Scanning or Scattering? Evaluating Very High Energy Electron Delivery Strategies for Ultra-High Dose-Rate Radiotherapy

Jade Fischer, Andreas Bratel, Deae-eddine Krim, Eric Landström, Erik Engwall and Magdalena Bazalova-Carter

CERN · University of Victoria · CITE · RayStation

INTRODUCTION

- Very high-energy electrons (VHEEs) are an emerging radiotherapy modality capable of treating deep-seated tumors while enabling ultra-high dose rate (FLASH) delivery, making them a promising candidate for next-generation radiotherapy[1].
- No dedicated clinical VHEE system exists; determining the choice of delivery technique will play a critical role in clinical implementation.

Aim: To compare the dosimetric quality and delivery efficiency of VHEE double-scattered 3D conformal radiotherapy (DS 3D-CRT) and pencil beam scanning (PBS) treatment plans.

METHODS

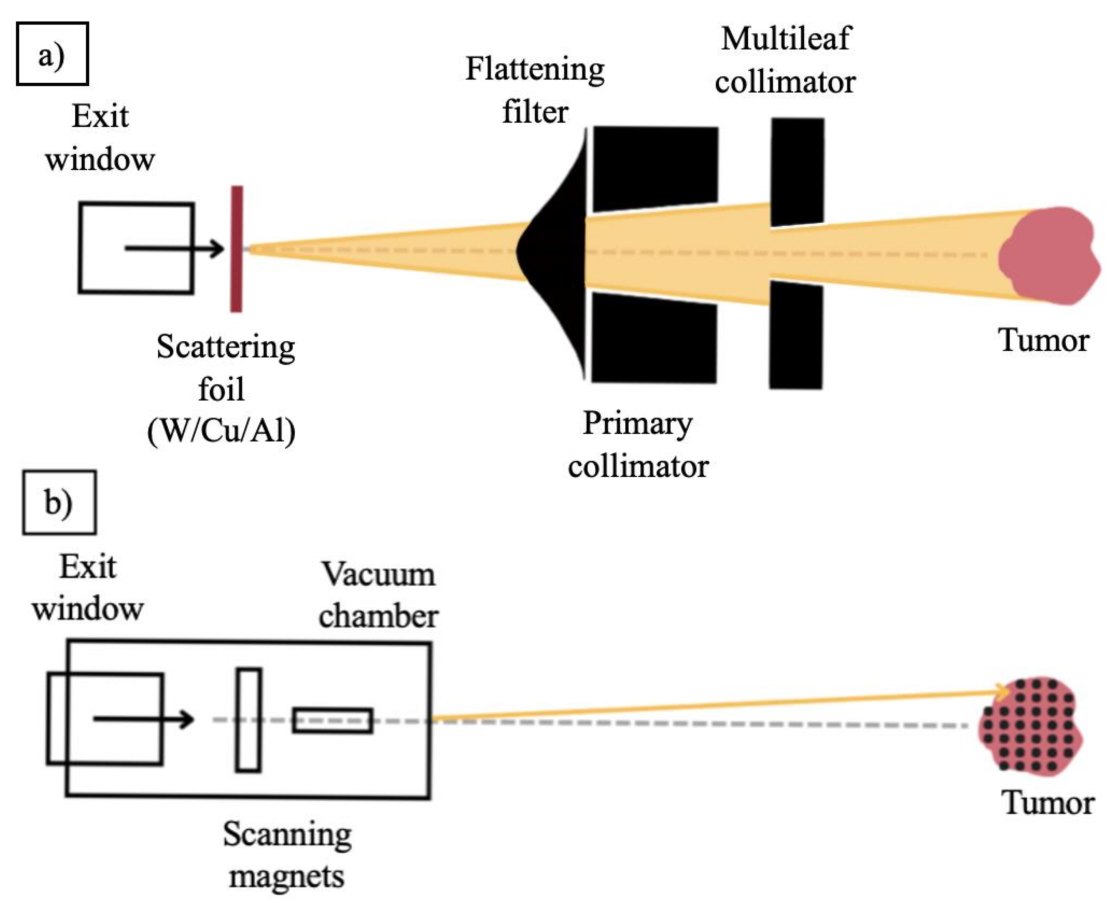

Figure 1. (a) Double scattering (DS) beamline consisting of a copper scattering foil, flattening filter, primary collimator and a secondary collimator. (b) Pencil beam scanning (PBS) beamline utilizing scanning magnets to direct the beam.

