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DEVELOPMENT OF AN ULTRAHIGH DOSE RATE RADIATION PLATFORM FOR X-RAY FLASH RADIOTHERAPY RESEARCH*

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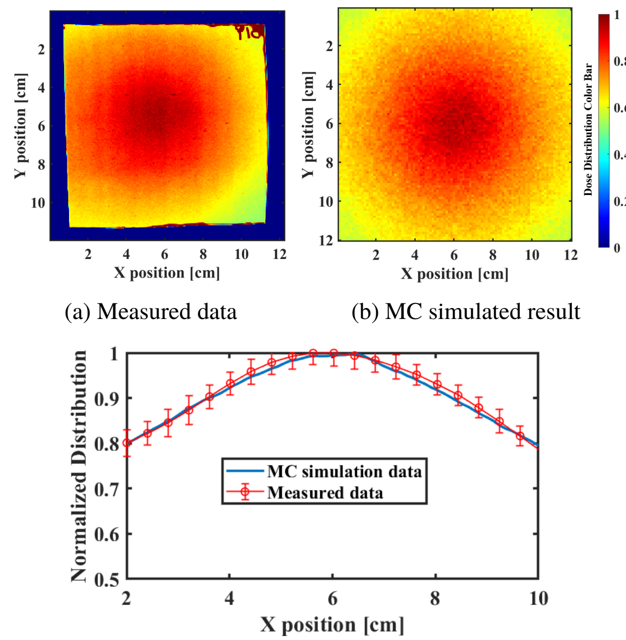
Abstract

An ultrahigh dose rate (UHDR) MV-level X-ray radiation platform for FLASH radiotherapy (RT) research based on a normal conducting linear accelerator is presented in this work. A S-band backward traveling-wave linear accelerator powered by a commercial klystron produces electron beams with 11 MeV energy, 300 mA pulse current, and 2.6 mA mean current at 0.88 % beam duty ratio. The radiation platform generates X-ray by bremsstrahlung. Flattening filters and collimators are included to produce a 4 cm × 3 cm field with flatted profile dose distribution. The measured dose rate was 129 Gy/s and the flatness was 14 % after flattening. The UHDR X-ray platform now is used for FLASH preclinical animal research.

INTRODUCTION

The FLASH effect triggered by ultrahigh dose rate radiotherapy (UHDR-RT) , which can significantly reduce normal tissue toxicity while maintaining antitumor efficacy, has been verified by many studies in vivo [1–6] and even applied in human clinical cases [7, 8]. Although there are several hypotheses to explain experimental results of FLASH effect, the mechanisms of the FLASH effect are not fully understood at present [9]. An UHDR radiation platform based on accelerators is the foundation for FLASH-RT preclinical research to explore optimum parameters in the treatment plan, including dose, dose rate and fractionation, and the mechanism of FLASH-RT.

Radiotherapy methods with charged particles, including electron, proton, and even heavy ion, can achieve the UHDR beams to trigger FLASH effect with adjusted clinical accelerator equipment, thus electron and proton FLASH-RT developed rapidly in the past several years. MV-level X-rays, which are widely used in conventional clinical radiotherapy, are secondary rays produced by the bremsstrahlung from electrons bombarding the conversion target, therefore it's difficult for existing clinical X-ray medical accelerators increasing dose rate by hundreds times to reach the FLASH dose rate threshold value 40 Gy/s. There are two main technical obstructions to build an UHDR X-ray platform. Firstly, ultrahigh dose rate requires high mean beam power. On the other hand, the X-ray conversion target should be optimized



(a) Measured data (b) MC simulated result

(c) Dose distribution comparison

Figure 1: Measured and MC simulated dose distribution at 67.9 cm SSD

to deal with rapid temperature rising caused by such high beam power. UHDR MV-level X-rays have been achieved based on a superconducting research linac [10] and a normal-conducting industrial linac [11], and there are many platforms are under designing to contribute to X-ray FLASH-RT researches [12–15].

In this work, the design and measurement of a 4 cm × 3 cm small field for X-ray FLASH-RT preclinical animal research are presented, based on the UHDR X-ray platform built by Tsinghua University [11]. Based on this work, FLASH-RT preclinical experiment has been operated in mice.

PLATFORM DESIGN

Beam Source

An UHDR MV-level X-ray radiation platform for FLASH-RT researches was built based on a normal conducting linear accelerator [11]. A S-band backward traveling-wave linear accelerator powered by a commercial klystron produces electron beams with 11 MeV energy, 300 mA pulse current, and 2.6 mA mean current at 0.88 % beam duty ratio. To decrease

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the pulse heating at the conversion target, electron beams are defocused after a 1.8 m drift tube. The materials of the conversion target on the beamline are 3 mm tungsten and 2 mm copper. The UHDR X-ray are generated by bremsstrahlung at the target. As a result, measured flat-filter-free (FFF) dose rates are approximately 80 and 45 Gy/s at source-surface distances (SSD) of 50 and 67.9 cm respectively. Parameters of the platform are shown in Table 1, and more details of the platform can be found in our past work [11].

Table 1: Parameters of the UHDR MV-level X-ray Radiation Platform

Parameters	Value
Linac Length	1.65 m
Peak RF input power	4.9 MW
Electron energy	11 MeV
Pulse electron current	300 mA
Repetition frequency	700 Hz
Beam pulse length	12.5 µs
Beam duty ratio	0.88 %
Mean electron current	2.6 mA
Mean beam power	29 kW
FFF Mean dose rate @50 cm	79.8 Gy/s
FFF Mean dose rate @67.9 cm	46.6 Gy/s

Small Radiation Field Design

In order to operate clinical FLASH-RT researches in small animals, small radiation fields with appropriate size are required. An aluminum flattening filter and a tungsten collimator were designed and optimized with Monte Carlo (MC) simulations using Geant4. To simplify the MC calculation, the electron source were defined as electron beams with 11 MeV energy and an uniform profile distribution with 7 mm radius. The target was defined as 3 mm tungsten and 2 mm copper. The measured dose distribution with EBT-3 radiochromic film and the MC simulation result at the SSD of 67.9 cm at a 2.1 cm depth of the water phantom are shown in Figs. 1. The simulation result agrees with the measured data, indicating the simplified electron distribution is a good approximation.

