End-to-End Verification of an Open-Source Preclinical Electron FLASH Treatment Planning System

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

INTRODUCTION

- FLASH delivers ultra-high dose rates (UHDR, ≥40 Gy/s), shown preclinically to spare normal tissue while maintaining tumor control.
- Clinical translation requires FLASH-specific treatment planning system (TPS). Vendor phase-space files do not apply to FLASH configurations, necessitating a custom beam model.
- We developed a forward-planning, Monte Carlo–based electron FLASH TPS with a custom beam model of a FLASH-configured clinical linac [1].
- We present its first end-to-end dosimetric verification using bilateral lung irradiation in a mouse phantom.

INNOVATION & IMPACT

- Modeled and verified on, to our knowledge, the **first FLASH-enabled Varian TrueBeam in clinical use**, via a reversible open-source FLASH configuration.
- Streamlines organ-specific collimator fabrication: auto-generates **3D-printing-ready CAD files** for Cerrobend molds and holders.
- Planned **open-source release** to make FLASH research accessible at institutions without dedicated FLASH platforms, enabling multi-institutional trials.
- Future: dynamic FLASH delivery with different *dose-rate* calculation methods for clinically relevant FLASH scenarios.

METHODS

- **Beam model:** Varian TrueBeam linac configured for 12 MeV electron FLASH, modeled in the TOPAS Monte Carlo toolkit [2].
- **TPS:** Python-based; CT/structure import, organ-conformed electron collimator CAD outputs, Monte Carlo dose calculation.
- **Two plans** (anterior–posterior single field, 25 Gy to bilateral lungs):
  - **Plan 1:** 20 × 40 mm^2 rectangular field; end-to-end verification in an anatomically realistic mouse phantom.
  - **Plan 2:** lung-conformed field (contour + 1 mm margin) on a mouse CT.
- **Measurement:** Plan 1 delivered; dose measured in lung at 9.5 mm depth with EBT-XD film; gamma analysis vs. TPS prediction. DVHs computed for both plans.