- Optimized a 200 MeV double-scattered (DS) VHEE beamline using Monte Carlo simulations to generate flat 5-7 cm fields and imported the resulting phase spaces into RayStation (Version 2024A).
- Validated the RayStation VHEE dose calculation against independent TOPAS Monte Carlo simulations for both PBS and DS.
- Generated VHEE treatment plans for lung, prostate, and glioblastoma patients using DS 3D-CRT and PBS, although only the lung patient is shown here
- Evaluated dosimetric performance and delivery efficiency using plan quality metrics, organ-at-risk doses, dose rates, and treatment times.

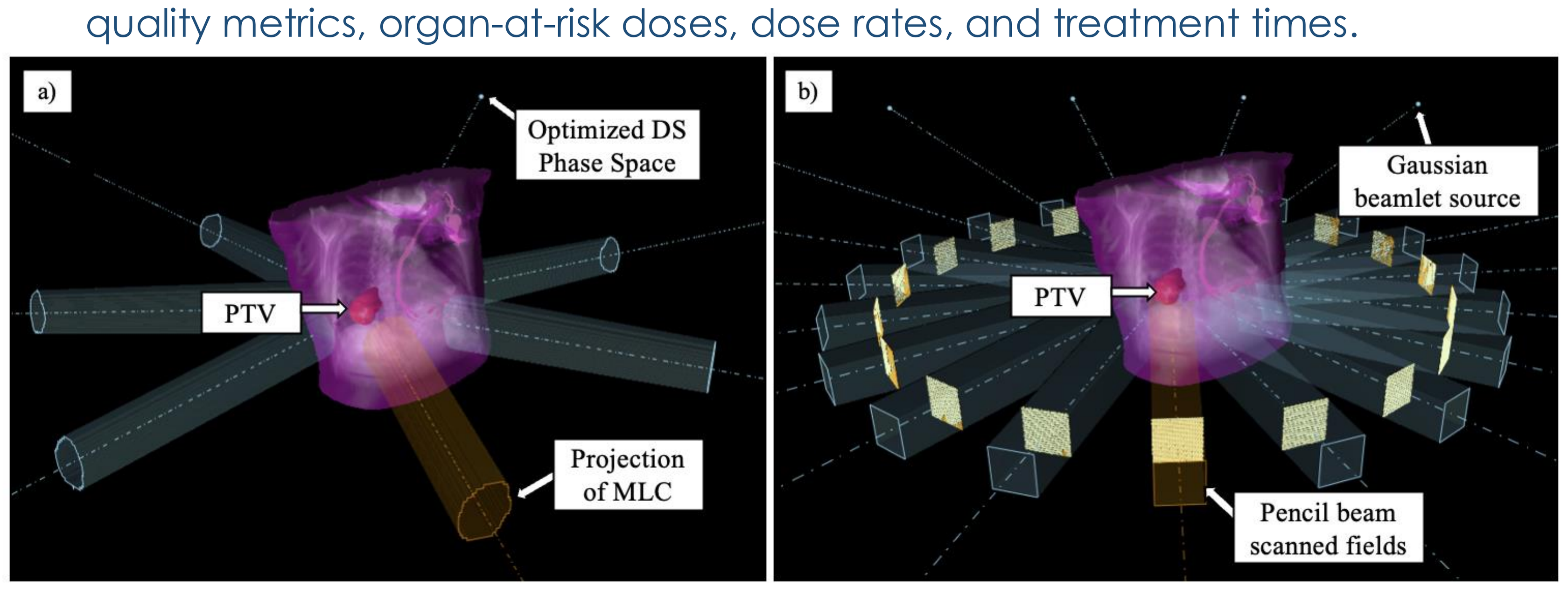

Figure 2. A 7-field DS treatment plan set-up using phase spaces imported into RayStation and conformed with an MLC. (d) A 19-field PBS treatment planning set-up using Gaussian beamlet sources and optimized scanned fields.

RESULTS

- Copper was selected as the optimal scatterer, balancing large field sizes with low photon contamination (<5%).
- An 8 cm tungsten collimator minimized out-of-field dose and beam penumbra
- Resulting fields at 10 cm depth showed clinically acceptable beam flatness (<3%) with penumbras of approximately 6–7 mm.

