

TOPAS Monte Carlo Simulation and Patient-Specific Cherenkov Dose Comparison for External Beam Radiation Therapy

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ABSTRACT

Cherenkov imaging offers real-time visualization of radiation delivery, but quantitative conversion of signal intensity to dose remains challenging. TOPAS Monte Carlo simulations were validated against water- and solid-water phantom measurements under clinical 6 MV beam conditions. Patient-specific simulations were generated using DICOM data and clinically planned delivery parameters, including dynamic multileaf collimator motion, and compared with Cherenkov-derived surface dose. Simulated phantom profiles, percentage depth-dose curves, and surface-dose distributions showed good agreement with experimental measurements. Patient results demonstrated spatial agreement between Cherenkov-derived and simulated surface-dose distributions, while remaining discrepancies may be attributed to patient geometry and tissue optical properties. These findings support TOPAS-based correction as a promising approach for quantitative, real-time Cherenkov dosimetry.

INTRODUCTION

Cherenkov radiation is visible light emitted when charged particles travel through a dielectric medium faster than the phase velocity of light in that medium. During megavoltage radiotherapy, secondary electrons generate Cherenkov emission in tissue, and in homogeneous media the detected intensity is approximately proportional to deposited dose, enabling non-contact, real-time visualization of radiation delivery.¹⁻²

In patients, however, Cherenkov intensity is affected by tissue optical properties, surface geometry, camera viewing angle, and treatment geometry, limiting direct conversion to dose. In this study, TOPAS simulations were validated against percentage depth-dose measurements in water and surface-dose measurements in solid water. Patient-specific simulations incorporating DICOM anatomy and clinical delivery parameters, including dynamic MLC motion, were then compared with Cherenkov-derived surface dose to evaluate a correction framework for quantitative Cherenkov dosimetry.

METHODS AND MATERIALS

A TOPAS Monte Carlo model of a clinical 6 MV photon beam was developed and validated using phantom measurements. Simulated percentage depth-dose curves in water were compared with ionization-chamber measurements. Surface and buildup-region doses in solid water were measured using a parallel-plate ionization chamber and compared with the corresponding TOPAS calculations.

For patient-specific analysis, CT images, structure sets, and treatment-plan DICOM files were imported into TOPAS. The simulations reproduced the planned beam geometry and delivery parameters, including gantry angles, monitor units, and dynamic MLC motion. Cherenkov images acquired during treatment were registered to the three-dimensional patient surface and converted to surface-dose distributions. The Cherenkov-derived dose was then compared with the TOPAS-simulated surface dose, and differences were evaluated in relation to patient surface geometry and camera viewing angle.

Results

Figure 1 summarizes the development and validation of the TOPAS Monte Carlo model for a clinical 6 MV photon beam. The treatment-head geometry was reproduced in TOPAS, and simulated crossline profiles and percentage depth-dose curves were compared with ionization-chamber measurements for multiple field sizes. The simulated surface-dose distribution in a solid-water phantom was also compared with the measured Cherenkov image and corresponding crossline profile. For the buildup-region PDD comparison in panel (f), measurements obtained with a PTW Markus 23343 parallel-plate ionization chamber were corrected for chamber overresponse using $P'(d) = P(d) - \xi(E, 0) \exp(-\alpha(\frac{d}{d_{max}}))$, where $\xi(E, 0) = 27.19 - 32.59IR$