RESULTS

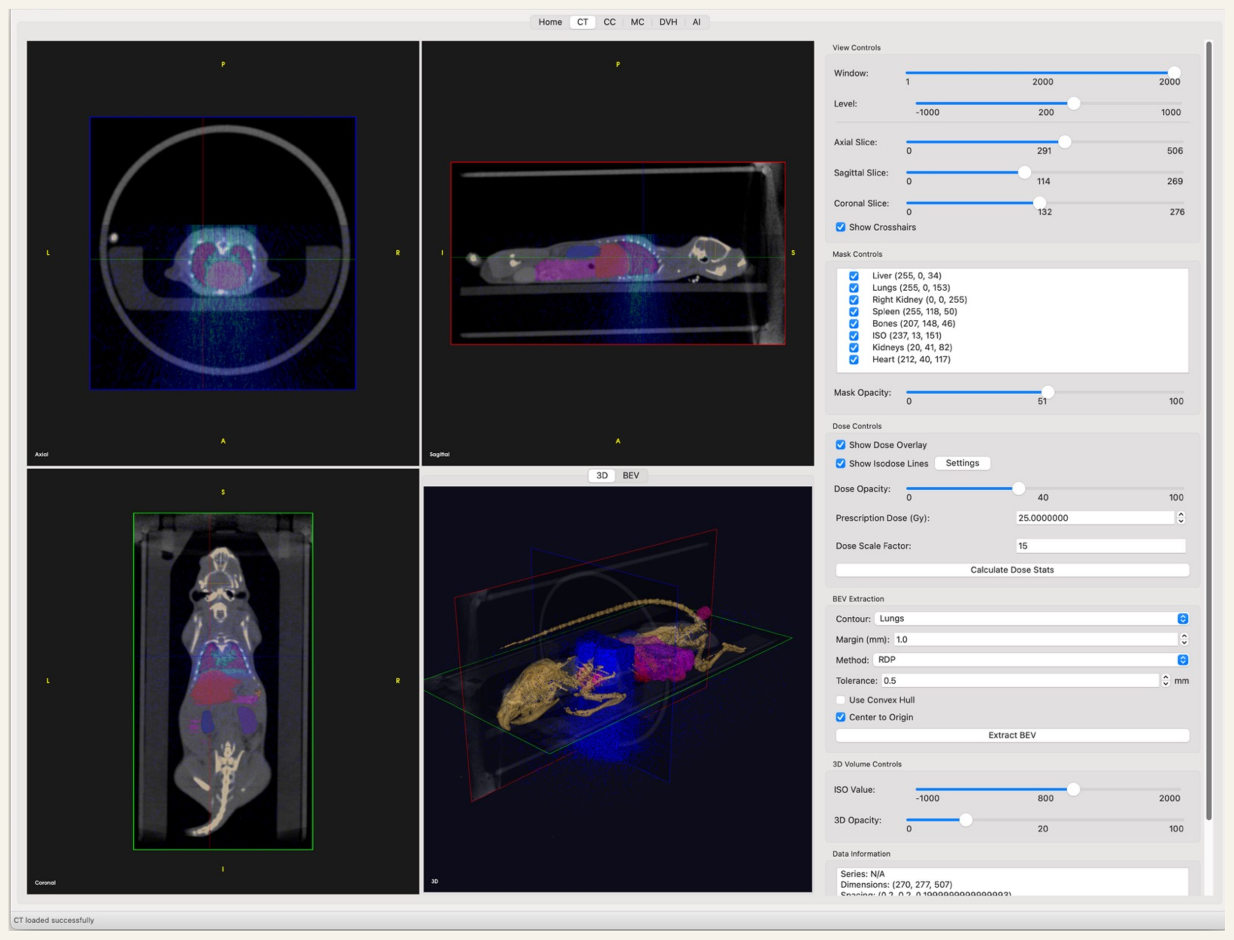


Figure 1. The CT tab of the FLASH TPS: synchronized axial, sagittal, coronal, 3D, and beam's-eye views of a mouse CT with structure contours and dose distribution of a bilateral lung irradiation plan (Plan 2).

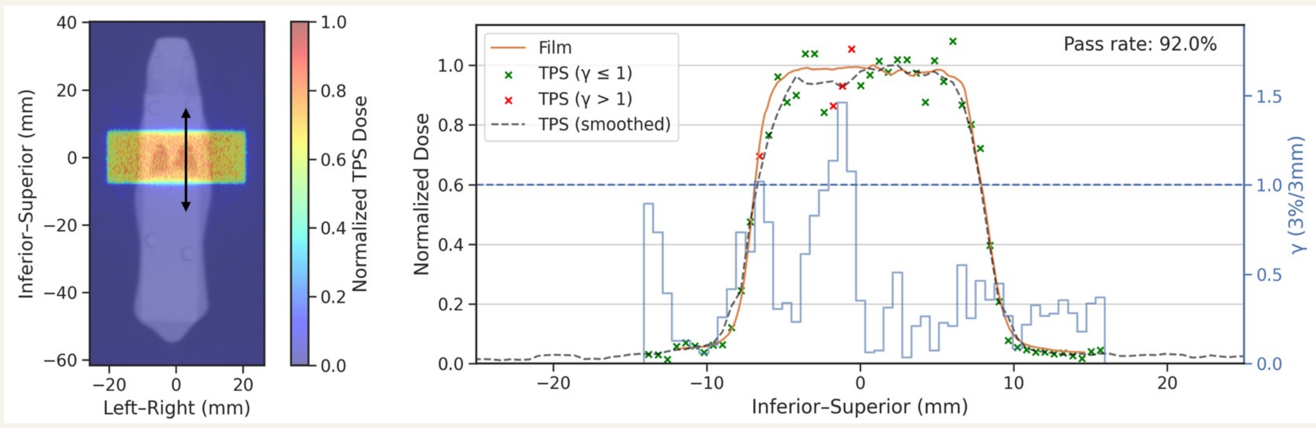


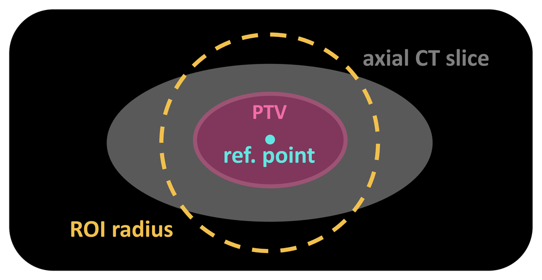
Figure 2. Left: Beam's-eye view of normalized TPS-predicted dose for Plan 1 overlaid on a coronal CT slice of the mouse phantom at 9.5 mm depth; the arrow marks the extracted inferior–superior profile. **Right:** EBT-XD film measurement (orange) vs. TPS prediction along that line; green/red crosses pass/fail 3%/3 mm gamma, with gamma values on the secondary axis.

92.0%	100%
gamma pass rate · 3%/3 mm	gamma pass rate · 5%/5 mm

TPS-predicted dose showed **good agreement with film measurement** in the anatomically realistic mouse phantom, establishing end-to-end dosimetric accuracy of the beam model and dose engine.

