JULY 19–22
2026 VANCOUVER, BC
JOINT AAPM | COMP MEETING

Systematic Optimization of Slit Collimator Design for MV Photon Minibeam Radiation Therapy

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ABSTRACT

Purpose. Photon MBRT creates millimeter-scale peak-valley dose heterogeneity with potential normal-tissue sparing, but practical collimator rules remain insufficiently defined.
Methods. GATE Monte Carlo simulations modeled a 6-MV source, water phantom, and accessory-tray slit collimator. Parameters included slit width/R, material-thickness, and air gap.
Results. Geometry dominated PVDR. Maximum PVDR was 18.7 at 2.0-mm slit width and R=0.2; a more balanced 1.0-mm/R=0.8 design yielded PVDR=7.4. PVDR peaked at a 200-mm air gap.
Conclusion. A quantitative design envelope can guide clinically feasible photon MBRT delivery on conventional linear accelerators.

POSTER AT A GLANCE

18.7 maximum PVDR 2.0 mm slit, R=0.2	**7.4** balanced design 1.0 mm slit, R=0.8
200 mm air-gap optimum for PVDR in this model	**≈58%** peak-dose drop 50 to 500 mm air gap

PARAMETRIC SEARCH SPACE

Geometry	slit width 0.5-2.0 mm; slit-to-blade ratio R=0.1-1.0; divergence-corrected openings
Shielding	materials: tungsten, Lead, brass, SS316, Al; thickness 60-200 mm
Air gap	collimator-to-surface distance 50-500 mm
Endpoints	PVDR, FWHM, peak & valley dose at clinically relevant depths
Selection goal	maximize modulation while respecting leakage, weight, clearance, and manufacturability

REVIEWER-FACING MESSAGE

Problem solved
Collimator design moves from empirical trial-and-error to parameterized selection.

Clinical practicality
The poster explicitly balances PVDR with FWHM, valley dose, shielding thickness, and setup geometry.

What is actionable
The output is a constrained design envelope plus a clear validation checklist, not a single over-optimized geometry.

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INTRODUCTION

Clinical need. Photon MBRT is an SFRT approach designed to preserve normal tissue by creating millimeter-scale peak-valley dose patterns while maintaining high-dose beam tracks.
Translation gap. Accessory-tray metallic slit collimators could enable MBRT on conventional linacs, but small changes in slit opening, blade ratio, shielding, and air gap can strongly alter PVDR, FWHM, and valley dose.
Study question. Which collimator parameters preserve strong modulation while remaining manufacturable and compatible with clinical linac geometry?
Poster focus. A clinically usable design envelope: geometry first, shielding practicality second, and air-gap tuning last.
Decision rule. Do not select by maximum PVDR alone; also consider beam width, valley dose, manufacturability, and QA feasibility.

METHODS AND MATERIALS

Beam model. GATE Monte Carlo simulation of a 6 MV clinical photon beam incident on a water phantom.
Collimator geometry. Source-to-collimator center distance = 425 mm; slit openings corrected for beam divergence.
Parameter sweep. Slit width 0.5-2.0 mm; R=0.1-1.0; tungsten, Lead, brass, SS316, Al; 60-200 mm; air gap 50-500 mm.
Endpoints. PVDR, FWHM, peak dose, and valley dose at clinically relevant depths.
Output. Figures 1-4 and Table 1 summarize representative fields, geometry maps, shielding behavior, and setup-distance response.

