# Radiochromic Film Dosimetry for QA, In-Vivo Dosimetry, and Range Assessment in PBS Proton Therapy

Lauren Wolstenholme, BS[1]; Nova Rose Drew, BS[1]; JW Snider, MD[2]; Sina Mossahebi, PhD[3]; Pouya Sabouri, PhD[1]
[1]University of Arkansas for Medical Sciences, [2]Proton International, [3]University of Maryland School of Medicine

UNIVERSITY OF ARKANSAS FOR MEDICAL SCIENCES

## INTRODUCTION

Pencil beam scanning (PBS) proton therapy requires accurate patient-specific quality assurance (PSQA), range verification, and, when feasible, in-vivo dose verification. Conventional QA devices, such as ion chamber arrays, have limited spatial resolution, reducing accuracy for small targets and steep dose gradients.

Radiochromic film offers submillimeter spatial resolution, tissue-equivalent response, and simple self-developing processing, making it an attractive tool for proton dosimetry. Clinical implementation, however, requires validation of proton calibration, LET-dependent response, and range accuracy.

This study evaluates Gafchromic™ EBT4 and EBT-XD films for:

1. Patient-specific quality assurance (PSQA)
2. In-vivo surface dose verification
3. Water-equivalent thickness (WET) and stopping-power ratio (SPR) assessment

## METHODS AND MATERIALS

Gafchromic™ EBT4 and EBT-XD films were commissioned for proton dosimetry using six PBS wedge calibration plans. Three 10-point transmission-to-dose calibration curves were generated for each film from dose levels spanning 0.5–10 Gy for EBT4 and 0.5-20Gy for EBT-XD. Calibration was performed with and without a range shifter at 3 and 10 cm depth and validated against a MatriXX ion chamber array (Figure 1A).

Films were scanned 18–24 hours post-irradiation using a flatbed scanner (300 dpi, 48-bit color). An in-house calibration script converted film transmission into dose maps (OPG), which were imported into MyQA for analysis.

Stopping-power ratio (SPR) measurements were performed using uniform proton fields delivered to 11 CIRS tissue-equivalent plugs embedded in a dosimetry cube or solid water. Water-equivalent thickness (WET) was determined from R90 pullback measurements and compared with water-tank ion chamber measurements.

Patient-specific QA (PSQA) was evaluated using solid water, a dosimetry cube, and a CIRS lung phantom. Clinical plans were delivered with collapsed gantry and couch angles and analyzed using absolute gamma analysis in MyQA. In-vivo surface dose measurements were performed on phantoms and at CT-identifiable patient landmarks.

## CONCLUSIONS

With calibration and awareness of LET response, radiochromic film provides a practical method for patient-specific QA, in-vivo dosimetry, and SPR-based range assessment in PBS proton therapy.

## Contact Information

Lauren (Ren) Wolstenholme
UAMS Department of Radiation Oncology
laurenwolst115@gmail.com

Pouya Sabouri
UAMS Department of Radiation Oncology
psabouri@gmail.com

## RESULTS

**Calibration and Reproducibility:** Calibration curves showed excellent agreement between film and ion-chamber measurements, with all validation measurements within 8% (Figure 1B). Calibration reproducibility was high for both film types, with transmission variations corresponding to dose differences of approximately 50 cGy across repeated measurements. The largest reproducibility deviations were observed for EBT-XD at 1800 cGy (170.61 cGy) and EBT4 at 900 cGy (49.6 cGy) (Figures 1C–D).