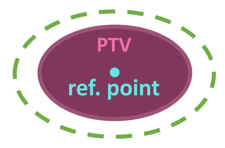
TPS WORKFLOW

1 CT Viewer — Load & Setup
- Load CT + structures (incl. PTV)
- Enter prescription dose
- Set reference point and ROI radius
  - User-defined point, or PTV centroid
  - Default radius = 2 mm



→ PTV ref. pt →

2 PTV Cutout — Creating Collimator
- Generate PTV cutout
  - User-defined margin
- Output: TOPAS collimator file
  - Sent to Monte Carlo
- Output: CAD files (3D-print ready)
  - Collimator holders
  - Cerrobend mold



→ Collimator →

3 Dose Calculation — Monte Carlo Simulation in TOPAS
- Load phase-space file, set # histories
- CT & collimator auto-loaded
  - or other .ap / premade collimator structure
- Preview simulation geometry
- Adjust CT position (if offset)
- iterate
- Run simulation
- Output: DICOM dose distribution
  - Auto-loaded back to TPS

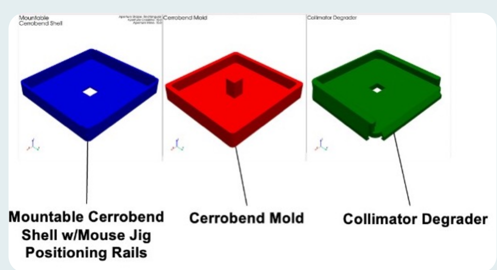
→ DICOM dose →

4 Plan evaluation — Dose & Dose-Rate
- View dose volume histogram (DVH)
  - PTV + OAR structures
- Dose-rate volume histogram (DRVH)
  - Define FLASH beam repetition rate
  - Define number of pulses delivered
  - Set UHDR threshold (default 40 Gy/s)
  - Compute DRVH
- Output: DVH, DRVH, dose parameters
  - Mean, max, min, D95, D50, D5
  - Other user defined parameters
- View dose distribution on CT
  - DICOM dose can be loaded in the CT viewer

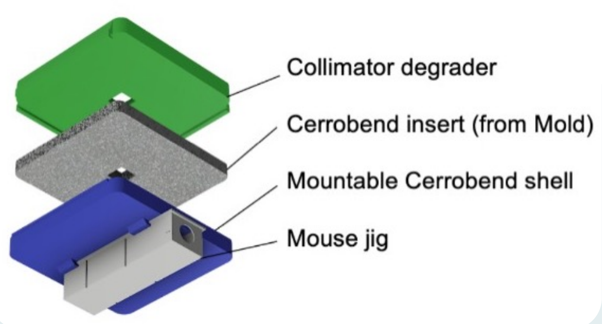
Parallel physical-fabrication output

Physical collimator casting

3D-printed Cerrobend mold (PETG) + holders (PLA)



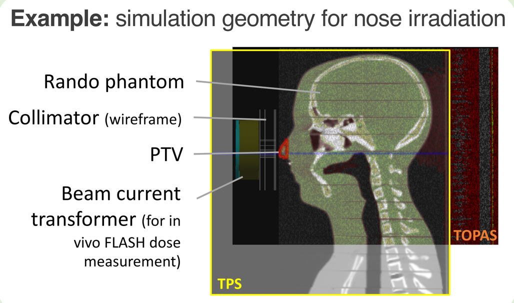
Example: collimator assemble for mouse irradiation



Preview geometry

Simulation Visualization

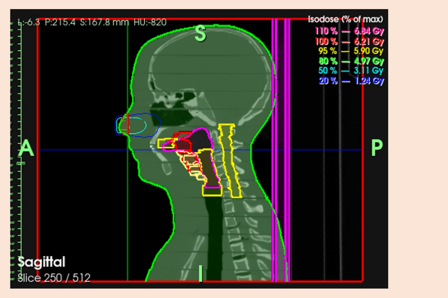
Example: simulation geometry for nose irradiation



Dose overlay on CT

Dose distribution in CT viewer

Isodose lines on CT with structure contours



RESULTS (continued)

Figure 3. Anterior-posterior beam's-eye view of Plan 2 with isodose lines (20–110% of prescription). The white contour is the lung target + 1 mm margin — also the shape of the upstream Cerrobend collimator. Mean lung dose: 27.4 Gy.