REPRESENTATIVE MINIBEAM FIELD

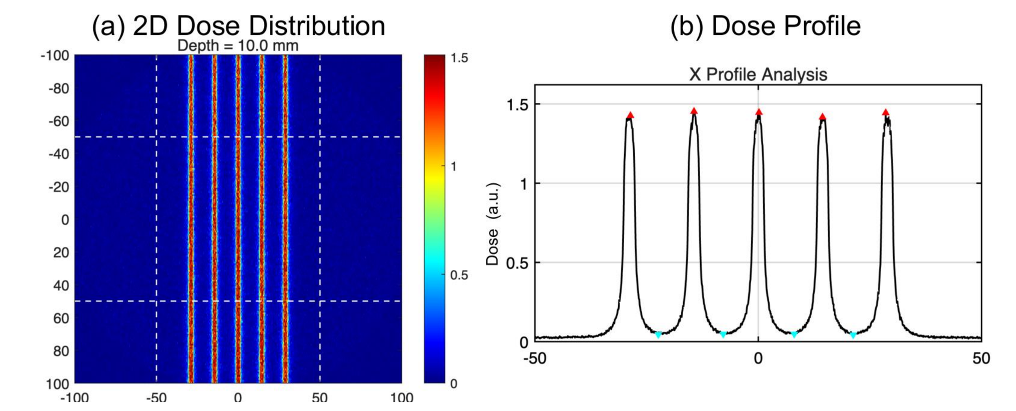

Figure 1. High-PVDR design at 10-mm depth: 2.0-mm slit width, R=0.2, PVDR=18.7.

This example anchors the optimization problem: narrow high-dose tracks must be preserved while suppressing valley dose between tracks.

INNOVATION / IMPACT

First comprehensive parametric map. The work systematically evaluates slit geometry, material/thickness, and air gap across clinically relevant depths.
Evidence-based design rules. Results connect PVDR, FWHM, valley dose, shielding material, and manufacturability into one usable design envelope.
Clinical translation. Accessory-tray photon MBRT becomes a hardware-selection and QA problem rather than a trial-and-error collimator build.
Design value. The same framework can be reused to choose conservative, balanced, or high-PVDR collimator configurations.

DESIGN-TO-QA WORKFLOW

1 Geometry	select slit width + R for PVDR/FWHM target
2 Shielding	choose material + thickness within leakage/weight limits
3 Air gap	tune around the 200-mm response optimum
4 Validate	film / high-resolution detector QA

Clinical use requires independent output, leakage, field-size, tray-clearance, and setup-reproducibility checks before patient translation.

RESULTS 1 | SLIT GEOMETRY MAPS THE DOSE-PATTERN SPACE

Geometry dominated PVDR. Low slit-to-blade ratio R (0.1-0.4) consistently preserved high PVDR across slit widths; wider slits increased FWHM and can raise valley dose.
Pareto interpretation. Maximum PVDR=18.7 occurred at 2.0-mm slit/R=0.2, while a balanced 1.0-mm/R=0.8 design achieved PVDR=7.4 with easier manufacturability.

