Experimental validation of magnetically focused proton minibeams

A. TERAN, G. MCAULEY, J. SLATER, and A. WROE
Loma Linda University, Loma Linda, CA, USAs

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INTRODUCTION

Proton minibeam radiation therapy allows normal tissue sparing by utilizing an array of beamlets to deliver a spatially fractionated proximal dose that blends into a homogeneous target dose[1-3]. However, proton mini beams produced using collimators have disadvantages including inefficient dose delivery and production of secondary particles. To ameliorate these effects, the current work proposes the use of a single high-gradient quadrupole Halbach cylinder to create planar beamlets.

AIM

To investigate a single quadrupole magnet's ability to create proton minibeams and evaluate whether clinically relevant composite and modulated dose distributions could be delivered with this technique

METHODS

A single prototype quadrupole Halbach cylinder with gradient of 250 T/m was used to focus a proton beam of 10 mm diameter and ~10 cm range into a narrow elongated planar beamlet. Depth and transverse dose distributions were measured in a water tank using a proton diode and EBT3 radiochromic film. Spatially fractionated composite dose distributions were generated by vertically shifting the tank with respect to exposed film placed every 5 mm (Fig 1).

Beamlets were also modulated and combined to produce a modulated composite dose distribution with a nominal 15 mm-wide spread-out Bragg Peak. Peak to valley dose ratio (PVDR) was assessed from transverse dose profile data.

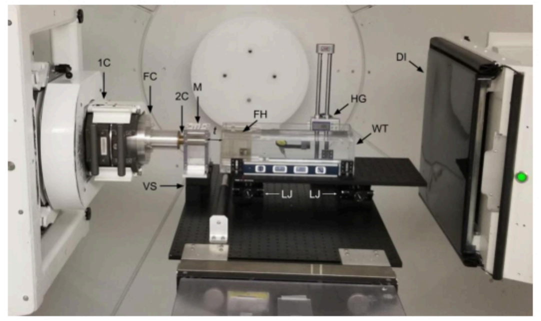
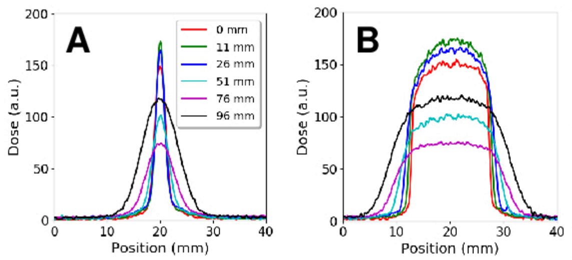


Fig 1: Experimental setup for EBT3 data. 1C=1st collimator, FC=functional cone (includes 2nd collimator inside), M=prototype quadrupole magnet, t=magnet/tank separation distance, FH=film holder, LJ=laboratory jack, HG=height gauge with dial indicator, WT=water tank, DI=digital imaging panel.

RESULTS

Single planar beamlets showed very narrow elongated cross sections over a large portion of the proximal region of proton range (Fig 2). The vertical FWHM was smallest (1.9 mm) at ~15 to 20 mm; < 3.0 mm for the first ~40 mm: and < 4.0 mm over the 1st ~50 mm WED.



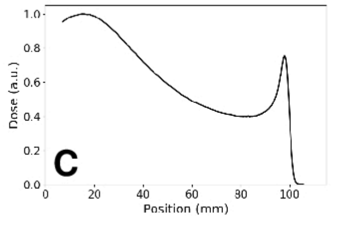


Fig 2: Vertical (A) and horizontal (B) transverse dose, and (C) depth dose profile of a single focused beamlet at various WED. The table shows single beamlet vertical (v) and horizontal (h) FWHM vs. WED.

WED (mm)	vFWHM (mm)	hFWHM (mm)
0	2.4	14.4
6	2.1	14.8
11	2.0	15.2
21	1.9	15.8
26	2.1	16.1
51	3.7	18.4
76	6.3	20.6
96	8.0	22.2

Composite beams (3 beamlets with c-t-c separation of 7.0 mm) showed spatial fractionation in entrance and proximal regions that blended into a ~homogeneous distribution ~96 mm WED. PVDR values were ~10 in 1st quarter of particle range decreasing to ~5 at half range (Fig 3).