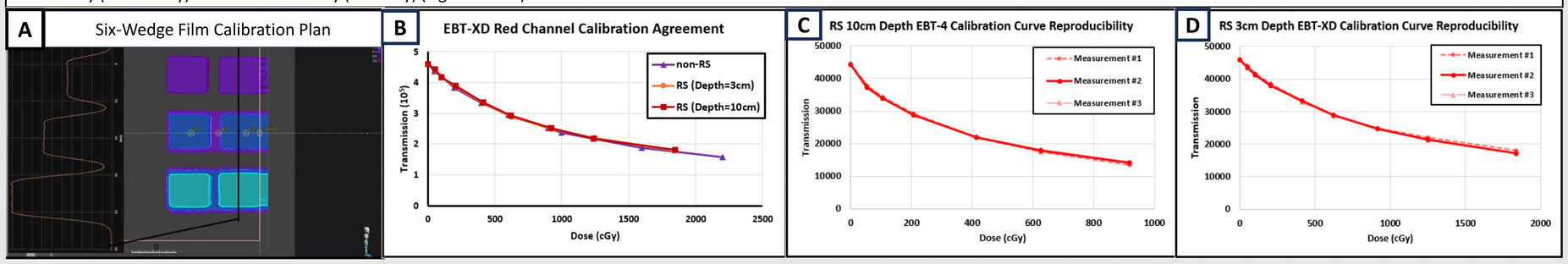
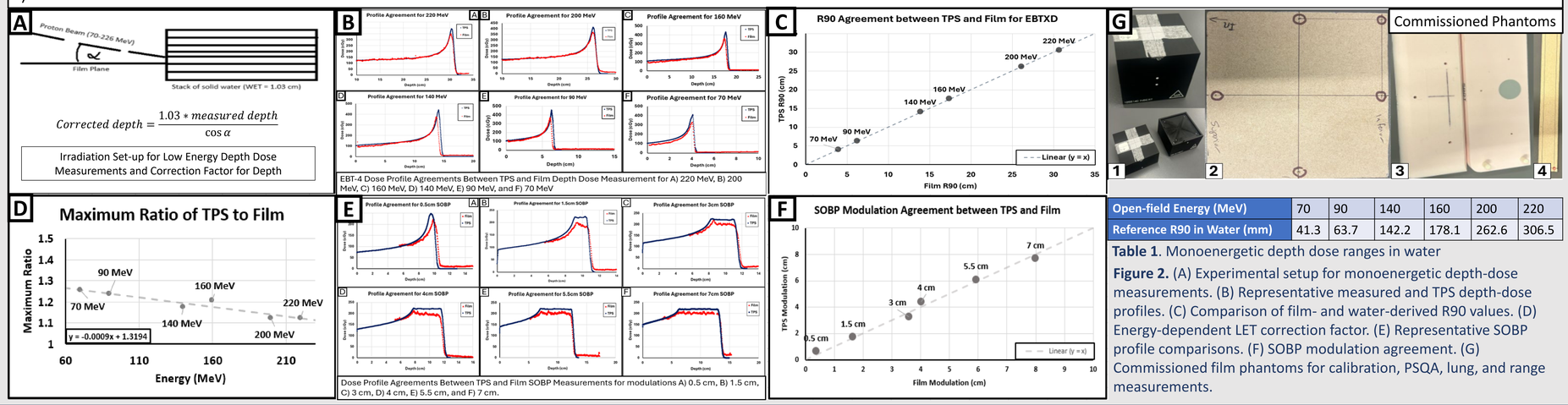



**Figure 1**. (A) Six-wedge PBS calibration plan used for film commissioning. (B) Red-channel calibration curves for range-shifter (RS) and non-range-shifter (non-RS) irradiations. (C–D) Calibration reproducibility across three independent measurements for EBT-XD and EBT4 films.

**Range Verification and LET Response:** Monoenergetic depth-dose measurements showed improved agreement at higher proton energies, with R90 differences ranging from 0.01–0.38 mm (Figure 2B). Lower-energy beams demonstrated greater sensitivity to air-gap and film alignment, resulting in a maximum R90 difference of 3.8 mm (2.7%) at 140 MeV (Figure 2C). As expected, film exhibited LET-dependent under-response near the Bragg peak, with the largest dose underestimation of 21.2% at 70 MeV (Figure 2D). A linear energy-dependent correction factor ($R^2 = 0.90$) was derived to account for this effect (Figure 2D). Agreement for spread-out Bragg peaks (SOBPs) improved with increasing modulation width; modulations >0.5 cm agreed within 10%, while the largest discrepancy (2.8 mm, 43.8%) occurred for the 0.5-cm modulation (Figures 2E–F).