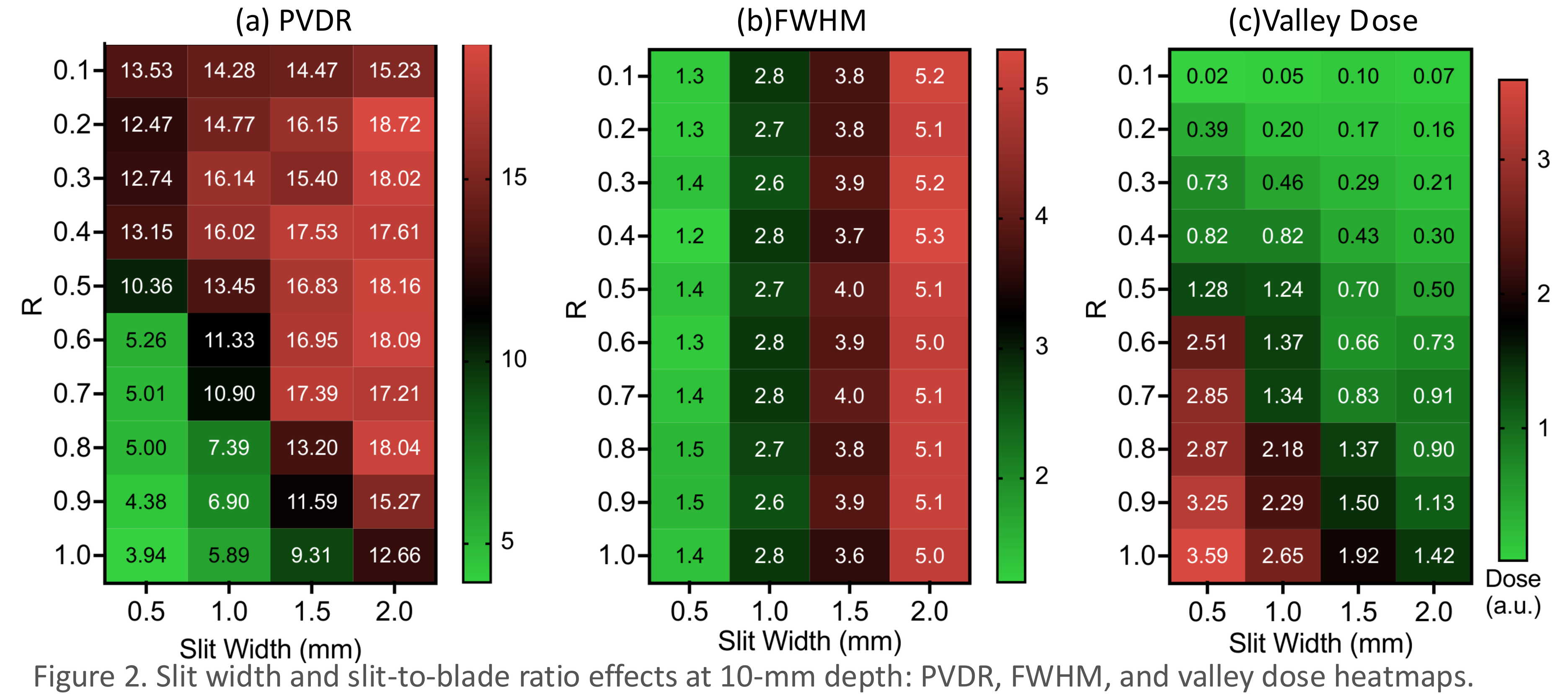

Figure 2. Slit width and slit-to-blade ratio effects at 10-mm depth: PVDR, FWHM, and valley dose heatmaps.

HOW TO READ FIGURE 2
Use the heatmaps to choose a slit width/R region that balances PVDR, FWHM, and valley dose. Low R favors higher modulation, whereas wider slits broaden beam tracks. The practical geometry is the one that meets the target dose pattern while remaining manufacturable and QA-feasible.

RESULTS 2 | MATERIAL AND THICKNESS SET SHIELDING PRACTICALITY

High-density materials reached useful PVDR with shorter collimators. Tungsten/lead were strongest; brass/SS316 required greater thickness; aluminum was not suitable even at 200 mm.
Depth dependence matters. Table 1 shows that material selection should be interpreted at clinically relevant depths, not only at the phantom surface.

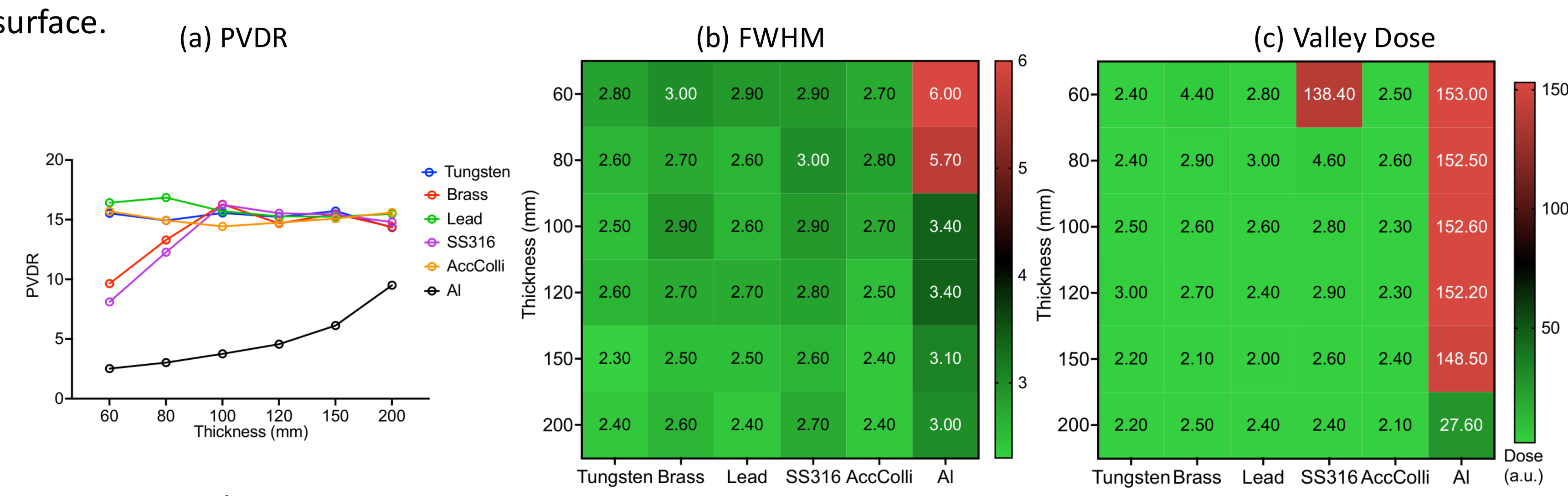

Figure 3. Material/thickness comparison at 10-mm depth: PVDR, FWHM, and valley dose parameter space.

