Feasibility of Proton Beam Delivery at Ultra-High Dose Rate FLASH Using a Gantry-Mounted Clinical Synchrocyclotron

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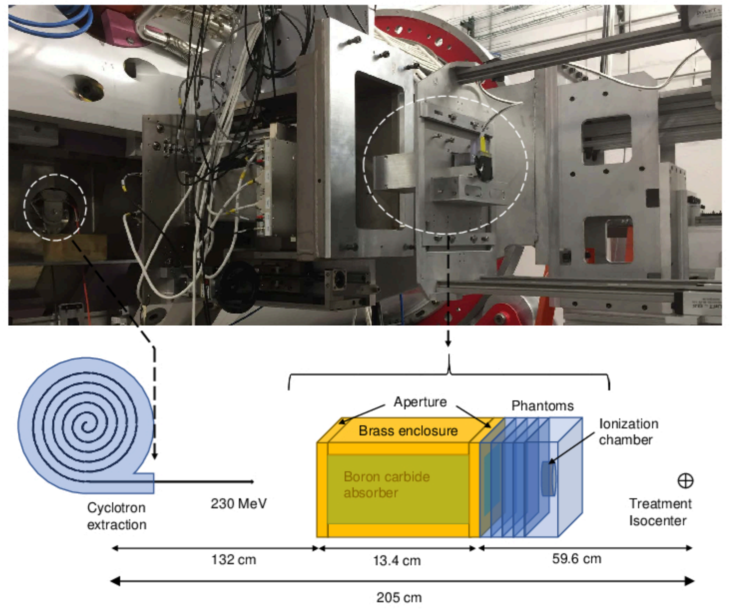
INTRODUCTION

It has been recently shown that radiotherapy at ultrahigh dose rates (>40 Gy/s, FLASH) has a potential advantage in sparing healthy organs compared to that at conventional dose rates [1]. The purpose of this work is to show the feasibility of proton FLASH irradiation using a gantry-mounted synchrocyclotron as a first step toward implementing an experimental setup for preclinical studies.

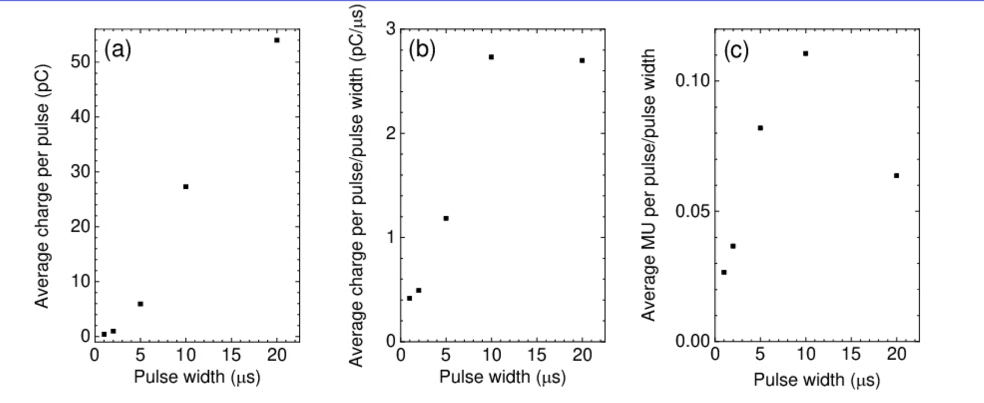
METHOD

A clinical Mevion HYPERSCAN® synchrocyclotron was modified to deliver ultrahigh dose rates. Pulse of protons with 230 MeV energy were manipulated (1-20 μs) to deliver in conventional and ultrahigh dose rate. A boron carbide absorber was placed in the beam for range modulation.

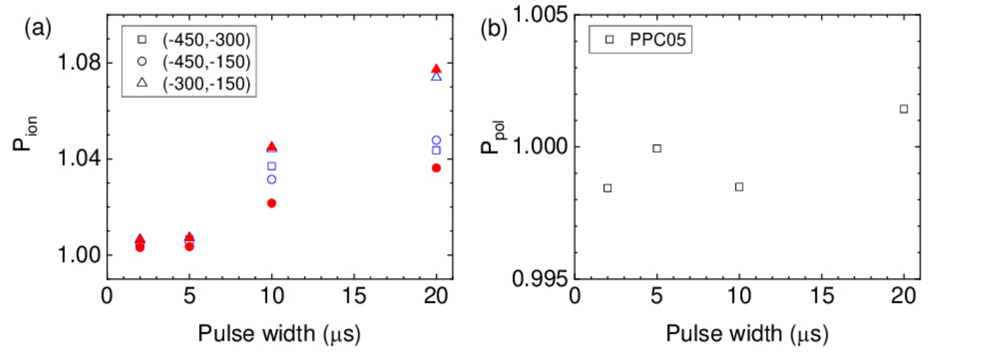


A Faraday cup was used to determine the number of protons per pulse at various dose rates. Dose rate was determined using a plane-parallel ionization chamber. The integral depth dose (IDD) was measured with a Bragg peak ionization chamber. Monte Carlo simulation was performed in TOPAS as the secondary check for the measurements.

RESULTS



Average measured (a) charge per pulse, (b) charge per pulse normalized by the pulse width, and (c) MU per pulse (normalized by the pulse width) at different pulse widths. Error bars are smaller than the square symbols [2].



