Mixed Voxelized-Mesh Phantoms for Accelerated Patient-Specific Monte Carlo-based HDR Brachytherapy Dosimetry

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Introduction

- RapidBrachyMCTPS [1]: Monte Carlo-based brachytherapy treatment planning system
  - Long simulation times (~hours/plan)
- Computational material phantoms (Fig. 1 top)
  - From CT or contours
  - Define geometry for radiation transport AND dose calculation

Methods

- Mixed voxelized-mesh (MVM) phantoms: accelerate simulations by limiting dose calculation volume (Fig. 1 bottom)
  - Body mesh preserves geometry for scatter
- Body mesh generation implemented into RapidBrachyMCTPS
  - + mesh coarsening
- Timing and dose benchmarked for 10 HDR prostate patients
  - 2×10^7 histories (<1% uncertainty in PTV)
  - Also w/ 3D Slicer body meshes [2]

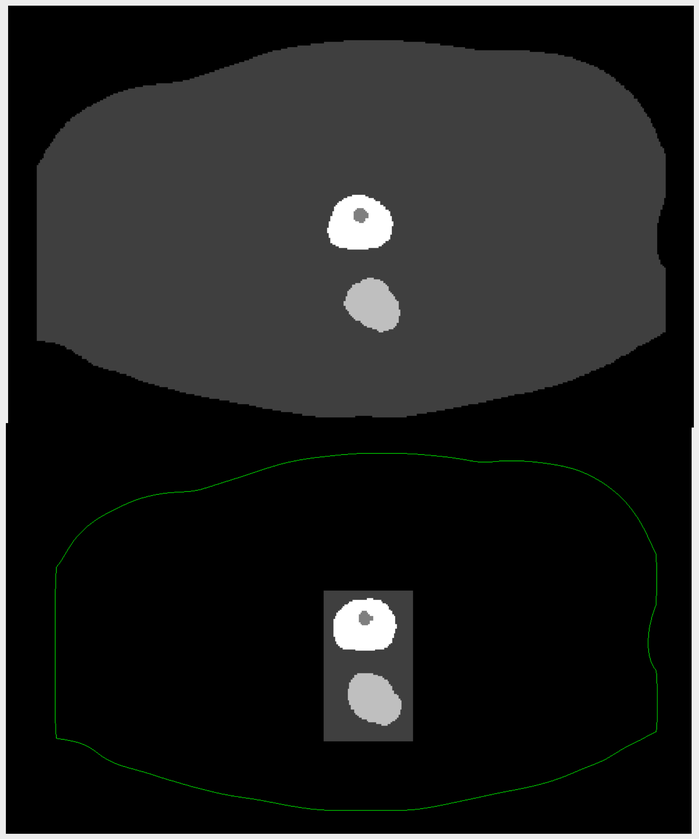

Figure 1: Top: Full voxelized patient phantom with prostate, urethra, bladder, soft tissue, and air (bony anatomy not modeled). Bottom: The same geometry represented using an MVM phantom, including a body mesh (green surface).

Table 1: Maximum percentage difference of key dose-volume histogram metrics for MVM phantoms relative to full voxelized phantoms observed across the 10-patient population.

Maximum Difference [%]	CTV			Rectum	Urethra	
	$D_{90\%}$	$V_{100\%}$	$V_{150\%}$	D_{2cc}	$D_{30\%}$	$D_{10\%}$
MVM + RapidBrachyMCTPS Mesh	0.12	0.17	0.02	0.15	0.11	0.16
MVM + 3D Slicer Mesh	0.09	0.21	0.02	0.13	0.10	0.10

Results

- RapidBrachyMCTPS MVM phantoms: coarse meshes + small phantoms (Fig. 2 left/center) → greatly reduced mean simulation times
  - 110.2 min. → 35.6 min. (Fig. 2 right)
- Root mean square dose differences within 1% for all patients
- Key DVH metrics agreed within 1% across all patients (Tab. 1)

Conclusions

- MVM phantoms: accelerated simulations ~3x while maintaining dose accuracy
- Will support meshes of other contours (bony anatomy)

References

1. RapidBrachyMCTPS 3.0: recent updates and validation of RapidBrachyMCTPS, a Monte Carlo-based brachytherapy treatment planning system. Physics in Medicine & Biology. 2026 Jun 28;71(12):12NT02.
2. Fedorov A, Beichel R, Kalpathy-Cramer J, Finet J, Fillion-Robin JC, Pujol S, Bauer C, Jennings D, Fennessy F, Sonka M, Buatti J. 3D Slicer as an image computing platform for the Quantitative Imaging Network. Magnetic resonance imaging. 2012 Nov 1;30(9):1323-41.

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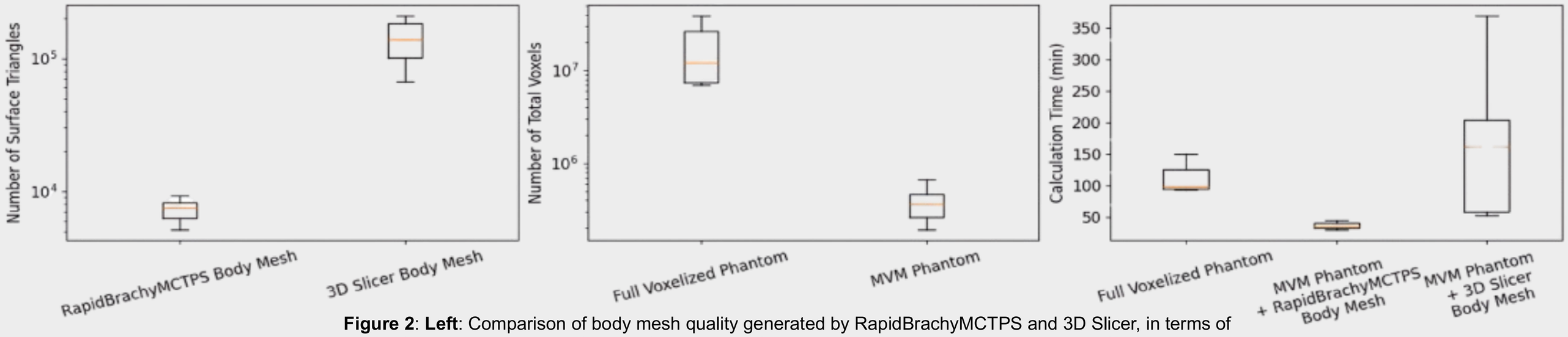

Figure 2: **Left**: Comparison of body mesh quality generated by RapidBrachyMCTPS and 3D Slicer, in terms of number of triangular elements. **Center**: Comparison of total voxelized phantom size between the full voxelized and MVM scenarios. **Right**: Comparison of simulation times across all three scenarios considered.

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