Feasibility of Single-Energy Proton Pencil Beam Scanning Using a Programmable Energy Modulation Filter

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PURPOSE

A programmable energy modulation filter (PEMF; Yi filter) was developed to enable single-energy proton pencil beam scanning (PBS). This study evaluated whether energy modulation by individual rods, combined with stable lateral profiles at sparse spot spacing, can generate a uniform spread-out Bragg peak (SOBP).

CONCEPT

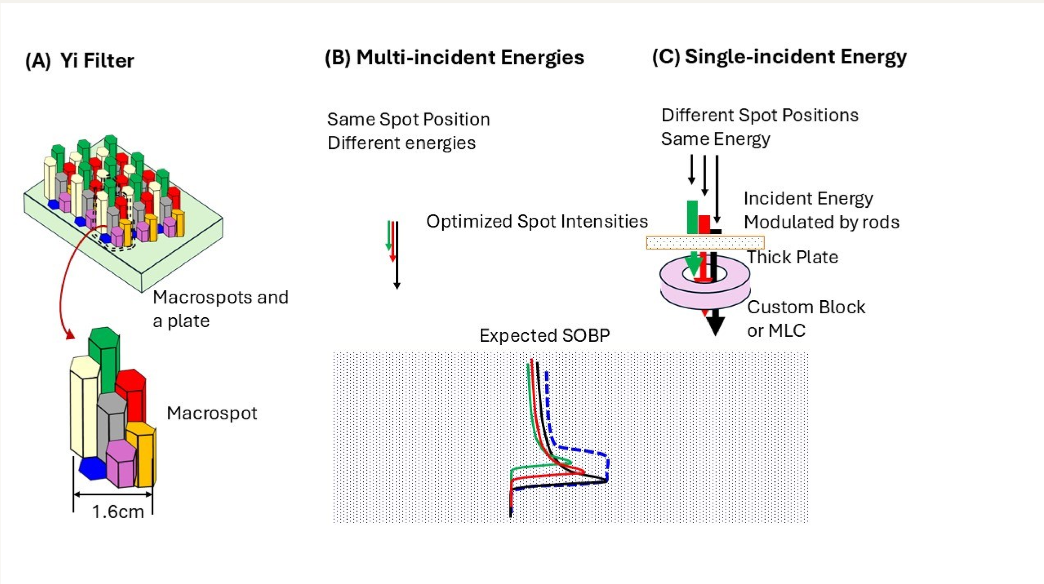

Figure 1. The Yi filter replaces sequential energy-layer switching with spatial energy modulation across 1.6-cm macrospots.

METHODS

- Each 1.6-cm macrospot contains rods with discrete water-equivalent thicknesses.
- A downstream 5-cm PMMA slab broadens the beam and promotes overlap among modulated spots.
- Spot sizes in water were estimated with Fermi–Eyges theory and independently verified by RayStation 11B Monte Carlo calculations.
- Feasibility criteria: ripple-free profiles and proton-spot FWHM exceeding the 1.6-cm macrospot diameter.
- Film measurements compared 5-cm SOBP-width single-energy and conventional multi-energy PBS deliveries.

TREATMENT-TIME REDUCTION

Plan	CTV (cc)	Dose/Fx (Gy)	Highest E (MeV)	Clinical (s)	SEPT (s)	Clinical layers	SEPT layers	Reduction
5×5×5	125	2	121	39.1	12.5	16	10	**68.0%**
10×10×10	1000	2	148	73.2	28.8	26	17	**60.7%**
20×20×10	4000	2	202	95.4	28.4	19	16	**70.2%**
C-shape	738	2	151	73.7	28.8	26	17	**60.9%**
Liver Case	606	3.87	209	126.8	45.1	53	38	**64.4%**
Breast Case	2092	2	175	258.1	33.3	47	41	**87.1%**

Table 1. SEPT reduced calculated delivery time by 60.7–87.1%. The breast plan showed the largest reduction because its conventional plan included low energies with slower delivery. For the liver plan, two-field delivery decreased from 126.8 to 45.1 seconds, approaching a clinically achievable breath-hold interval.

