Simulation-Free Radiation Therapy for Knee Osteoarthritis: A Streamlined, Dosimetrically Robust, Measurement-Based Approach

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INTRODUCTION

Background: Low-dose radiotherapy (LDRT) is an increasingly adopted modality for mitigating pain and inflammation in benign joint disorders, such as knee osteoarthritis (OA) [1].

Clinical Motivation: As the adoption of OA radiotherapy increases, the logistical burden on imaging and treatment planning resources scales proportionally. CT simulation slots are highly impacted, forcing benign cases to compete with complex, curative-intent oncology cases. Minimizing or eliminating CT simulation time for OA patients is critical to preserving clinic throughput and expanding patient access.

Current Paradigm: Simulation-free radiotherapy (SFRT) has gained traction in palliative care to expedite treatment for bone metastases by utilizing simple anatomical landmarks with great success in reducing clinic load [2]. Given the geometric simplicity and patient to patient consistency of the knee joint, adapting the SFRT paradigm for OA treatments represents an intuitive and safe operational advancement.

Objective: To design, validate, and implement a simulation-free setup for LDRT of knee OA relying exclusively on simple external patient measurements and a customized AP-PA hand-calculation model to provide dosimetrically robust treatments without the need for CT simulation.

MATERIALS AND METHODS

Workflow Design: A Simless-RT workflow was established where anterior-posterior (AP) and lateral knee separations are acquired with calipers during consultation or clinical sim/treat.

Hand Calculation: Measurements are input into an in-house spreadsheet utilizing simplified TG-71 formalism to calculate MUs.

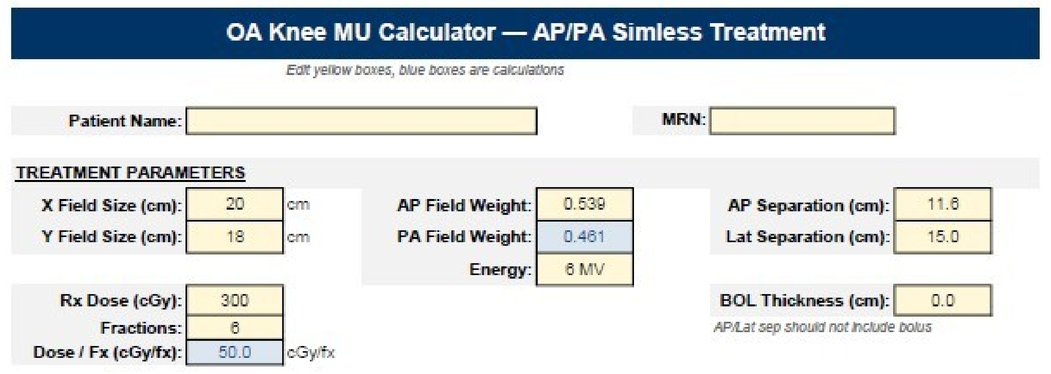
Dosimetric Validation: Knee phantoms were modeled in Eclipse representing a range of AP separations from 9.5 cm up to 16.1 cm.