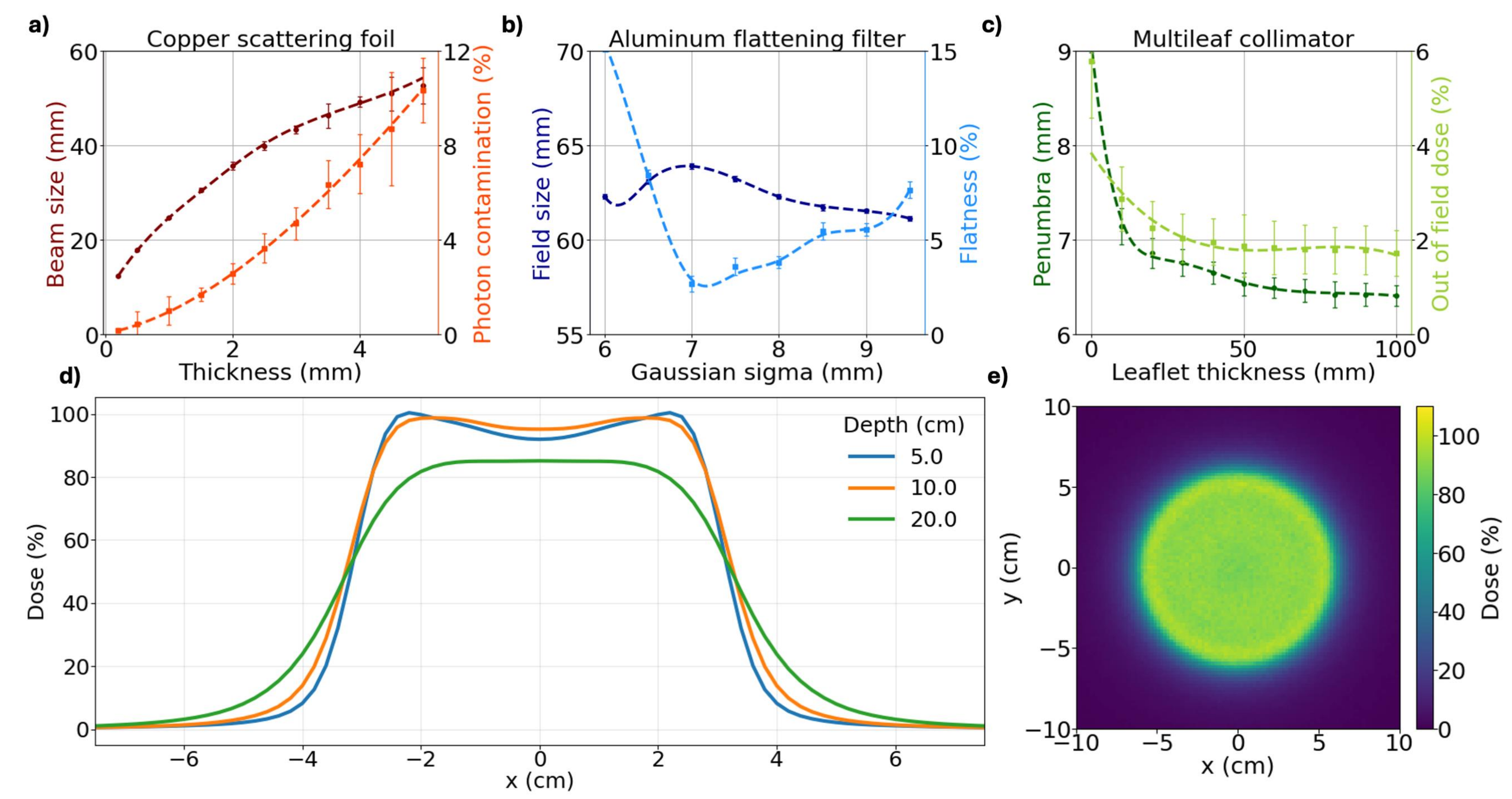

Figure 3. Analytical investigation of double-scattering parameters for a 6 cm field. (a) Scatterer thickness aimed to maximize beam size while minimizing photon contribution. (b) Gaussian flattening-filter width for profile flatness and field size at 10 cm depth. (c) Collimator developed to minimize leakage and penumbra. (d) Dose profiles for the final 6 cm circular field at three depths. (e) 2D dose distribution at 10 cm depth.

