Monte Carlo 4D Dose-Rate Distribution for Ultra-High-Dose-Rate Radiation Therapy

A. Badalan[1,2], T. Popescu[1,2]

1 BC Cancer, Vancouver Canada

2 University of British Columbia Department of Physics and Astronomy, Vancouver Canada

BC CANCER
Provincial Health Services Authority

GOALS

- Validate a Monte Carlo model of a 10 MeV e-FLASH beam.
- Apply the model to real patient anatomy to assess the FLASH effect on organs at risk.

INTRODUCTION

FLASH Radiotherapy

- Ultra-High dose-rate (FLASH) radiation therapy has shown normal tissue sparing while maintaining tumour control in preclinical models.[1]
- Electron FLASH (e-FLASH) beams can be produced on modified medical linacs.[2]

Clinical Translation

- Clinical implementation requires treatment planning tools that can resolve FLASH dose-rates.[3]
- Monte Carlo (MC) 4D dose-rate distribution calculations can determine the temporal and spatial beam properties resulting in FLASH effect sparing of healthy tissues.

Electron FLASH for Head and Neck

- Superficial lesions are good candidates for e-FLASH
- Organs at risk (OARs) near the surface can benefit from FLASH sparing such as skin and salivary Glands.[4,5]
- Electron range limits dose to deeper OARS such as spinal cord and brain stem.

METHODS

Electron FLASH beam

- **10 MeV e-FLASH** beam on a Varian TrueBeam.
  - Photon target removed, scattering foil added to a nominal 10 MV beam path.
- **Beam delivery control** pulse counting.
- **Dose measurement:** L-alanine in a 20 x 20 x 20 cm^3 solid water phantom at 100 cm SSD.
- **Beam PDDs and Profiles:** measured at conventional dose-rates in a 40 x 40 x 40 cm^3 water phantom.
  - 10 x 10 cm^2 beam at SSD 100 cm.
  - Plane parallel and diode chambers.

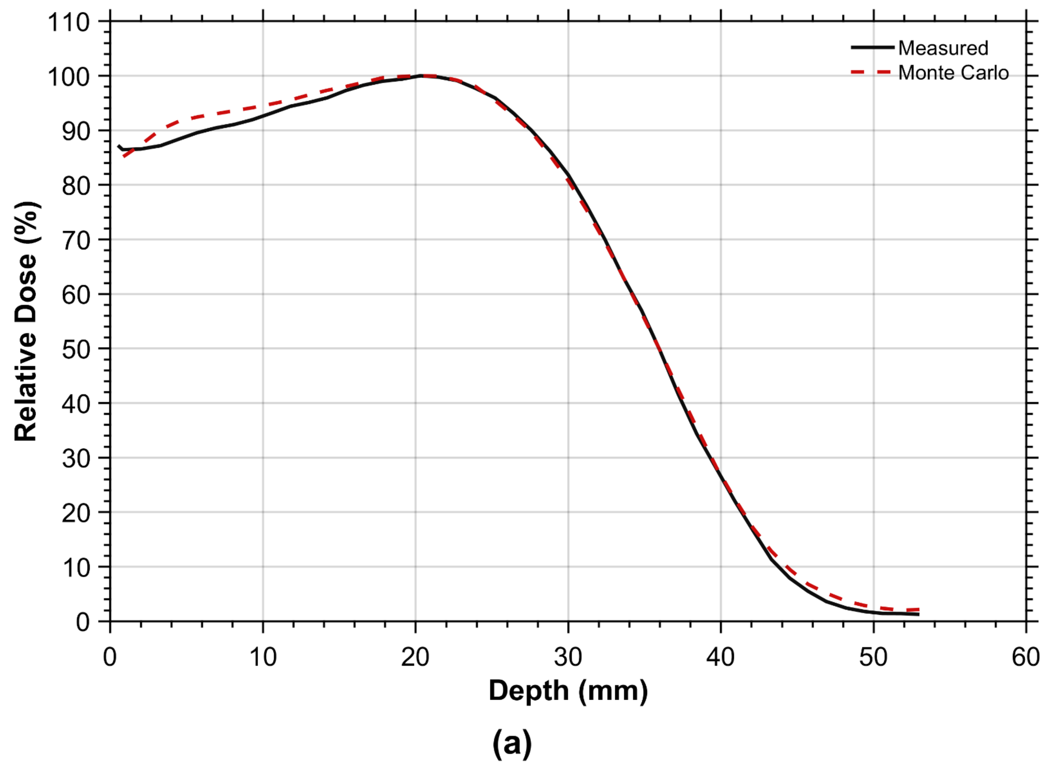
Monte Carlo model:

- **Particle source:** vendor provided phase space scored upstream of linac jaws.
- **BEAMnrc**: particle transport through jaws, MLCs, electron applicator.
- **DOSXYZnrc** dose calculation in:
  - water phantoms for MC model validation.
  - patient geometry for treatment plan evaluation.

Dose Simulation:

- **Cases:** two head-and-neck skin lesions.
- **SSD:** 70 cm.
- **Lesion depths:** 3.5 cm and 5.0 cm.
- **Fractionation:** single-fraction delivery.
  - 50 Gy to the lesion at 3.5 cm depth in 0.85 s.
  - 60 Gy to the lesion at 5.0 cm depth in 1.01 s.
- **Optimization:** Monte Carlo direct aperture optimization (MC-DAO).
- **Beam shaping:** photon multi leaf collimators without an applicator.

RESULTS



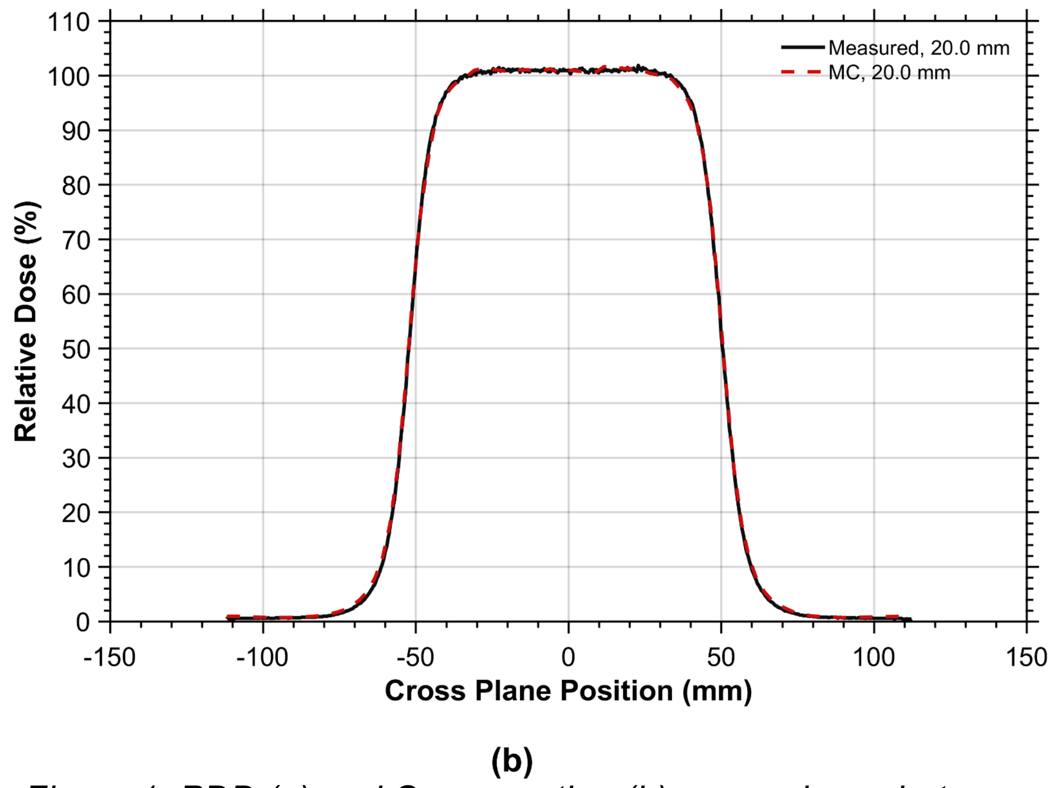


Figure 1: PDD (a) and Cross section (b) comparisons between MC (dashed) and measurements (solid).