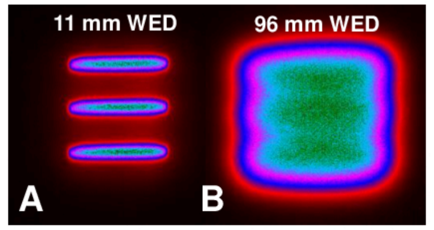
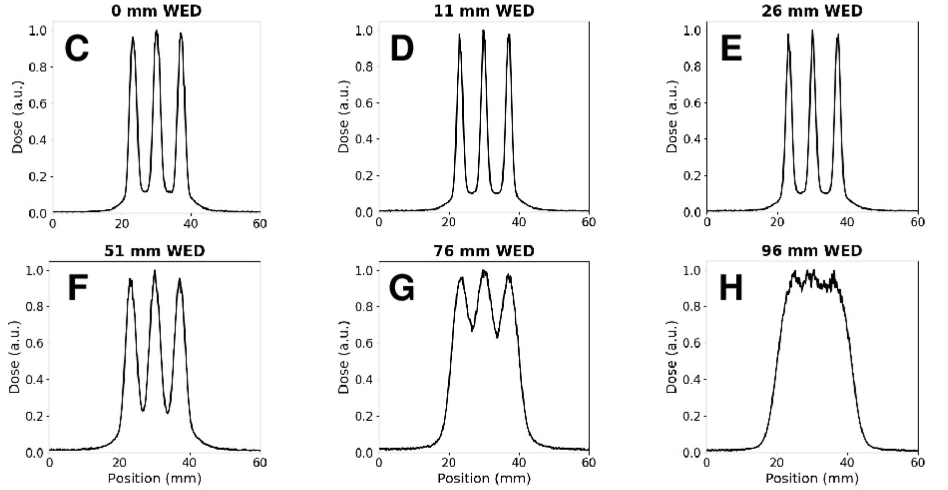
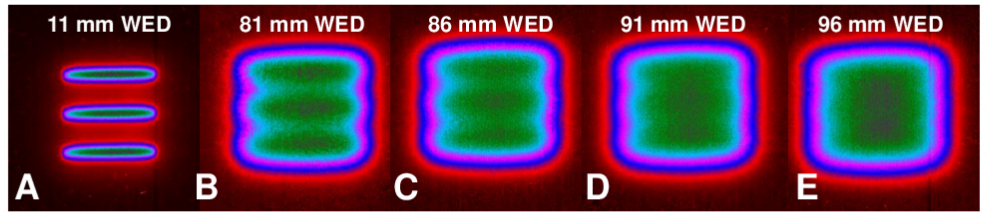


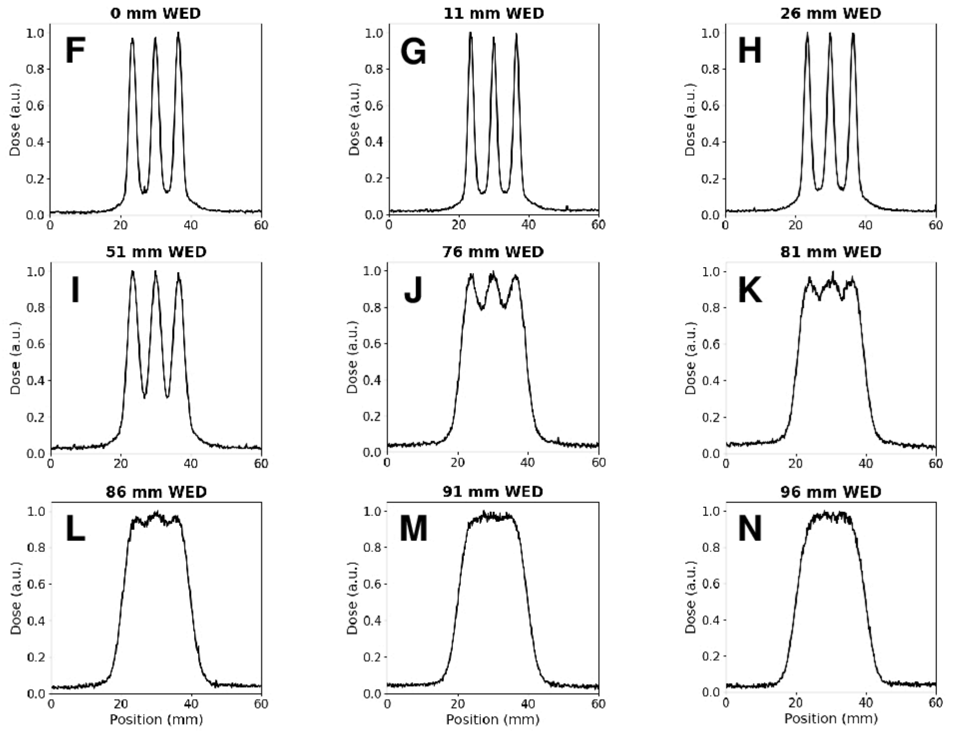
Fig 3: 2D (A & B), and 1D (C – H) dose profiles for composite beam and PVDRs (Table) at various WEDs.