GEOMETRIC PLAN EVALUATION

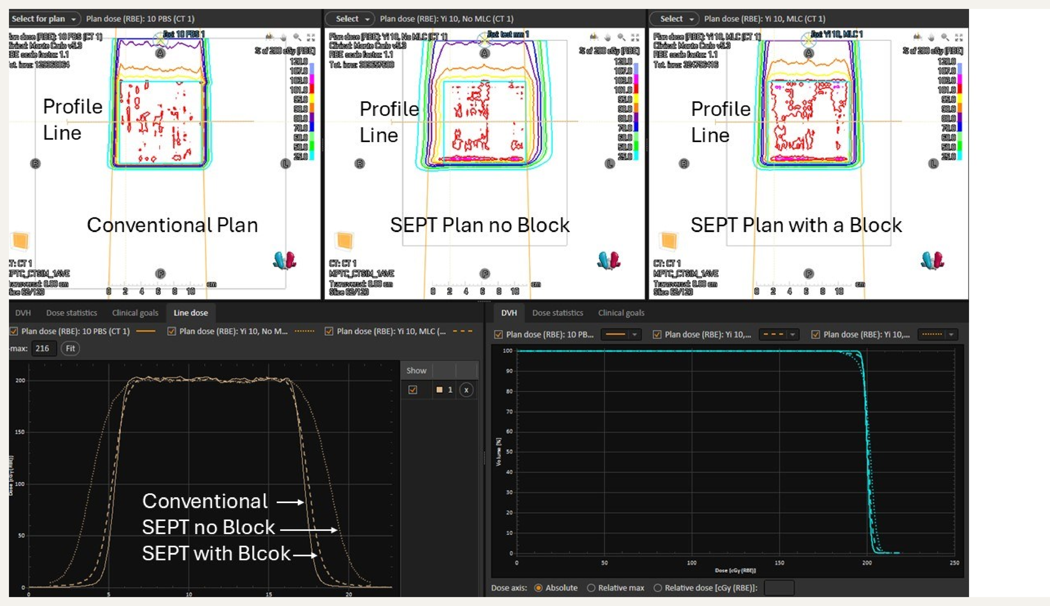

Figure 2. Conventional PBS and single-energy plans for a cuboidal target, with and without collimation.

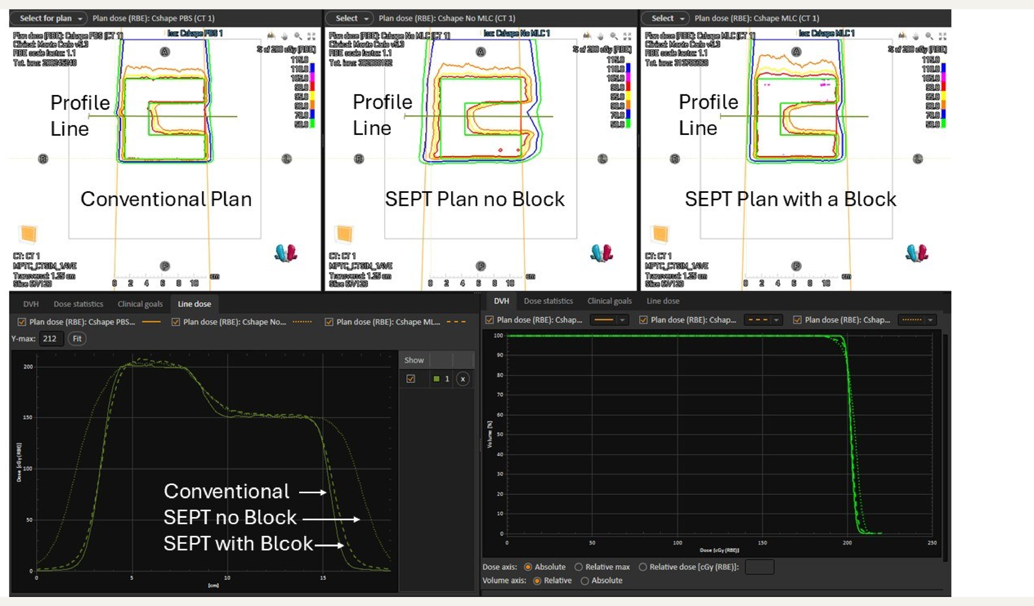

Figure 3. C-shaped target comparison. Collimation reduces the lateral-penumbra penalty of sparse macrospot spacing.