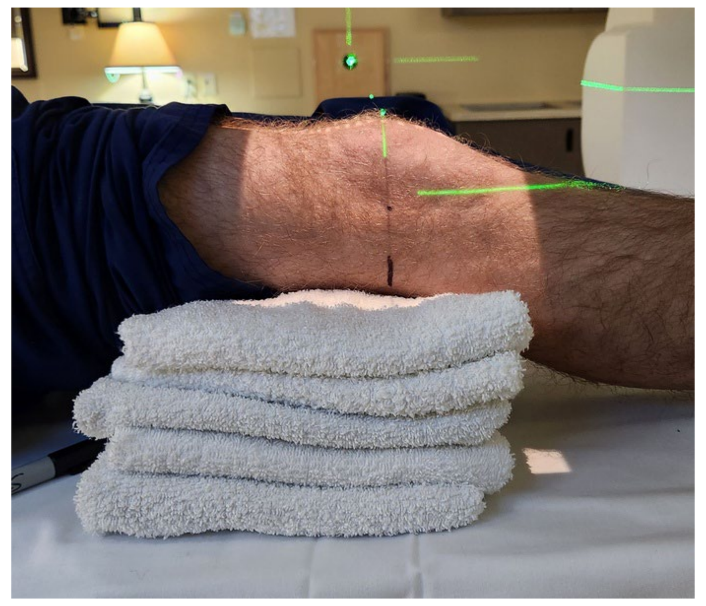
Treatment Parameters: Standardized AP-PA plans calculated using 6 MV photons, SAD setup, 20x15 cm fields. The plans are calculated using the Eclipse AAA dose calculation algorithm and normalized to 300 cGy at isocenter to function as a standard reference normalization. To emulate setup error on the 13.3cm AP sep plan, isocenter is shifted on between 2cm anterior to 2cm posterior, keeping MU the same.

Dose Distribution: Modest anterior beam weighting was applied to prioritize dose to the patella.

RESULTS

Clinical Efficiency: The setup and planning are streamlined with therapist input. The input section of the calculation spreadsheet (left) is optimized to only require two measurements and a handful of beam parameters. The plan showed relative insensitivity to realistic anatomic variation and substantial shifts in isocenter placement.





Left: Best results were found by using low-Z/density knee support. Isocenter is placed at midline of knee, separation is measured just inferior to the patella.

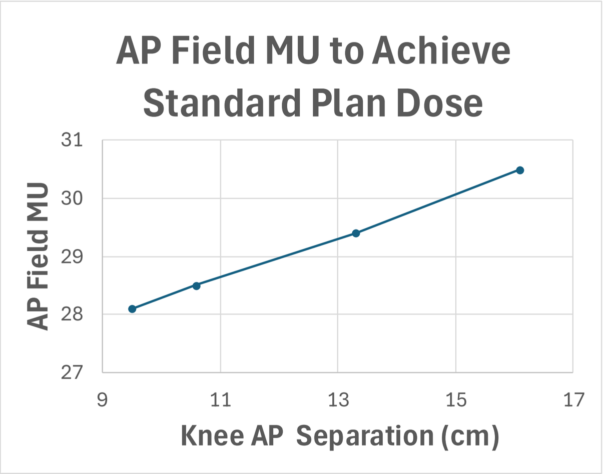


Figure 1: The difference in MU on the AP beam to achieve standard normalization dose

MU Consistency: Across the clinically relevant range of knee separations (9.5 cm to 16.1 cm), calculated MUs demonstrated only 2.4 MU variation across extremes of knee sizes using the 6 MV baseline as seen in Figure 1.