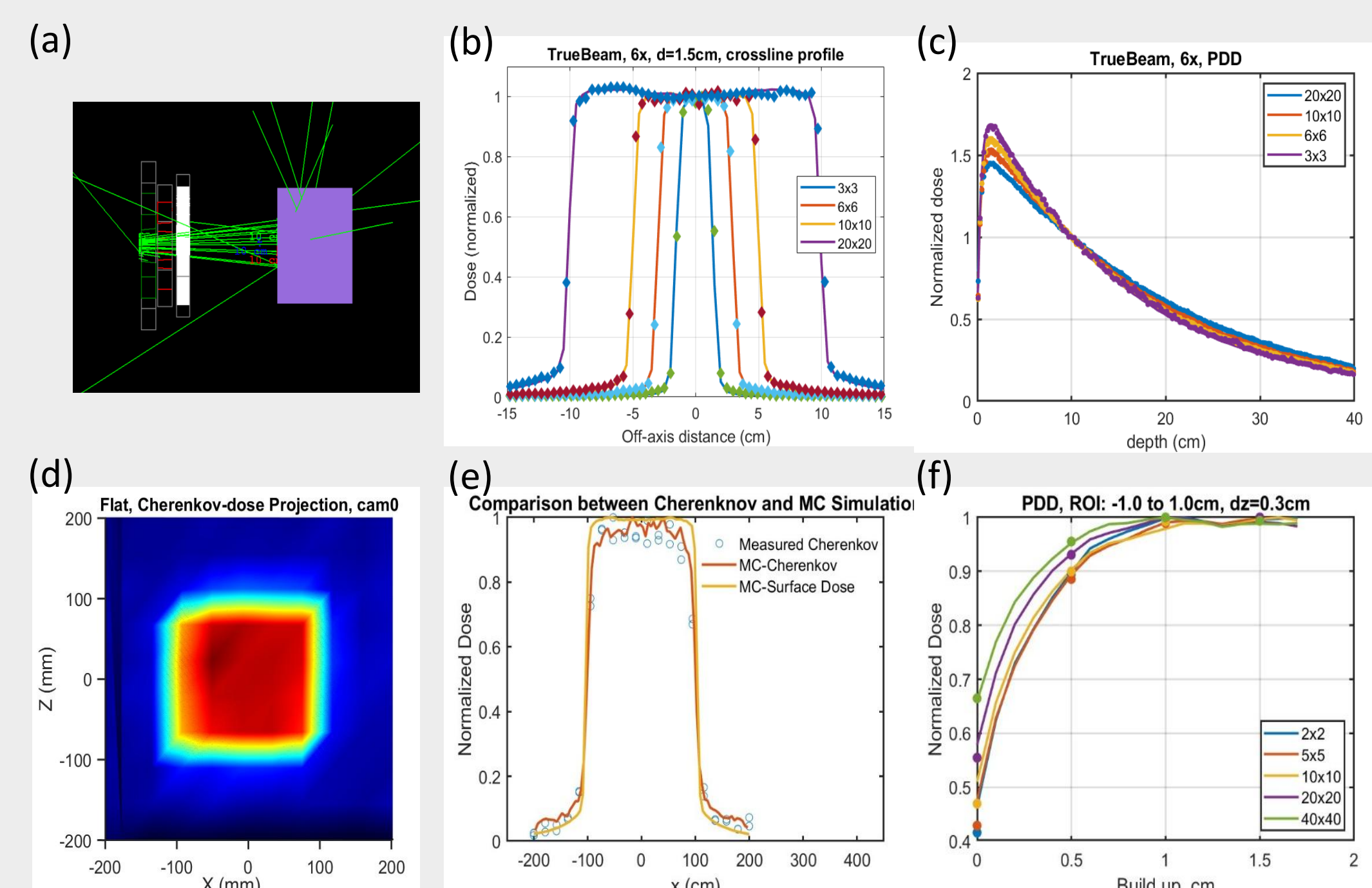


Figure 1. TOPAS dose simulation and validation using water and solid phantoms. (a) TOPAS Monte Carlo simulation geometry. (b) TOPAS dose crossline profile at 1.5 cm depth for a 6 MeV beam, compared with measured dose in water. (c) Percentage depth dose (PDD) comparison between TOPAS-simulated dose and measured water phantom dose. (d) Projection of Cherenkov signal onto a three-dimensional solid water phantom. (e) Comparison of TOPAS surface dose, MC-derived Cherenkov dose, and measured Cherenkov signal. (f) PDD comparison between simulated dose and dose measured using a parallel-plate ionization chamber.