| Open-field Energy (MeV) | 70 | 90 | 140 | 160 | 200 | 220 |
|---|---|---|---|---|---|---|
| Reference R90 in Water (mm) | 41.3 | 63.7 | 142.2 | 178.1 | 262.6 | 306.5 |

**Table 1**. Monoenergetic depth dose ranges in water

**Figure 2.** (A) Experimental setup for monoenergetic depth-dose measurements. (B) Representative measured and TPS depth-dose profiles. (C) Comparison of film- and water-derived R90 values. (D) Energy-dependent LET correction factor. (E) Representative SOBP profile comparisons. (F) SOBP modulation agreement. (G) Commissioned film phantoms for calibration, PSQA, lung, and range measurements.

**WET and SPR Validation:** WET-based SPR measurements were obtained in two setups. Soft tissue substitute plugs (CIRS-61M) were measured using a dosimetry cube (Figure 3A). Denser plugs were measured using solid water phantom (Figure 3B). Film pull-backs were measured using myQA (Figure 3C). Measured WET differed from reference by a maximum of 4.4mm (8.89%), observed for breast density. Film underestimated WET on average by 2.15 mm (Table 2). Film-derived SPR assessments showed an average absolute difference in SPR of 0.043 for biological replacement plugs. Maximum difference in SPR was observed for breast tissue mimicking plug with a 0.088 discrepancy (Figure 3D).

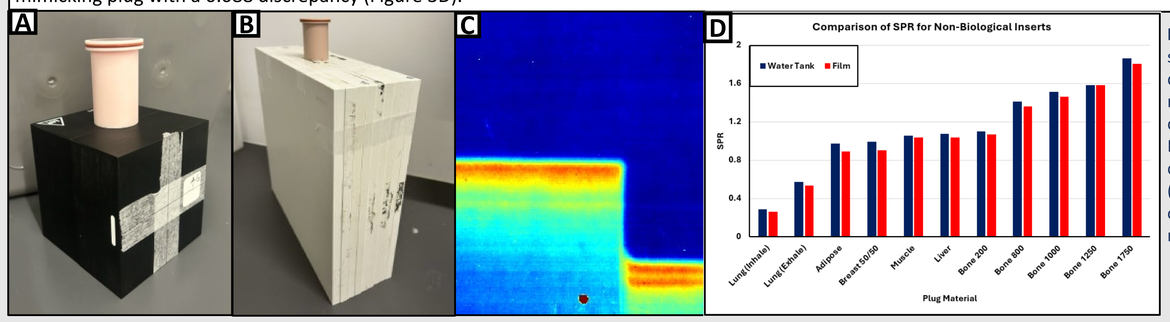



**Figure 3.** A) WET measurement setup for soft tissue plugs with dosimetry cube. B) WET measurement setup for high density plugs with solid water. C) Example of open field reference dose (left) and pulled back dose (right). D) Experimental SPRs as compared to water tank measurements.

| Plug Material | Water Tank WET (mm) | Film WET (mm) | Difference (%) |
|---|---|---|---|
| Lung (Inhale) | 14.0 | 12.9 | -7.86 |
| Lung (Exhale) | 28.5 | 26.6 | -6.67 |
| Adipose | 48.5 | 44.3 | -8.66 |
| Breast 50/50 | 49.5 | 45.1 | -8.89 |
| Muscle | 52.5 | 51.7 | -1.52 |
| Liver | 53.5 | 51.8 | -3.18 |
| Bone 200 | 55.0 | 53.3 | -3.09 |
| Bone 800 | 70.5 | 67.9 | -3.72 |
| Bone 1000 | 75.5 | 73.0 | -3.28 |
| Bone 1250 | 79.0 | 79.0 | 0 |
| Bone 1750 | 93.0 | 90.2 | -2.98 |

**Table 2**. WET differences for non-biological density plugs

**Patient Specific QA:** Film-based PSQA agreed well with TPS dose distributions (Figure 4). All plans met institutional gamma criteria (>90% at 3%/3 mm); lowest passing rate was 81.6% (Table 3). Multiple plans achieved 100% gamma passing.