SUPPORTING PLANNING FINDINGS

The full-study simulations support the abstract's feasibility result:

- Single-energy plans maintained target coverage and depth-dose characteristics comparable to conventional PBS.
- Without collimation, the lateral 80–20% penumbra increased by an average of 0.9 cm (range, 0.5–1.4 cm).
- With a collimating block, the increase was reduced to 0.3 cm (range, 0.1–0.4 cm).

CLINICAL EXAMPLES

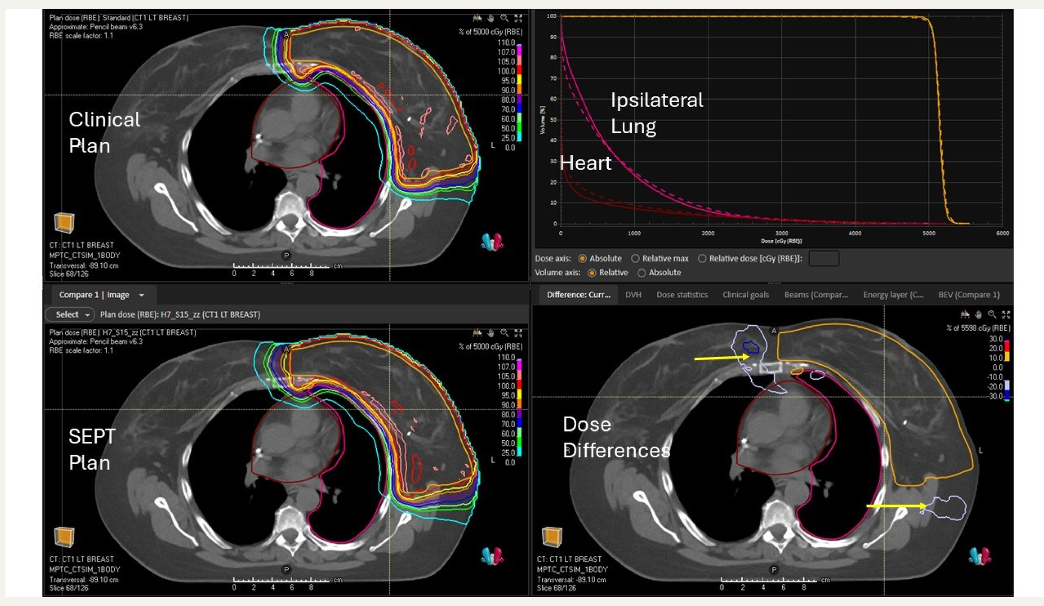

Figure 4. Breast case: single-energy and clinical PBS plans were comparable; with**out collimation, lat**eral differences remained visible.

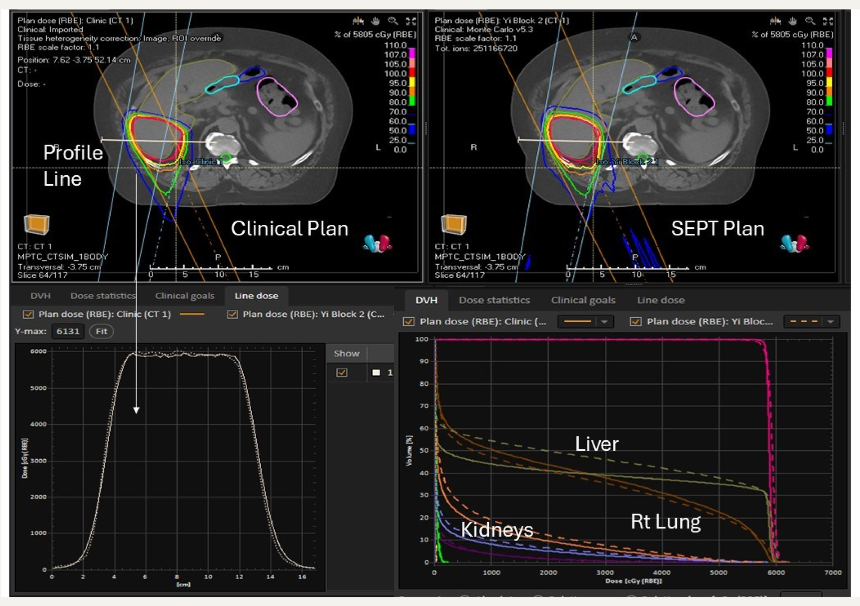

Figure 5. Liver case: **a custom block** controlled lateral penumbra while preserving target coverage and organ-at-risk dose.