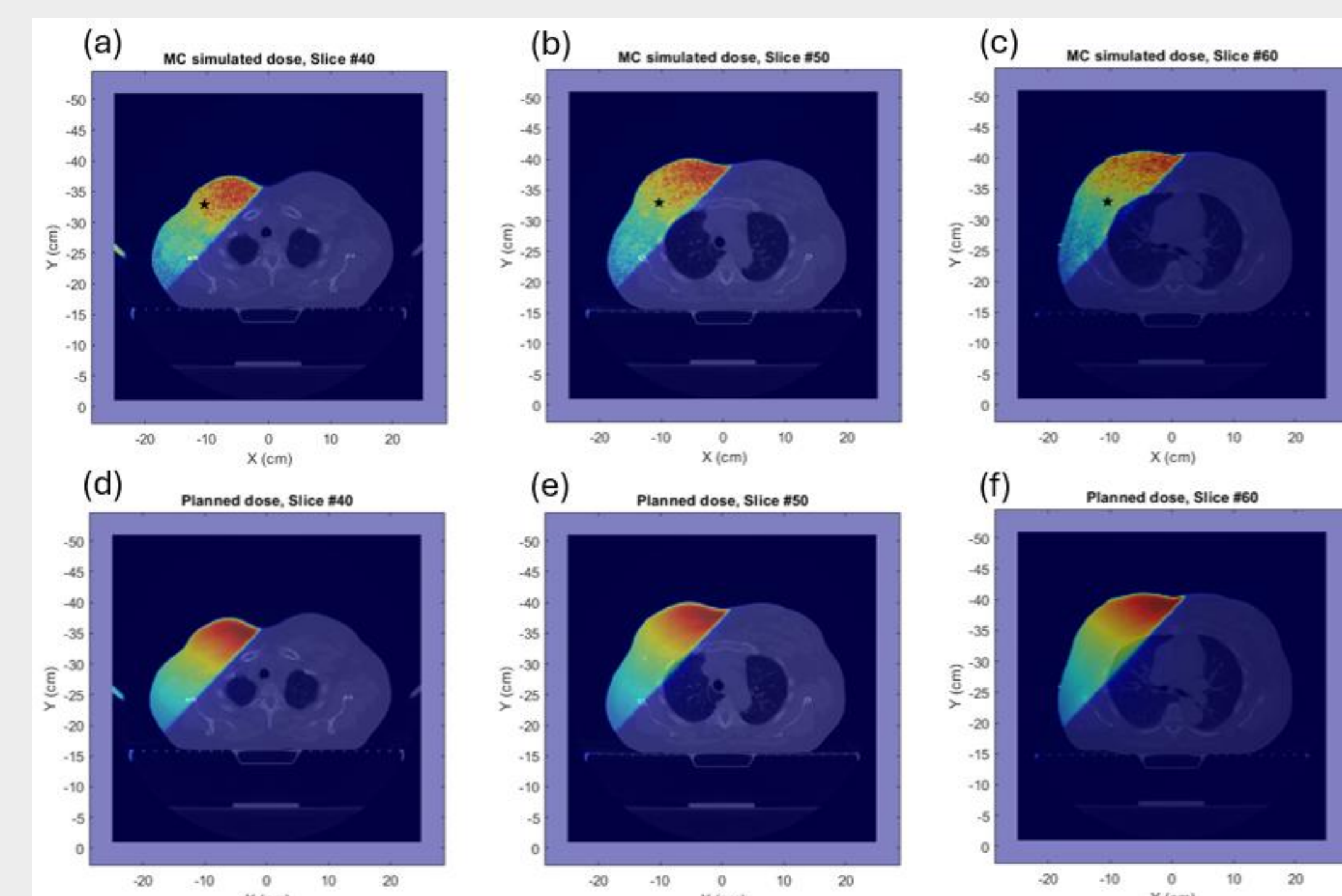


Figure 2. Comparison of TOPAS Monte Carlo-simulated dose distributions with AAA treatment-planning dose distributions. (a–c) TOPAS-simulated dose at patient CT slices 40, 50, and 60, respectively. (d–f) Corresponding AAA-calculated dose distributions at the same slice locations.