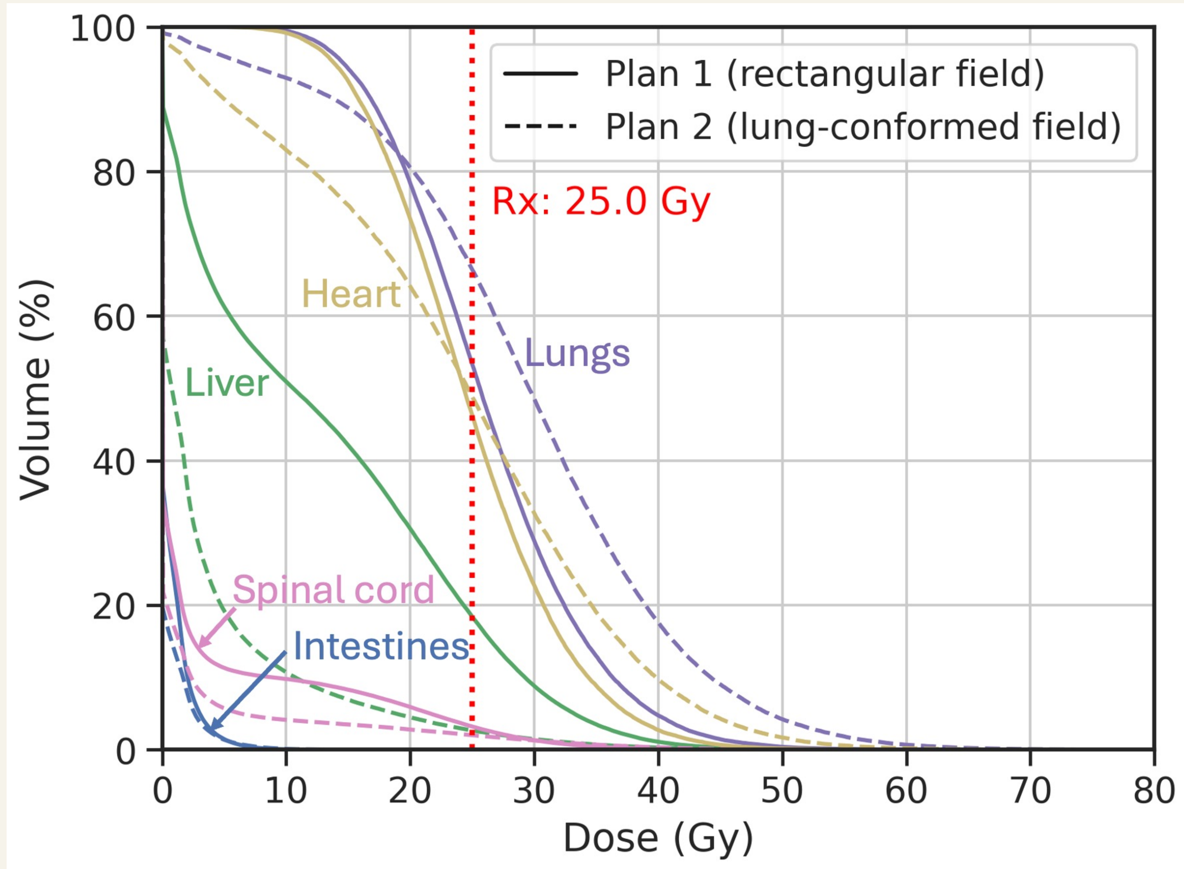


Figure 4. DVHs of the lungs and surrounding organs for Plan 1 (solid) and Plan 2 (dashed); prescription 25 Gy dotted.

Mean-dose reduction with the lung-conformed field (Plan 2 vs. Plan 1):

–72.2%	–44.4%	–32.8%	–2.0%
liver	spinal cord	intestines	heart*

*Heart reduction is modest due to its geometric proximity to the lungs (mean 24.5 → 24.0 Gy).

CONCLUSION

- First end-to-end dosimetric verification of the electron FLASH TPS, using a bilateral lung plan in an anatomically realistic mouse phantom.
- The TPS accurately predicts FLASH-delivered dose, and the conformal workflow substantially spares organs at risk.
- These results enable a future open-source release to make FLASH research accessible and support its clinical translation.

REFERENCES

[1] Melemenidis S, Chen D, Jensen C, Schulz JB, Surucu M, Yu AS, et al. Noninvasive Reversible Software-Based Electron FLASH Irradiation Configuration of a Linear Accelerator in Clinical Use. International Journal of Radiation Oncology*Biology*Physics. 2026 May;S036030162600725X. doi:10.1016/j.ijrobp.2026.05.010

[2] Faddegon B, Ramos-Méndez J, Schuemann J, McNamara A, Shin J, Perl J, et al. The TOPAS tool for particle simulation, a Monte Carlo simulation tool for physics, biology and clinical research. Physica Medica. 2020 Apr;72:114–21. doi:10.1016/j.ejmp.2020.03.019

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