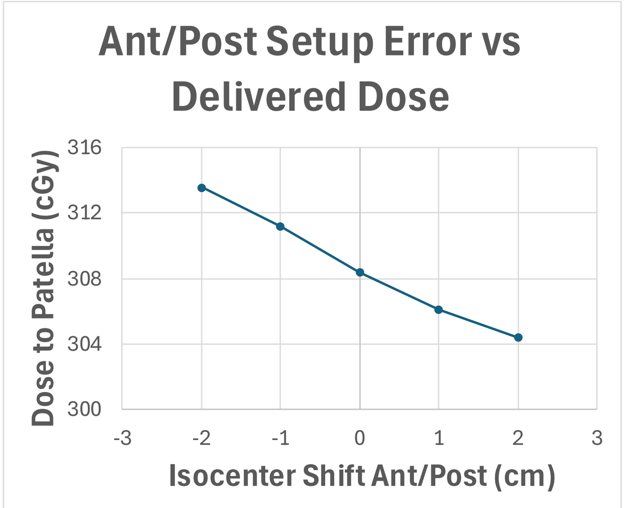
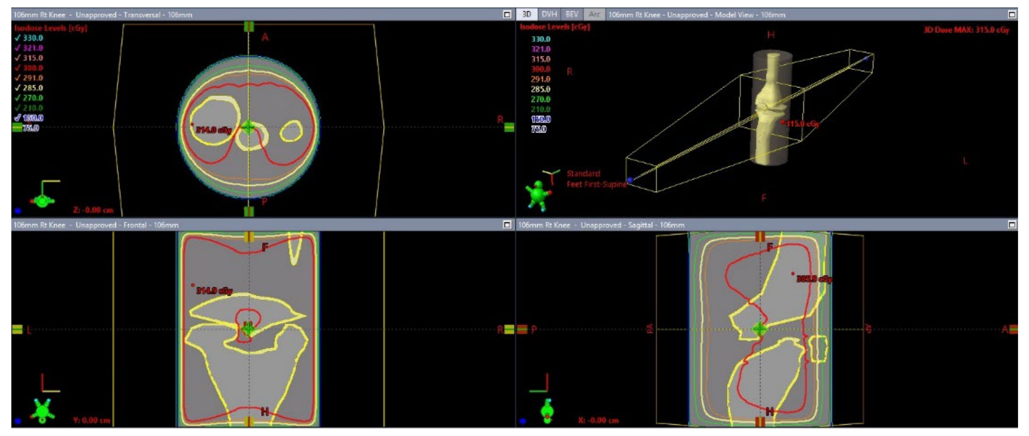


Figure 2: The difference in dose to a point located to the inferior-posterior aspect of the patella and shifting the isocenter ant/post (+shift = anterior) by up to 2 cm. Global hotspot only changed by 1% in extrema.



Above: Eclipse TPS planning setup. Plans are normalized to Rx at isocenter for easy comparison, creating a standard normalization for comparisons

Knee Sep Measurement Tip: Have patient bend their knee like so, place calipers into crook of the knee, then have them relax back down while keeping calipers in place. Once relaxed, drop upper part of calipers to rest on anterior knee (just below patella)

Robustness: The plans appeared highly robust to up to 2cm anterior/posterior setup errors (Figure 2), with only about 5 cGy difference to intended dose to a calculation point chosen in the inferior/posterior aspect of the patella (near the knee joint), corresponding to less than 2% error.

DISCUSSION

Dosimetric Robustness: Hand-calculated AP-PA knee plans based purely on external measurements are dosimetrically reliable.

Setup Verification: First-fraction port imaging (single field) is recommended to verify initial setup, while subsequent fractions rely on external landmarks to limit imaging dose, which could otherwise result in a proportionally significant contribution to total dose.

Clinical Limitations: Patients with knee AP separations outside the validated range (9.5 cm to 16.1 cm) or those requiring complex setups should default to standard CT simulation.

Uncertainty Correction: Uncertainties in the phantom scattering and TPR for non-square phantoms was found to be significant. However, a simple linear correction managed to bring the hand calculator spreadsheet in agreement with the TPS. This can be easily modified to match physician preference by cross calibrating the spreadsheet with a couple simulated cases.

CONCLUSION

Impact: The Simless-RT approach establishes a low-resource, highly efficient treatment paradigm for benign radiotherapy.

Scalability: By removing the CT simulation bottleneck, clinics can improve access for OA patients without compromising dose consistency.

Future Work: Formal Failure Mode and Effects Analysis (FMEA), expansion of validated measurement ranges, and prospective clinical outcome tracking.

REFERENCES

[1] Ott OJ, et al. "DEGRO guidelines for the radiotherapy of non-malignant disorders." Strahlentherapie und Onkologie (2015).
[2] Schuler T, et al. "Real-World Implementation of Simulation-Free Radiation Therapy (SFRT-1000): A propensity score-matched analysis..." International Journal of Radiation Oncology Biology Physics (2024).