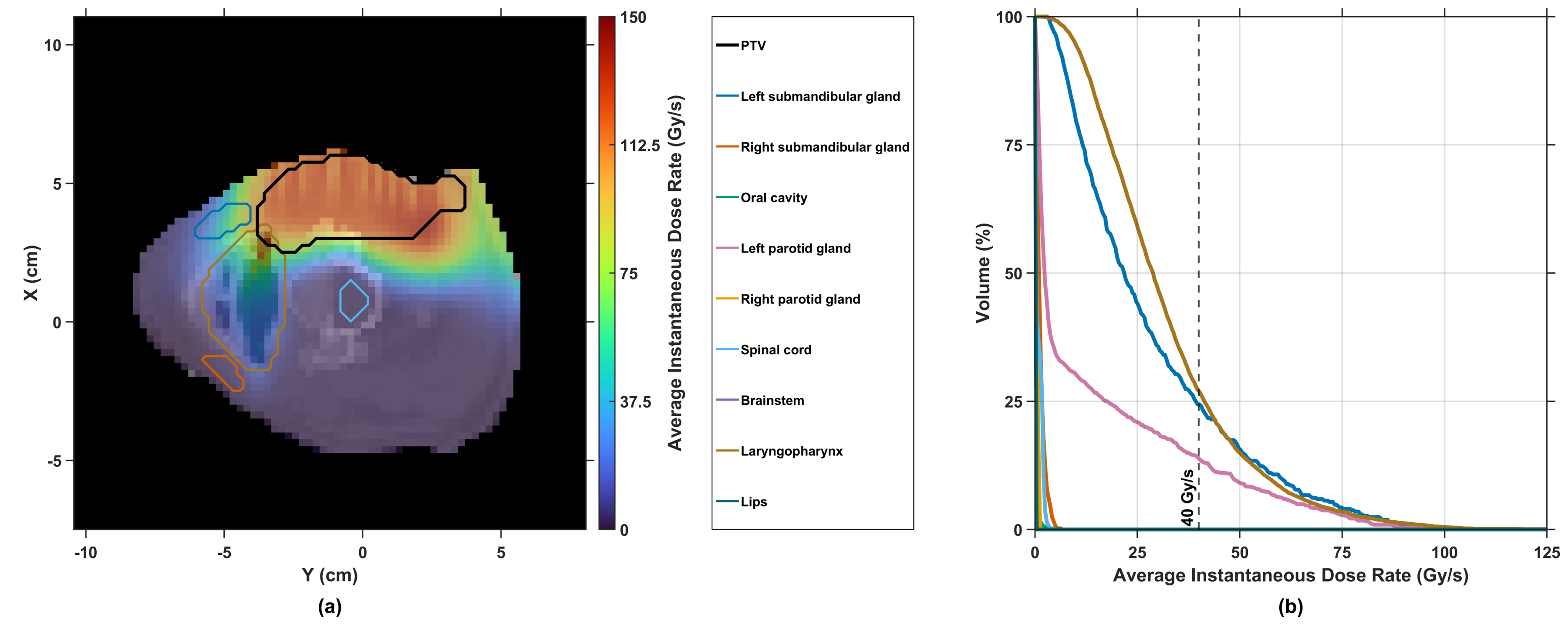


Figure 2: Axial dose-rate slice (a) and dose-rate volume histogram (b). 50 Gy to the lesion at 3.5 cm depth in 0.85 s. The dashed line indicates the 40 Gy/s FLASH threshold.