MODULATED BEAM CHARACTERISTICS

- For incident energies of 100–240 MeV, spot sigma ranged from 1.0 to 1.7 cm between the 50% dose depth and Bragg-peak depth.
- FWHM consistently exceeded the 1.6-cm macrospot diameter.
- Ripple from individual modulated energies remained below 3%, satisfying the requirement for a uniform SOBP.

FEASIBILITY INTERPRETATION

Beam broadening was sufficient to blend the discrete rod contributions without clinically meaningful ripple. Agreement within 1 mm supports the analytic model, while the film measurements confirm that the resulting SOBP can be reproduced experimentally.

LIMITATIONS

The film experiment emulated rod water-equivalent thicknesses with PMMA plates and intentionally excluded physical filter-positioning uncertainty. Mechanical tolerances, alignment accuracy, and clinical quality assurance remain to be evaluated.

EXPERIMENTAL VALIDATION

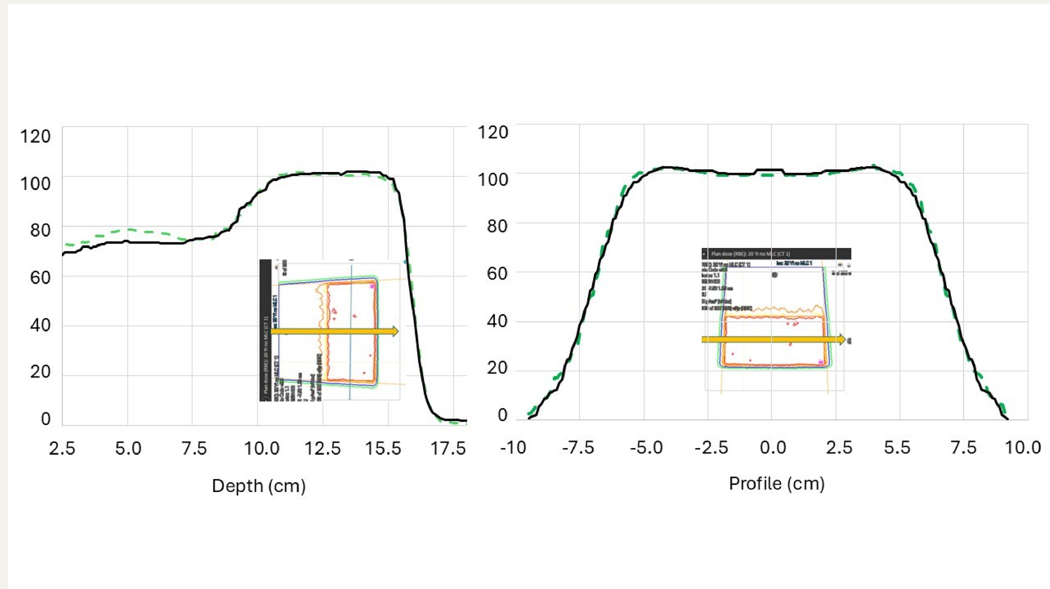

Figure 6. Film dosimetry for 5-cm SOBP-width plans. Conventional PBS (solid black) and PEMF single-energy delivery (dashed green) show close depth-dose and lateral-profile agreement.

CONCLUSION

Single-energy proton therapy using the Yi filter generated clinically acceptable SOBPs without energy switching.

Across geometric and clinical cases, SEPT maintained target coverage and dose distributions comparable to conventional PBS.

Collimation reduced the average lateral-penumbra increase from 0.9 cm to 0.3 cm. Calculated delivery times decreased by 60–87% through elimination of energy-layer switching and use of the highest field energy.

TAKE-HOME MESSAGE

SEPT maintains dosimetric quality while substantially shortening delivery—supporting breath-hold treatments and future time-sensitive applications such as proton arc and FLASH therapy.

NEXT STEPS

- Optimize rod geometry and macrospot size.
- Quantify alignment and manufacturing tolerances.
- Establish filter-positioning verification and quality assurance.
- Evaluate treatment-delivery workflows and clinical robustness.
- Assess time-sensitive applications enabled by single-energy delivery.