WED (mm)	0.0	11.0	26.0	51.0	76.0	96.0
PVDR	9.0	10.2	10.2	4.7	1.6	1.2



Modulated composite beam (3 modulated beamlets (formed by 5 range shifts using 0, 3, 6, 9 and 12 mm solid water blocks) with c-t-c separation of 6.5 mm, and middle beamlet weighted 0.97 with respect to outer beamlets) showed spatial fractionation in entrance and proximal regions that blended into ~ homogeneous distribution over a SOBP of nominal width 15 mm. PVDR values were ~ 8 to 9 in 1st quarter of particle range, decreased to ~3.5 at half range, and ~≤ 1.2 over the SOBP (Fig 4).





WED (mm)	0.0	11.0	26.0	51.0	76.0	81.0	86.0	91.0	96.0
PVDR	8.7	8.8	7.6	3.3	1.3	1.2	1.1	1.1	1.2

Fig 4: 2D (A – E), and 1D (F – N) transverse dose profiles of modulated composite beam with a SOBP of nominal width 15 mm. The table shows PVDR values at various WEDs. Panels A) and G) show profiles at 11 mm WED. Panels (B – E) and (K – N) show profiles over the SOBP at 81 mm, 86 mm, 91 mm and 96 mm WED.

DISCUSSION

The single high-gradient quadrupole produced spatially fractionated beams with PVDRs comparable to recent reports[4-5]. Moreover, recent investigations in our laboratory involving magnet design and Monte Carlo simulations suggest even higher PVDR (comparable to [6-7]) and smaller minimum FWHM can be achieved with the proposed technique using available technology (Fig 5). In addition, the high-gradient magnets are capable of focusing entrance beams with moderate divergence values (~15 mrad RMS in the present study) into narrow focused beam waists. Thus, with lower divergence (eg, as in a scanning nozzle) even further improvements in FWHM and PVDR are expected[7].

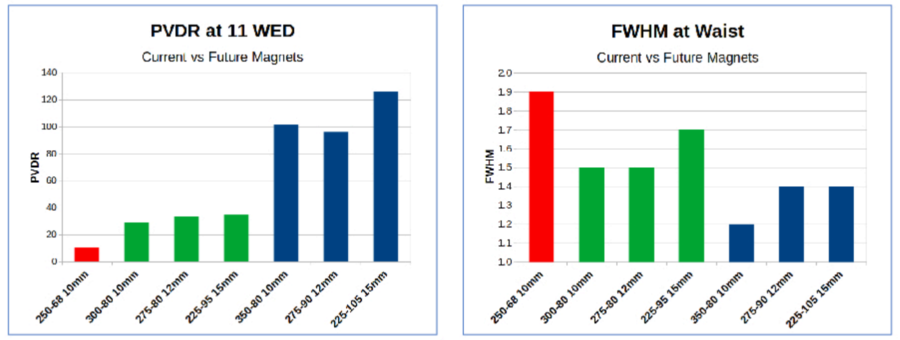


Fig 5: A) PVDR at 11 mm WED, and B) minimum FWHM data from this poster (red), the same energy but using magnets with higher lens power (green), or higher energy (~150 mm range) and lens power. 300-80 10mm = magnet of 300 T/m gradient, 80 mm length, and 10 mm diameter, etc.

CONCLUSIONS

Our results suggest proton minibeams with clinically relevant dimensions and PVDR values can be created using a single high-gradient quadrupole magnet using current magnet and beam delivery technologies.

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CONTACT INFORMATION

Grant McAuley: gmcauley@llu.edu