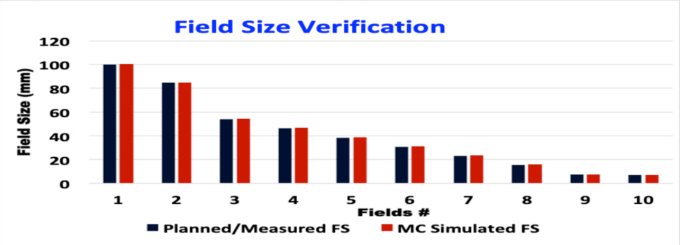
- The phase space files in the BEAMnrc are stored before and after IMLC for every particle crossing a scoring plane, and then fed into the DOSXYZnrc for MC dose calculations in a phantom[6].
- Several simulations were performed by varying the number of initial histories (10-20 millions), energy (6.5-7MeV) and FWHM (1.8-2.4mm) of primary beam and the voxel size (1-5mm) of the phantom. The dose profiles and depth dose curves were plotted for all open fields from 100x100.1 -7.6x7.7 mm² at 800 SAD in water phantom[7].
- The MC simulated dose profiles for all the open fields were compared with those generated by Accuray Precision tools (measurements) to validate our MC model.
- During the simulation, various variance reduction techniques (range rejection, photon forcing, Bremsstrahlung splitting) were applied to minimize the statistical uncertainties and optimize the simulation efficiency.

RESULTS

MC Model Validation Process: Our MC model verification involves the following steps:

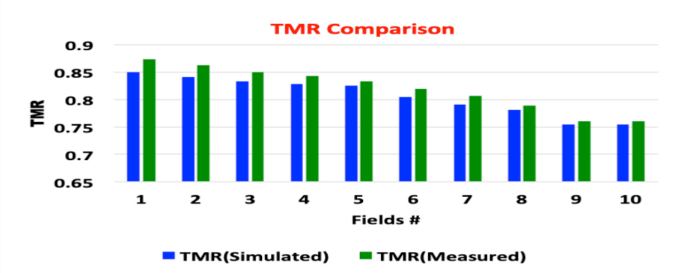
1. Field Size Verification: Dose Profiles

- Comparison of dose profiles (800 mm SAD in water phantom) for the open fields (100x100.1 to 7.6x7.7 mm²) between MC and treatment plans by defining the Full Width-Half Maximum (FWHM). Agreement ~ 2% was found.



2. Depth Dose Comparison: TMR Method

- Depth dose curves for open fields (100x100.1 to 7.6x7.7 mm²) between the treatment plans and MC plans were compared using TMR method, and an agreement ~ 3% was found.



3. Gamma Evaluation:

- Gamma analysis with 3%/3mm and 2%/2mm criteria between the MC and treatment plans have satisfied ≥95% passing rate[8].

CONCLUSIONS AND FUTURE WORK

- The preliminary results have shown that our MC model can be applied for the M6CK system with 6MV nominal photon beam (equivalent to E=7MeV, FWHM=2.2mm) for accurate dose calculations.
- Good agreements for all the open fields (100x100.1 to 7.6x7.7 mm²) ~ 2% for dose profiles and ~3% for dose outputs between the treatment plans and MC plans were found along with 2% dose uncertainties.
- We are working on simulations for higher numbers of initial particles/histories by using parallel processing to further reduce the dose uncertainty (<1%).
- We calculate the field-specific correction factors, specifically in small fields (CAX and Off axis), which could have potential implications in patient specific quality assurance.

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