Table 1. PVDR comparison for different collimator materials at 80-mm thickness.

Materials	Density (g/cm³)	PVDR at Different Depth (mm)					
		0	10	20	30	40	50
Tungsten	19.3	6.22	14.94	15.24	14.39	13.89	13.42
AccColli	18	6.14	14.94	15.83	13.33	14.4	12.43
Lead	11.4	5.84	16.85	14.54	13.65	13.62	13.2
Brass	8.55	5.65	13.3	12.79	11.84	10.43	11.85
SS316	8.03	6.43	12.27	12.84	10.87	10.99	13.63
Al	2.7	3.23	3.02	2.64	2.66	2.76	2.78

At 10-mm depth, lead and tungsten achieved PVDR ≈15-17 at 80-mm thickness; aluminum remained low across depths.

RESULTS 3 + DISCUSSION | AIR GAP RESPONSE IS NON-MONOTONIC

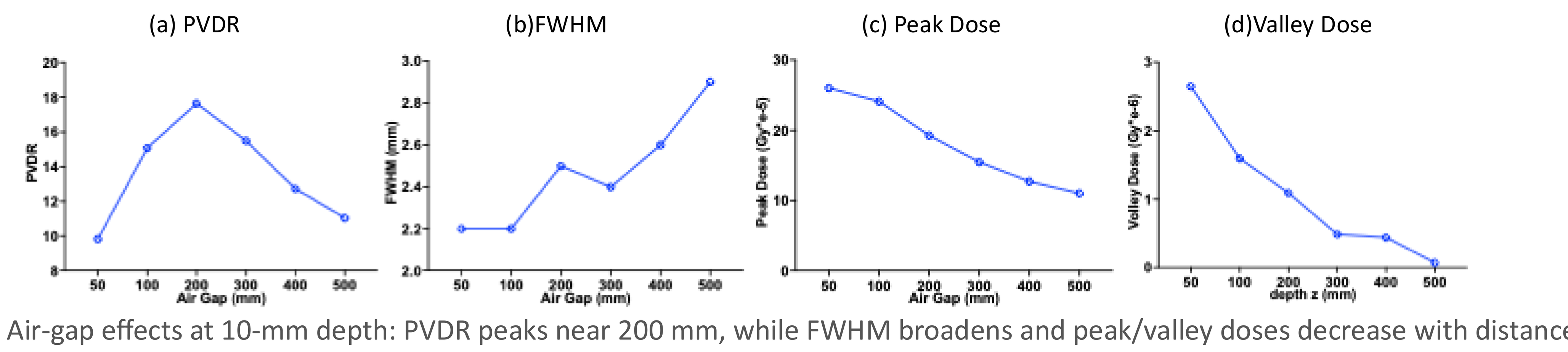

Figure 4. Air-gap effects at 10-mm depth: PVDR peaks near 200 mm, while FWHM broadens and peak/valley doses decrease with distance.

Mechanism. Short gaps suffer from collimator scatter; long gaps increase divergence and valley filling.
Design implication. Select geometry first, then shielding, then tune the air gap around the non-monotonic optimum while checking clearance and QA feasibility.

CONCLUSIONS / REFERENCES

1. Monte Carlo optimization defines a clinically feasible MV photon MBRT slit-collimator design envelope.
2. Geometry is the dominant control; low R values preserve PVDR, but practical choices must consider FWHM and manufacturability.
3. Tungsten/lead provide the strongest shielding; aluminum is inadequate for high-PVDR designs.
4. An air gap near 200 mm provided the best PVDR balance in this model.

TAKE-HOME MESSAGE
A feasible photon MBRT collimator can be selected by jointly optimizing geometry, shielding, and air gap rather than maximizing PVDR alone.