Parameterization of brachytherapy source phase space files for GPU-accelerated Monte Carlo particle transport simulation

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ABSTRACT

Purpose: Develop a parameterized brachytherapy source geometry modeling framework for GPU Monte Carlo simulation with an integrated DICOM workflow

Methods:
- Phase-space data generated in egs_brachy; parameterized into probability distributions (position, direction, energy)
- Distributions sampled at runtime on GPU; DICOM RT plan defines dwell positions
- Dose validated against egs_brachy in 3D voxelized water phantoms

Results:
- 0.94 GB phase space compressed to 78 KB
- GPU-sampled distributions closely reproduced reference particle distributions
- g(r), F(r,θ) confirmed against egs_brachy, consistent with TG-43

Conclusion: Parameterized source reduces memory requirements, enabling practical GPU-MC dose calculation for the DMBT tandem Direction Modulated Brachytherapy Tandem(DMBT).

INTRODUCTION

- The Direction Modulated Brachytherapy (DMBT) tandem uses tungsten shielding (Fig 1) to selectively direct dose, sparing organs at risk (rectum, bladder, sigmoid) without compromising target coverage — enabling dose escalation not achievable with conventional tandem-and-ring applicators
- TG-43 cannot model shielded applicators; Monte Carlo is the gold standard but too slow for clinical use
- GPU-MC can close this gap — most relevant for shielded designs like DMBT
- **This study builds the first step:** a parameterized, GPU-efficient source model — the foundation for fast DMBT dose calculation.

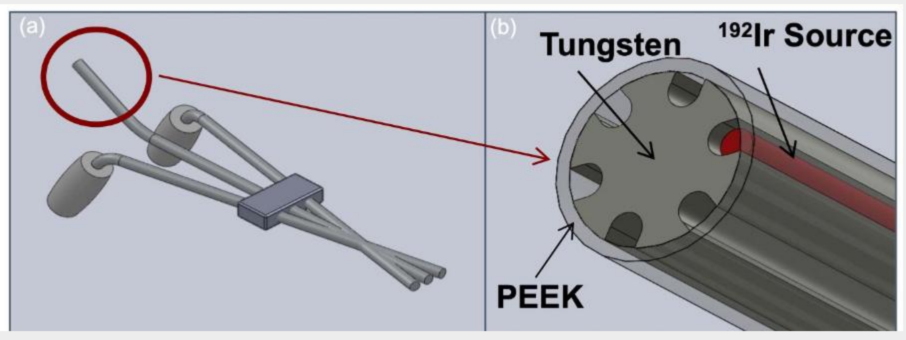


Figure 1. The six-groove DMBT tandem applicator design. (a) a traditional Tandem & Ovoids GYN applicator (b) with the DMBT tandem incorporated in the design.

METHODS AND MATERIALS

1. Source Modelling & Phase-Space Parameterization
- GMP 2012 ^{192}Ir (Fig2) modeled in egs_brachy → 0.94 GB phase space (3.3×10^7 photons)
- Parameterized into position/direction/energy distributions; direction conditioned on 4 regions × 2 energy bins (8 total)

2. GPU Implementation & Validation
- Distributions sampled at runtime on GPU; verified against reference
- Dose validated vs egs_brachy (10.1–30.1 cm³ phantoms, $1\times10^{10}/1\times10^{9}$ histories)

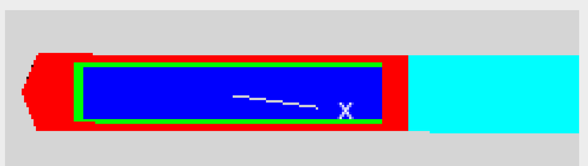


Fig 2. Crossection view of GMP Ir192 source in egs_brachy.