- RayStation VHEE dose calculations agreed well with TOPAS Monte Carlo, with maximum PDD differences of ≤3.3% for DS fields and ≤4.2% for PBS beams.
- DS beam penumbra agreed within 0.7 mm between RayStation and TOPAS, while PBS beam widths agreed within 10% at all evaluated depths

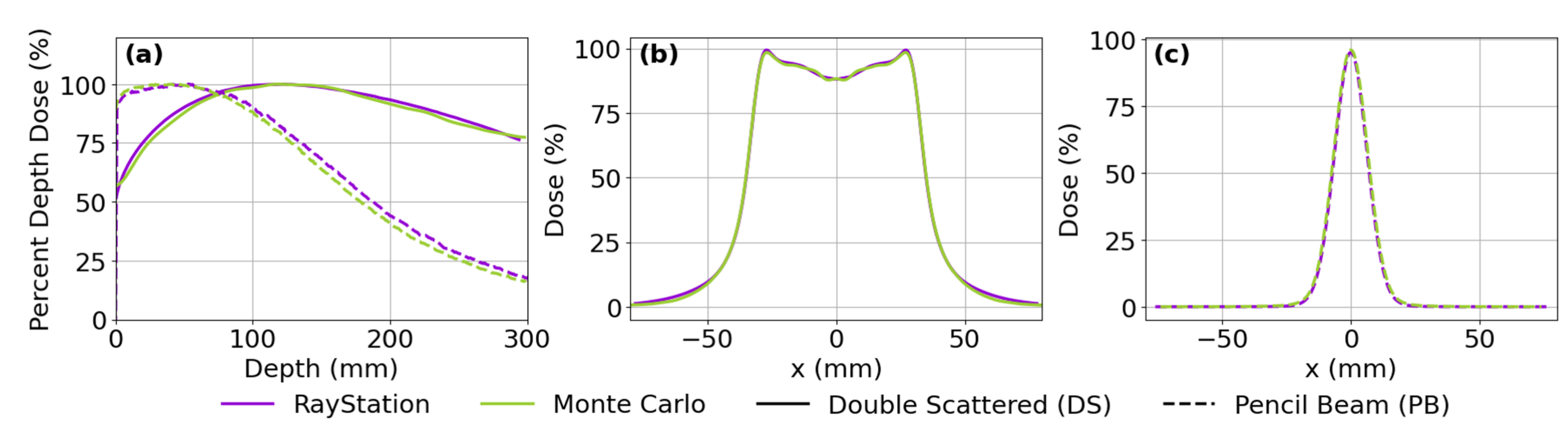

Figure 4. Comparison of the RayStation VHEE dose calculation and TOPAS Monte Carlo with (a) PDD curves and lateral dose profiles at 10 cm depth for (b) a 6 cm DS field with 1 cm MLC margin and for a (c) pencil beam with σ of 5 mm.

- PBS VHEE achieved dose conformity comparable to VMAT, while DS 3D-CRT produced substantially poorer conformity across all tested cases
- For the lung case, PBS reduced mean dose to several organs at risk, including the heart (−20.8%), chest wall (−14.3%), and right lung (−12.5%) relative to VMAT.
- DS 3D-CRT increased dose to most normal tissues, with the spinal cord mean dose in the lung case increasing by over 100% compared with VMAT.