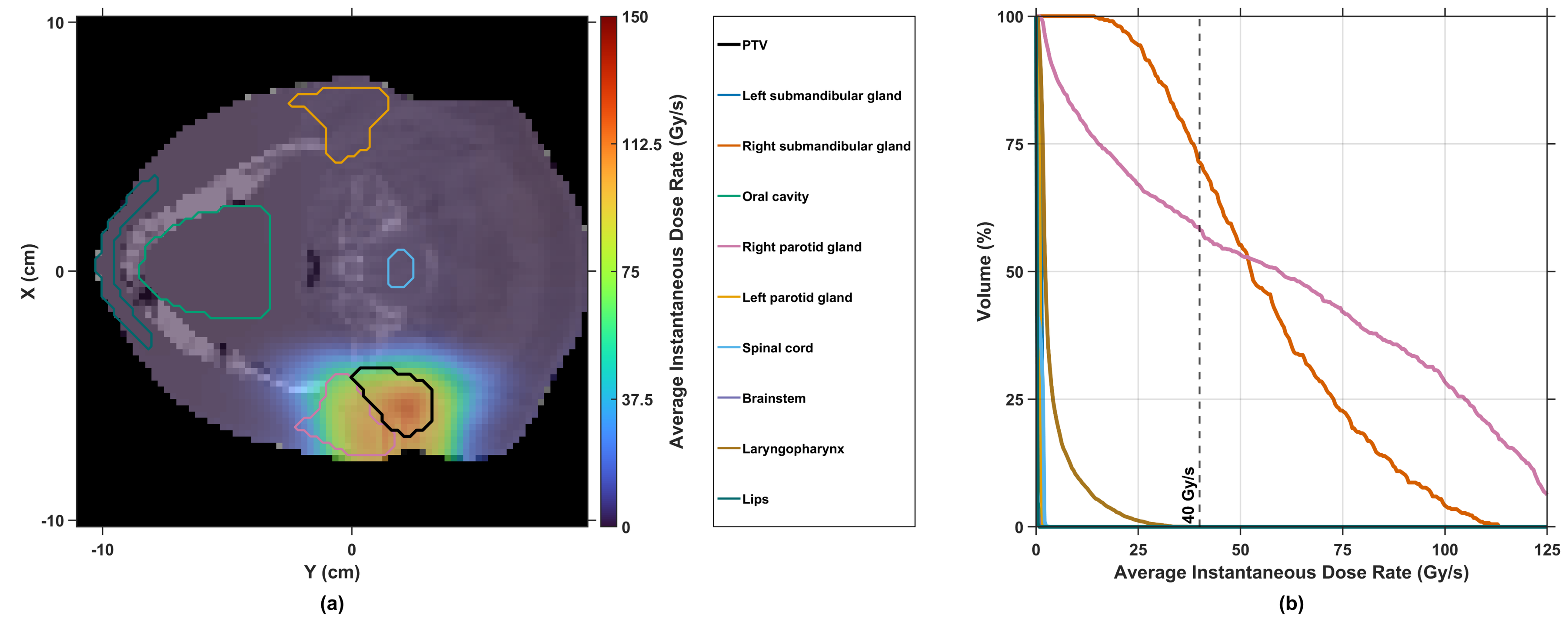


Figure 3: Axial dose-rate slice (a) and dose-rate volume histogram (b). 60 Gy was delivered to the lesion at 5.0 cm depth in 1.01 s. The dashed line indicates the 40 Gy/s FLASH threshold.

- Measured a dose-rate of 59.13 Gy/s at 2 cm depth in solid water with L-Alanine.
- The agreement between measured and MC is within 3 % for the pdd and within 1.5 % for the cross profile.
- Errors in total MC dose were below 5 %
- DOSXYZnrc simulation show FLASH dose-rates can be achieved in patient anatomy.
- Representative slices visually show a FLASH sparing capable region up to 4 cm beneath the skin surface.
- Superficial OARs reached FLASH dose-rates: Right Submandibular (71.5 % of volume >40 Gy/s) and Right Parotid Gland (58.1 %) in Figure 2; Left Submandibular Gland (24.4 %) in Figure 3.
- Deeper OARs stayed well below threshold: Brainstem, Spinal Cord, Oral Cavity, and glands all showed <1 % volume >40 Gy/s, with median dose-rates under 1 Gy/s in most cases.

CONCLUSIONS

- We validated a Monte Carlo model of a 10 MeV e-FLASH beam with measured dose-rates and profiles and applied it to real patient anatomy.
- This 10 MeV e-FLASH beam is only able to achieve FLASH dose-rates in regions shallower than 4 cm.
- We demonstrated a proof-of-concept method for validating clinical FLASH beams and calculating instantaneous dose-rate distribution for treatment planning.

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CONTACT

Alexandru.badalan1@bccancer.bc.ca

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