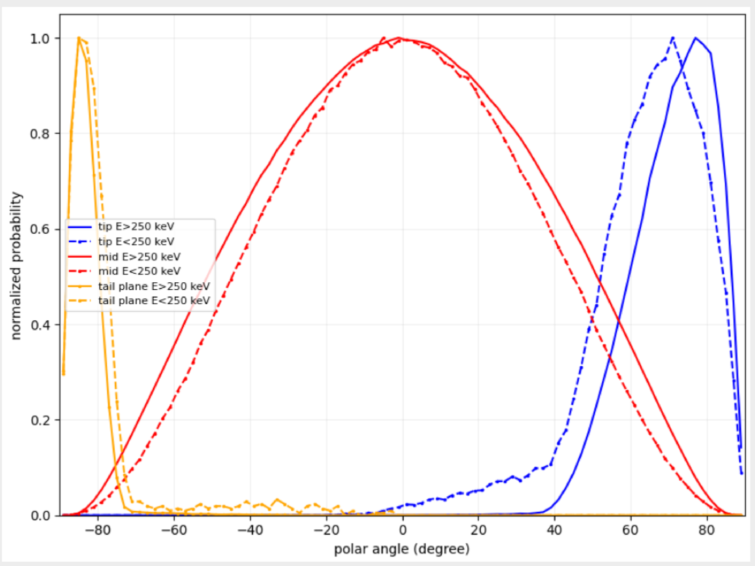


Figure 3. Normalized polar angle distributions for three axial source regions (tip, mid, tail plane), split by photon energy (>250 keV solid, <250 keV dashed). The distinct peak locations and shapes across regions and energy bins justify conditioning the sampled polar angle on both axial position and energy in the parameterized source model.

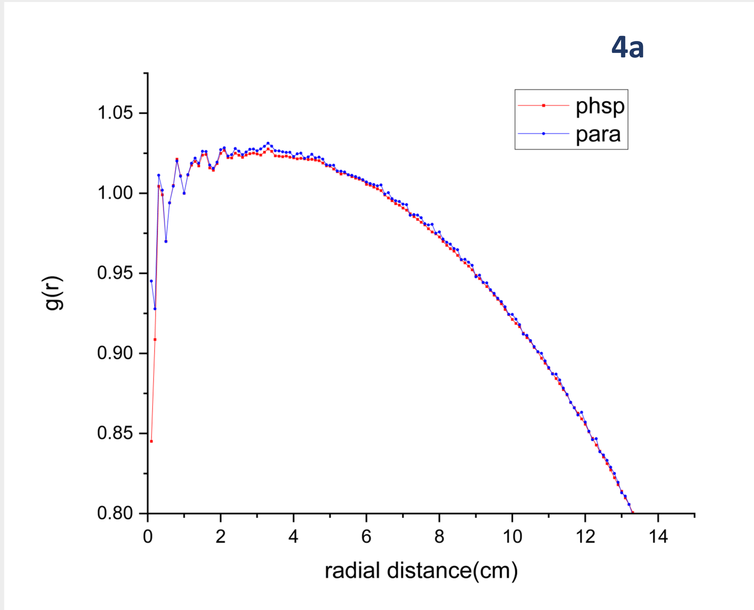
RESULTS

- GPU-sampled distributions (position, energy, angle) closely matched reference phase space across all source regions (Fig 3)
- **g(r):** 0.21% average agreement, r = 0.3–15 cm (Fig 4a)
- **F(r,θ):** within 5% agreement, 15°–165
- **2D dose** (30.1 cm³ phantom, Fig 4b)
- **Phantom-size effect**: consistent across all three sizes tested (Table 1)
- DMBT tandem dose distribution shows comparable agreement between GPU MC and egs_brachy(Fig. 5)
- **Computation time:**

Monte carlo package	egs_brachy	GPU MC
10.1 cm3 water phantom(1mm voxel size)	6.4 hours	**3.3 seconds**

Table 1. Summary of statistical analysis of the percentage dose difference (GPU MC vs. egs_brachy) across three phantom sizes. The range includes 95% of all voxels in the region of interest. Mean and RMS are extracted from a Gaussian fit to the difference distribution.

