Assessment of Gafchromic Film Dosimetry for Low-Energy Proton Beams Using Geant4 Monte Carlo Simulations

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ABSTRACT

Purpose: Accurate dosimetry of low-energy proton beams (2–4 MeV) for radiobiological experiments is challenging due to beam modification in air. This study extends previous work on Gafchromic HD-V2 film dosimetry by quantitatively validating experimental dose measurements using Geant4 Monte Carlo simulations.

Methods: Gafchromic HD-V2 films were irradiated with 2–4 MeV proton beams at the ECU Accelerator Laboratory under vacuum conditions at a fixed distance and under in-air conditions at varying distances (13, 17, and 24 mm) from the beamline exit window. Calibration curves were obtained by correlating film gray values with delivered dose. Lateral dose profiles were extracted from the irradiated films using radial line analysis across the 1-inch film diameter. Geant4 simulations were performed using a geometry matching the experimental setup, and dose distributions were scored in regions corresponding to the film active layer. Dose values at the maximum, 50%, and 13% relative dose levels were extracted from the lateral profiles to quantitatively compare experimental film measurements with Geant4 simulations.

Results: Calibrated Gafchromic HD-V2 film measurements showed good agreement with Geant4 Monte Carlo simulations across all investigated proton energies and distances from the exit window. Agreement at the 50% and 13% relative dose confirmed consistency in the central and low-dose regions of the lateral beam profile, while maximum dose comparisons demonstrated accurate reproduction of peak dose characteristics. Lateral dose profile comparisons further showed agreement in profile shape and dose fall-off behavior.

Conclusion: Calibrated Gafchromic HD-V2 film dosimetry was validated against Geant4 Monte Carlo simulations, demonstrating accurate characterization of low-energy proton beam dose distributions for radiobiological applications.

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INTRODUCTION

Low-energy proton beams (2–4 MeV) generated at the East Carolina University (ECU) Accelerator Laboratory are increasingly used in radiobiological research because their high LET and short range enable localized irradiation of biological samples. Accurate dosimetry is challenging due to energy degradation, air scattering, and beam divergence, requiring dedicated measurement techniques.
Gafchromic HD-V2 film provides high spatial resolution for proton dosimetry but requires proton-specific calibration because of LET-dependent response. This study validates proton-calibrated HD-V2 film by comparison with Geant4 Monte Carlo simulations across multiple proton energies and irradiation distances.

METHODS AND MATERIALS

Proton Irradiation

HD-V2 films were irradiated with 2–4 MeV proton beams at the ECU Accelerator Laboratory using two experimental beamlines. The R-30 vacuum beamline was used to establish the proton calibration curve, while the L-15 Cell Irradiation Beamline was used for dosimetric validation under in-air conditions at 13, 17, and 24 mm from the exit window.

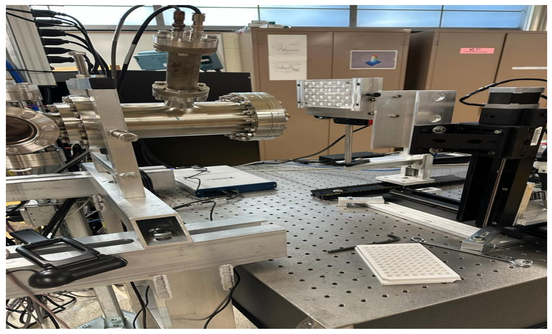


Figure 1.Experimental proton irradiation setup at the ECU Accelerator Laborator

Film Dosimetry

SRIM simulations were used to select HD-V2 from five Gafchromic films based on proton energy deposition. HD-V2 films were also irradiated with an XRAD-350 X-ray system for comparison; however, proton-specific calibration was required because of LET dependence and the absence of a Bragg peak. Films were scanned 24 h after irradiation. ImageJ extracted gray values, and Mathematica generated the proton calibration curve. The fitted parameters were applied to reconstruct dose in the L-15 Cell Beamline.

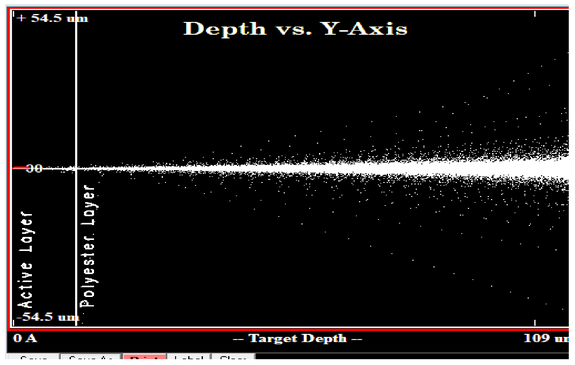


Figure 2. SRIM simulation of proton energy deposition in HD-V2 film

Geant4 Simulation & Data Analysis

A detailed Geant4 model was developed to reproduce the experimental geometry, including the proton source, exit window, air gap, and HD-V2 film. The absorbed dose was calculated from the energy deposited in the HD-V2 active layer divided by the active-layer mass. Film geometry and material composition were incorporated to accurately model energy deposition. Lateral dose profiles were extracted from both calibrated films and Geant4 simulations. Agreement was quantitatively evaluated using the maximum dose, 50% relative dose, and 13% relative dose levels.