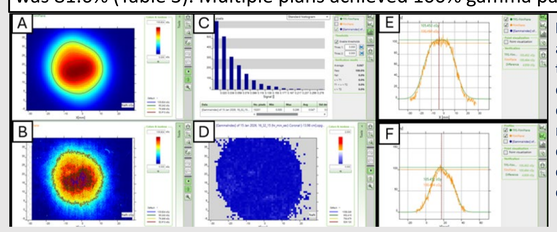



**Figure 4.** Representative gamma analysis for a small-field brain treatment plan. (A) TPS dose distribution. (B) Measured film dose distribution. (C) Gamma map. (D) Gamma pass/fail distribution. (E) X-profile comparison. (F) Y-profile comparison.

| Film Type | Phantom | RS | Depth (cm) | 3%/3mm (%) | 5%/3mm (%) | 3%/2mm(%) | 5%/2mm (%) |
|---|---|---|---|---|---|---|---|
| EBTXD | SW | Y | 8.0 | 93.5 | 96 | 81.6 | 90.6 |
| EBTXD | Cube | N | 6.54 | 100 | 100 | 99.5 | 99.5 |
| EBTXD | Cube | N | 5.0 | 96.3 | 98.6 | 92.3 | 97 |
| EBTXD | Cube | N | 4.1 | 100 | 100 | 100 | 100 |
| EBT4 | Cube | N | 6.1 | 99.2 | 100 | 98.6 | 100 |
| EBT4 | SW | Y | 7.1 | 96.2 | 94.6 | 84.6 | 90.6 |

**Table 3**. Gamma analyses for PSQA planar measurements

**In-Vivo Dosimetry:** Film measurements slightly overestimated TPS surface dose (Figure 5A). All measurements were within the institutional tolerance of 15%, with a maximum difference of 7.3% (Table 4). Consistent agreement across breast and head-and-neck treatments supports the feasibility of radiochromic film for routine in-vivo surface dose verification in PBS proton therapy. Representative measurement sites are shown in Figures 5B–C.

| TPS (cGy) | Mean (cGy) | Diff (%) | Min | Max | Site | RS | Film Type |
|---|---|---|---|---|---|---|---|
| 150 | 156 | 4.0 | 65 | 336 | Breast | Y | EBTXD |
| 185 | 185 | 0.0 | 86 | 321 | Breast | Y | EBTXD |
| 200 | 192 | -4.0 | 83 | 336 | Breast | Y | EBTXD |
| 149 | 145 | -2.68 | 61 | 328 | Breast | Y | EBTXD |
| 163 | 154 | -5.52 | 64 | 422 | HN | Y | EBTXD |
| 150 | 154 | 2.67 | 178 | 209 | HN | Y | EBTXD |
| 157 | 155 | 1.27 | 105 | 284 | Breast | Y | EBTXD |
| 178 | 165 | 7.30 | 151 | 221 | HN | Y | EBT4 |

**Table 4**. Dose differences for in-vivo measurements

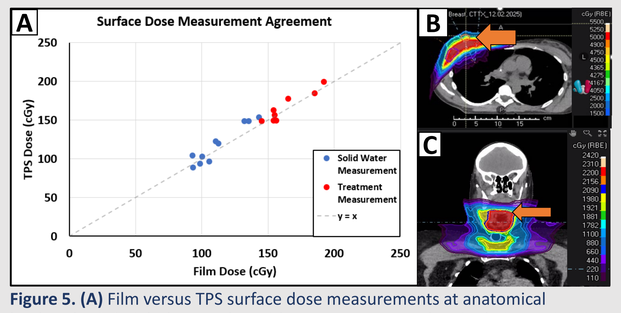



**Figure 5. (A)** Film versus TPS surface dose measurements at anatomical landmarks. **(B)** Right breast plan with measurement at the nipple (arrow). **(C)** Head-and-neck plan with measurement superior to the tracheostomy stoma.