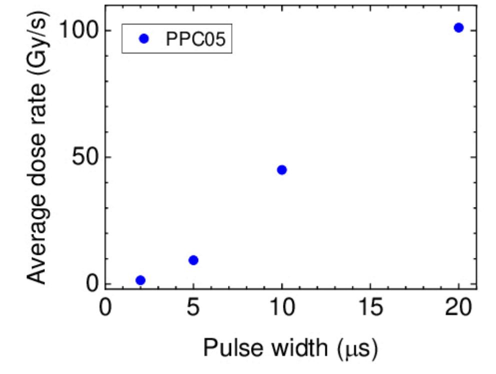
Ion recombination correction factor calculated for hollow symbols using Eq. (1) and for solid symbols Eq. (2). (b) Polarity correction factor calculated at different dose rates using Eq. (3) [2].

$$P_{ion}(V_H) = \frac{1 - V_H/V_L}{M^H_{raw}/M^L_{raw} - V_H/V_L}, \text{ Eq. (1)}$$

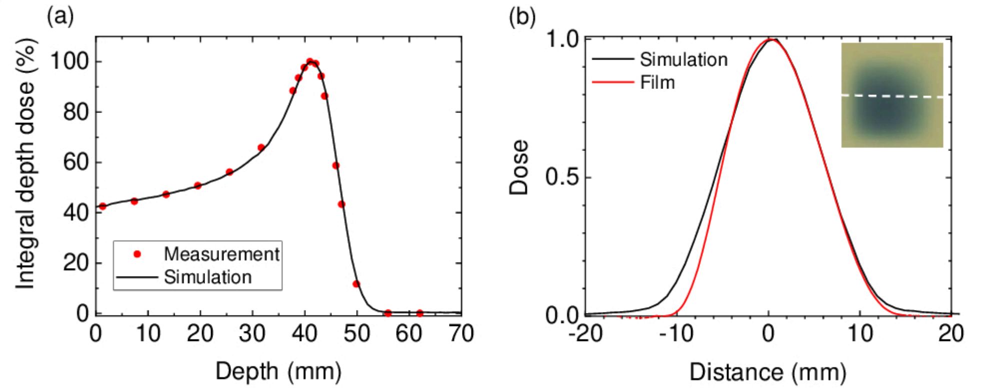
$$P_{ion}(V_H) = a_0 + a_1\left(\frac{M^H_{raw}}{M^L_{raw}}\right) + a_3\left(\frac{M^H_{raw}}{M^L_{raw}}\right)^2, \text{ Eq. (2)}$$

$$P_{pol} = \left|\frac{M^+_{raw} - M^-_{raw}}{2M^-_{raw}}\right|, \text{ Eq. (3)}$$

The average dose rate in each pulse structure was calculated from $\dot{D} = \frac{D.f}{N}$, where N is the number of pulses, f = 648 Hz is the pulse repetition rate, and D is the measured dose using TRS-398 protocol.



Measured average dose rate at 2 mm depth using PPC05 ion chamber [2].



(a) Integral depth dose measured using a Bragg Peak® chamber. The pulse width was 5 μs corresponding to 9.5 Gy/s average dose rate. For comparison, integral depth dose measured from Monte Carlo simulation is plotted in the same graph. (b) Longitudinal profile measured using EBT-XD radiochromic film at the Bragg peak when 50 pulses with 20 μs pulse width were delivered (~200 Gy/s average dose rate). A slight asymmetry was noticeable in the beam profile, which is due to the removal of a beam collimation element near the exit of the cyclotron. [2].

The measured average dose at the Bragg peak was 216 Gy/s. The corresponding instantaneous dose rate was 1.66×10^4 Gy/s. The simulated average dose rate at the Bragg peak was 206 Gy/s when delivered in pulse width of 20 μs. The discrepancy between the simulation and the measurement at the highest dose rate could be contributed by either the lack of accuracy in collecting charges received by the Faraday cup or the deficit in handling the ion recombination with the two-voltage and quadratic methods in synchrocyclotron. The vacuumless Faraday cup used in this study provides measurement of charges with accuracy between −1% and −5% in general.

Due to the pulsed structure of the beam generated in a synchrocyclotron, akin to that in a linear accelerator, a detector with capability to evaluate dose per pulse is highly desirable. This fact is irrelevant for isochronous cyclotrons due to their quasi-continuous radiation. A unique feature inherent with a synchrocyclotron system is that it provides a platform for further investigation with the intention to clarify whether instantaneous dose rate vs average dose rate is the main driver of the FLASH-irradiation protective effect in proton therapy.

CONCLUSIONS

As a first step toward implementing an experimental setup for preclinical studies, feasibility of delivering proton beam in FLASH dose rate of 100 and 200 Gy/s at the entrance and at the Bragg peak, respectively, using a clinical synchrocyclotron system was demonstrated. Due to FWHM field size of 1.2 cm, the system could potentially provide a platform for further *in vitro* and *in vivo* animal studies in FLASH mode.

Further optimization in the design is required to improve the beam profile in terms of range, uniformity, and field size. To treat larger, clinically relevant target volumes with FLASH, techniques will have to be developed to spread the beam both laterally and in depth while maintaining the local dose rate. These techniques may include the use of ridge filters, modulation wheels, or very fast layer switching to distribute the beam in depth and fast scanning or scattering to distribute the beam laterally. Beam current will have to be scaled up as larger target volumes are attempted.

There is a need for developing dosimeters and dosimetry protocols for ultrahigh dose rate FLASH radiation beams.

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CONFLICT OF INTERESTS

Townsend Zwart, Miles Wagner, and Daniel Catanzano are Mevion Medical Systems employees.

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