RESULTS

1. Proton Calibration

Following proton irradiation, HD-V2 films were scanned, and the red channel was selected for calibration because it provided the widest dynamic dose range and highest sensitivity. An inverse calibration model

$$\mathbf{Dose} = \mathbf{c} + \frac{\mathbf{b}}{\mathbf{Gray\ Value} - \mathbf{a}}$$

Was fitted to the measured data to determine the calibration parameters **(a, b, and c).** The resulting proton-specific calibration curve established a strong relationship between gray value and absorbed dose and was subsequently used to reconstruct dose in the L-15 beamline, demonstrating the necessity of proton-specific calibration over conventional X-ray calibration.

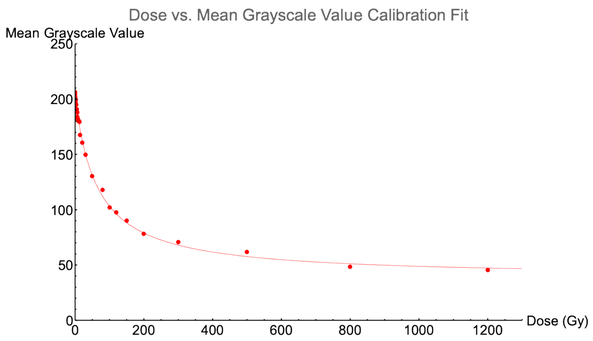


Figure 3.Proton-specific calibration curve for HD-V2 film

2. Geant4 Dose Validation

A detailed Geant4 model accurately reproduced the experimental dose distributions for all investigated proton energies. The difference between the proton calibration curve–derived doses and the Geant4-calculated doses was approximately 3–7%, demonstrating excellent agreement. Simulated lateral dose profiles also closely matched the experimental film measurements, validating both the proton-specific calibration and the Monte Carlo model for predicting dose deposition in the HD-V2 active layer.

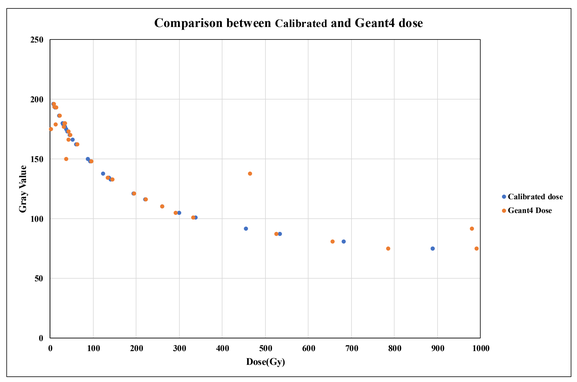


Figure 4. Comparison of calibrated film doses and Geant4 simulations

3. Beam Profile Validation

Dose profiles reconstructed using the proton calibration curve showed excellent agreement with Geant4 simulations. Strong agreement was observed in the central beam region, beam penumbra, and lateral beam broadening, validating the proposed methodology for low-energy proton dosimetry.

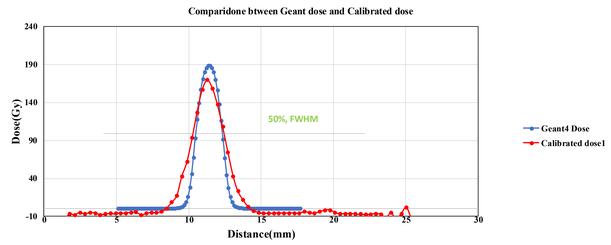
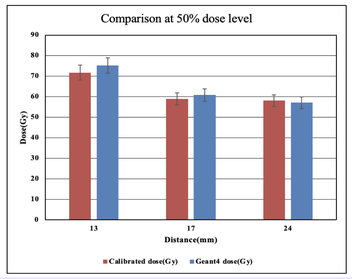


Figure 5. Comparison of experimental and Geant4 lateral dose profiles

4. Quantitative Comparison

Quantitative comparison demonstrated excellent agreement between experimental measurements and Geant4 simulations. Dose differences remained within 3–7% across all investigated proton energies and irradiation distances.



Dose difference summary

Region	Difference
13%	0-3%
50%	0-5%
Max	0-7%

Agreement within 0–7% confirms high accuracy of the calibration method

Figure 6. Quantitative comparison of calibrated film and Geant4 doses at the 50% relative dose level

DISCUSSION

Excellent agreement between proton-calibrated HD-V2 film measurements and Geant4 simulations demonstrates the reliability of the proposed dosimetric methodology. The results highlight the importance of proton-specific calibration for accurate radiochromic film dosimetry. This validated approach provides a robust framework for future low-energy proton radiobiology studies.

CONCLUSIONS

Proton-specific calibration of Gafchromic HD-V2 film was successfully established for 2–4 MeV proton beams.
Geant4 simulations showed excellent agreement with proton-calibrated film measurements across multiple proton energies and irradiation distances.
Quantitative validation (maximum, 50%, and 13% relative dose levels) confirmed the accuracy of the proposed dosimetric methodology.
The validated approach provides a reliable tool for accurate low-energy proton dosimetry and future radiobiological research.

REFERENCES

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