Phantom size (cm³)	Range(%)	Mean(%)	RMS(%)
10.1	[−3.45−0.2]	-2.07	2.26
20.1	[−3.30−0.4]	-1.93	2.08
30.1	[−2.68+0.05]	-1.38	1.56



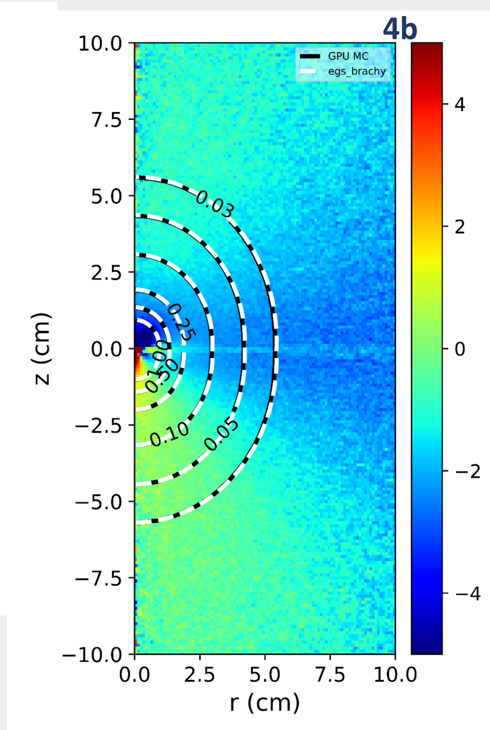


Fig 4a. Radial dose function g(r) computed from the reference phase space (phsp) and the parameterized GPU source (para) in the 30.1 cm³ water phantom.

Fig 4b: Percentage dose difference, $\Delta D(\%) = (D_{(GPU)} - D_{(EGS)})/D_{(EGS)} \times 100$, between GPU MC and egs_brachy in the 30.1 cm³ phantom, with overlaid isodose contours

DISCUSSION

Parameterization: g(r)/F(r,θ) agreement confirms accuracy at >99% smaller file size
Phantom-size trend: matches known scatter-condition effects
DMBT tandem: comparable agreement (Fig 5) — extends method to shielded geometry

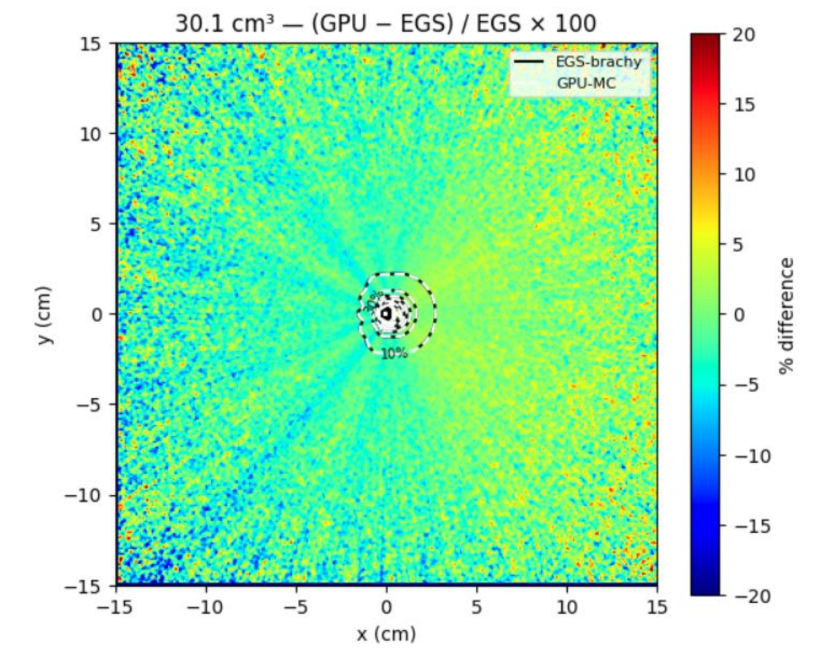


Figure 5. Percentage dose difference, (GPU − EGS)/EGS × 100, between GPU MC and egs_brachy for the DMBT applicator in the 30.1 cm³ phantom (transverse plane), with overlaid isodose contours (EGS-brachy solid, GPU-MC dashed)

CONCLUSIONS

- Parameterized source model provides an accurate, **memory-efficient foundation** for GPU-MC dose calculation, validated for both unshielded and DMBT-shielded geometries.
- **Next**: patient-specific validation against a commercial TPS (BrachyVision ACUROS) on real clinical scenario, extending toward fast adaptive brachytherapy planning.

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