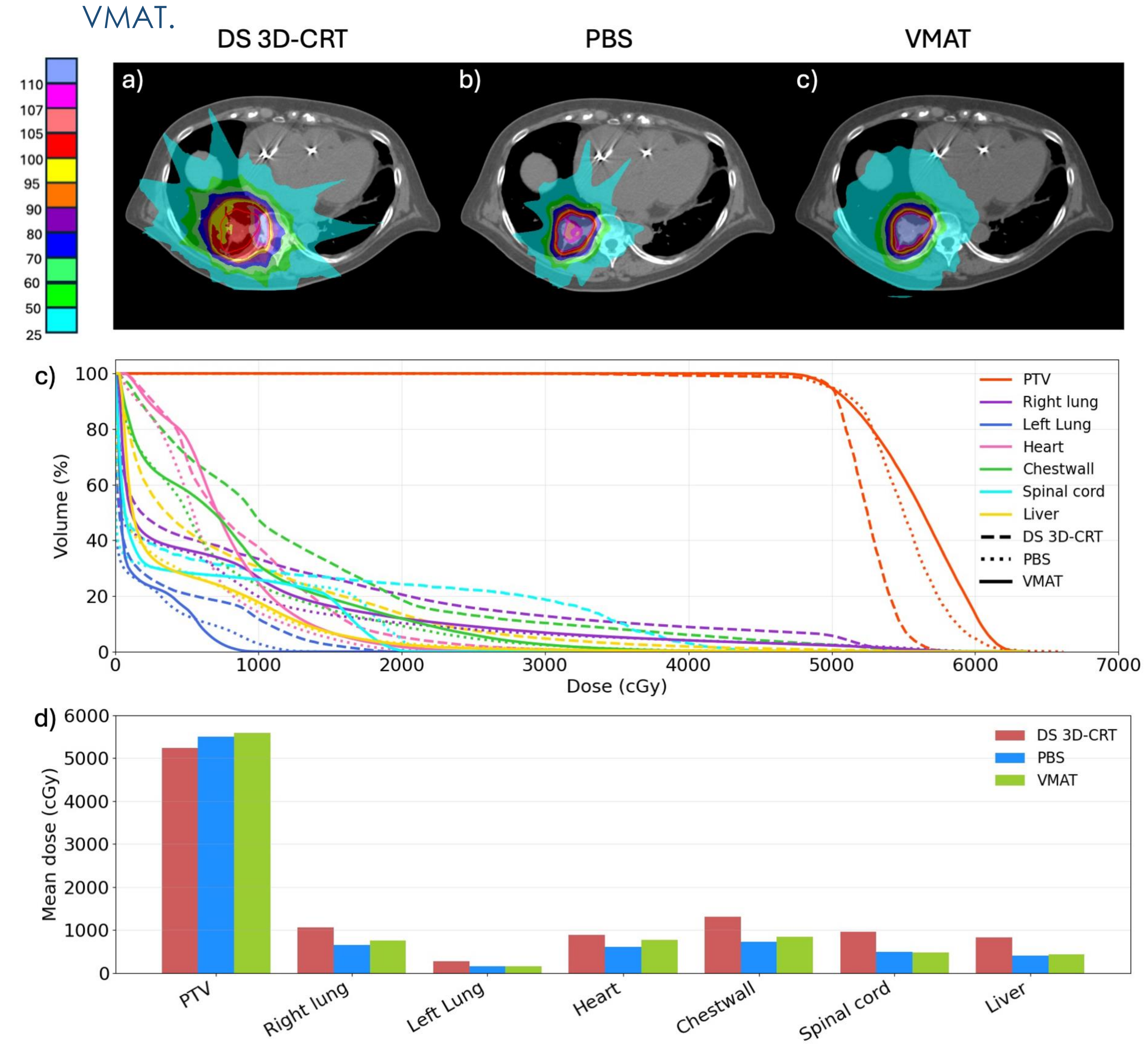

Figure 5. Dose distribution for lung patient planned with (a) 200 MeV DS 3D-CRT, (b) 200 MeV VHEE PBS and (c) 6 MV VMAT (d) Dose-volume histograms for PTV and OARs and (e) mean doses to OARs.

- Estimated treatment times for the lung case were comparable between techniques, with PBS requiring 20.0 s and DS 3D-CRT 17.2 s for a 3-rpm patient rotation
- PBS may achieve instantaneous dose rate of 1.45×10⁸ Gy/s, approximately three orders of magnitude greater than the DS technique ~6×10⁵ Gy/s), with both approaches capable of ultra-high dose rate delivery.

CONCLUSIONS

- PBS VHEE produced treatment plans with target conformity and normal tissue sparing comparable to or better than clinical VMAT.
- DS 3D-CRT consistently resulted in poorer conformity and increased organ-at-risk doses across all treatment sites.
- Despite the greater delivery complexity of PBS, estimated treatment times were similar for both VHEE techniques, with patient rotation dominating overall delivery time.
- These findings support PBS as the preferred delivery strategy for future clinical VHEE radiotherapy systems.

REFERENCES

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Contact: JadeFischer@uvic.ca