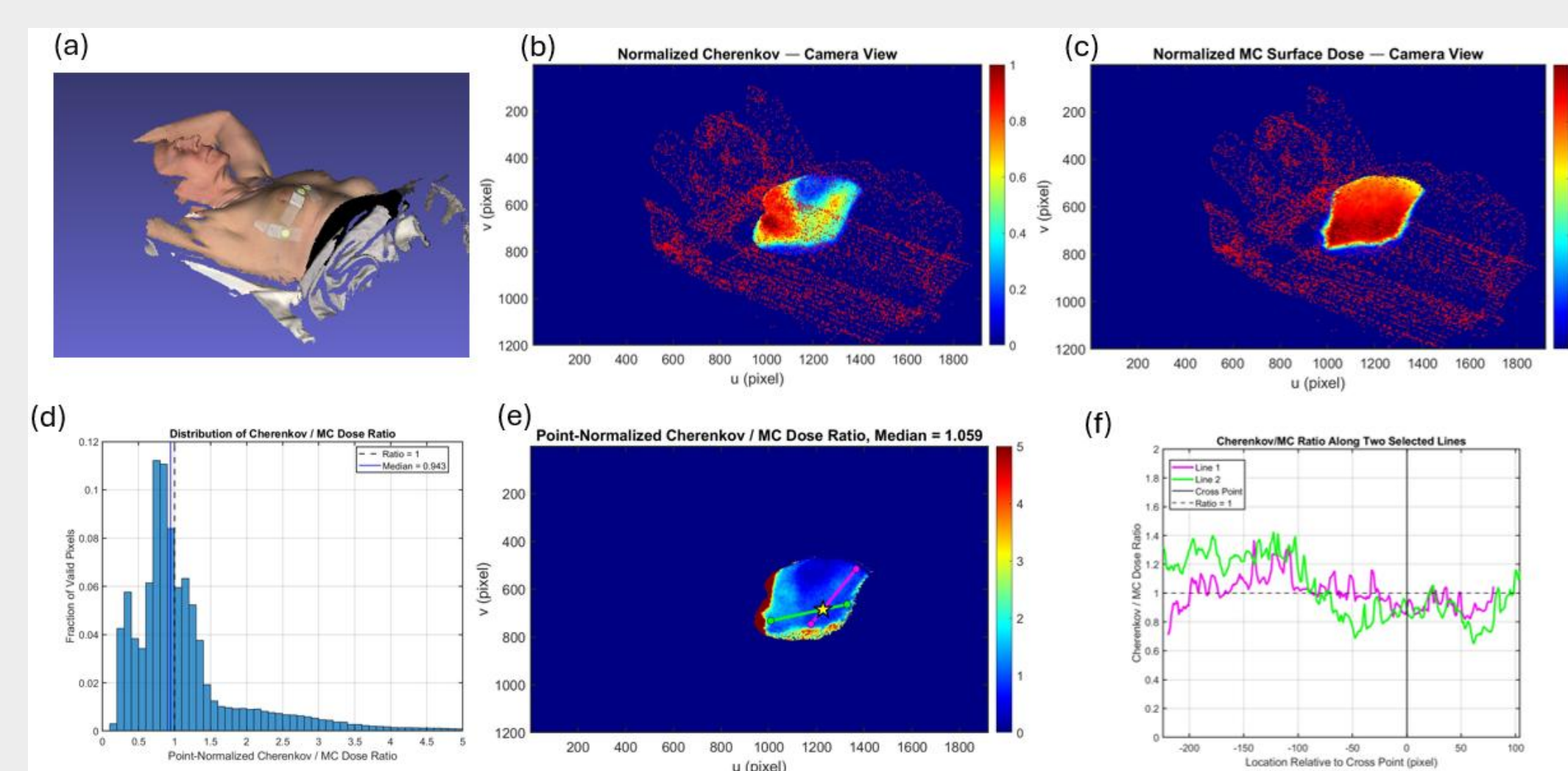


Figure 3. Comparison of Cherenkov-derived and TOPAS-simulated surface dose distributions. (a) Three-dimensional surface scan of the patient. (b) Cherenkov-derived surface dose registered to the patient CT surface and projected into the camera view. (c) TOPAS-simulated surface dose registered to the patient CT surface and projected into the same camera view. (d) Distribution of the Cherenkov-to-TOPAS surface dose ratio over the common valid comparison region. (e) Spatial distribution of the ratio of Cherenkov-derived dose to TOPAS-simulated surface dose in the camera view. (f) Cherenkov-to-TOPAS surface dose ratio as a function of position along the profiles indicated in panel (e).

$+(-1.666 + 1.982IR)C$. For the 6 MV beam, $\alpha=5.5$, $IR=0.672$, $C=0.35$ mm, and $l=2$ mm. The corrected measurements showed good agreement with the TOPAS-calculated buildup and surface doses. Figure 2 compares patient-specific TOPAS Monte Carlo dose distributions with the corresponding AAA-calculated treatment-planning dose distributions at CT slices 40, 50, and 60. The TOPAS simulations reproduced the overall spatial distribution, field shape, and dose penetration observed in the AAA calculations. Remaining differences near field boundaries and heterogeneous tissue interfaces may arise from differences in dose-calculation algorithms and material assignment.

Overall, the agreement indicates that the patient anatomy and clinical delivery parameters were appropriately reproduced in the TOPAS model.

In Figure 3, the Cherenkov-derived and TOPAS-simulated surface dose distributions showed similar overall spatial patterns when registered to the patient-specific geometry and projected into the same camera view. However, regional differences were observed, particularly near the field edges and lower-dose regions, as reflected in the Cherenkov-to-TOPAS ratio map. The ratio distribution was centered near unity but exhibited a right-skewed tail, indicating localized overestimation of the Cherenkov-derived dose relative to TOPAS. Line-profile analysis further demonstrated that the agreement varied with position, with most ratios remaining close to 1 across the selected paths.

DISCUSSION

The agreement of the TOPAS-simulated PDD, surface dose, and patient CT dose distributions with measurements and the AAA plan supports the validity of the simulation framework. The Cherenkov-derived and TOPAS-simulated surface dose distributions also showed similar overall spatial patterns. However, localized differences were observed near the field edges and in highly pigmented regions such as the areola. This is expected because TOPAS calculates deposited dose, whereas the detected Cherenkov signal is also affected by tissue absorption and scattering. Surface curvature and viewing angle can further alter the amount of light collected by the camera. Small registration errors and image noise may also contribute, particularly in low-dose or high-gradient regions. Incorporating patient-specific optical properties and geometric corrections may improve quantitative agreement.

CONCLUSIONS

The TOPAS framework was validated against measured PDD, surface-dose data, and AAA dose distributions. Cherenkov-derived and TOPAS-simulated surface doses showed good overall agreement, with localized differences near field edges and optically heterogeneous regions. Patient-specific optical and geometric corrections may further improve quantitative accuracy.

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