The dose rate follows the inverse square law of the distance, so the SSD of FLASH-RT research in small animals is changed into 28 cm to achieve a higher dose rate. The set-up of the flattening filter and the collimator in MC simulation model is shown in Fig. 2. The aluminum flattening filter consists of two circular truncated cones, placed on the top of the collimator. The tungsten collimator is hollowed-out with a 2.4 cm × 3.2 cm square on the top and a 2.6 cm × 3.6 cm square on the bottom. The thickness of the collimator is 8 cm, and the height between the bottom of the collimator and the water phantom is 7.5 cm. The thickness and profile size of the water detector are 3 cm and 6 cm × 6 cm. The Water phantom with 10 cm thickness are added to decrease the contribution of scattering beams.

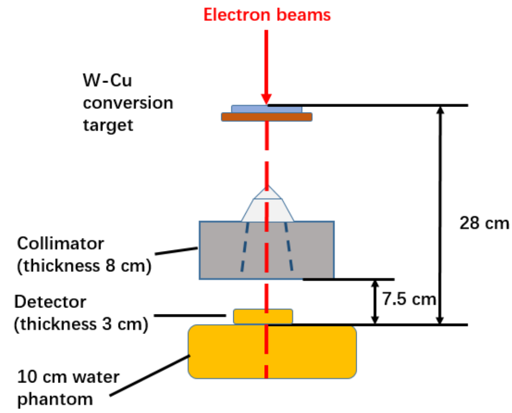
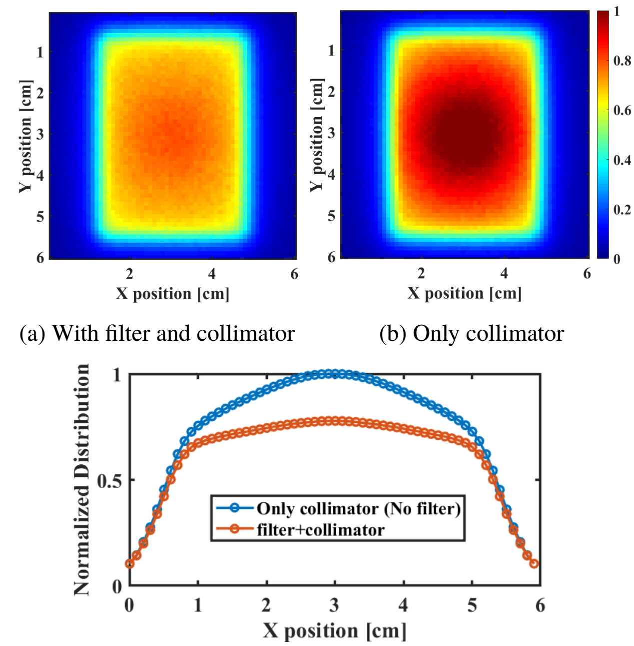


Figure 2: Set-up of MC simulation model



(a) With filter and collimator (b) Only collimator

(c) Dose distribution comparison

Figure 3: MC simulated dose distribution with filter and collimator at 28 cm SSD

The MC simulation results at the depth of 2 cm are shown in Figs. 3. The flattening filter would decrease the dose and dose rate around the center. The max dose value with filter is decreased to 77.8 % compared to the max dose without filter. In the 4 cm × 3 cm field, the flatness F with filter is improved to 12 % while the value is 25 % without filter. The definition of F is shown in Eq. (1), where D is the dose value in the field. Dose rate is one of the most important parameter in FLASH-RT, thus the FFF mode should be considered to maintain higher dose rate.

$$F = \frac{|\min D - \max D|}{\max D} \qquad (1)$$

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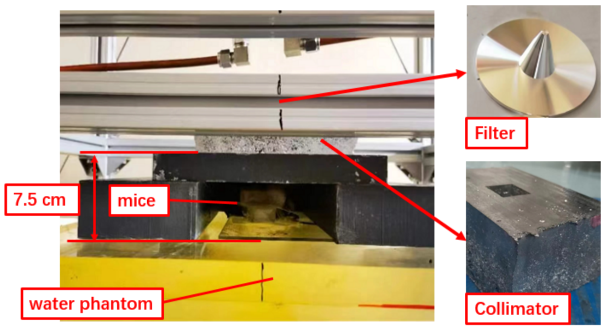
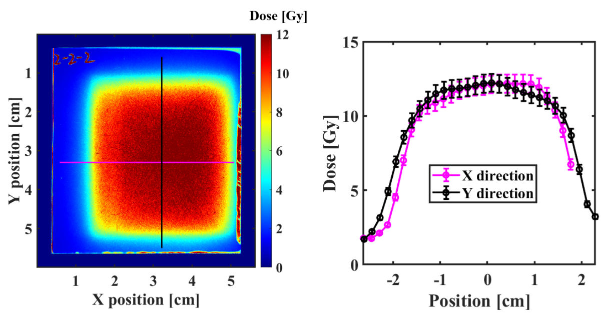


Figure 4: Set-up of Experimental platform



(a) 2D dose distribution (b) profile distribution

Figure 5: Measuered dose distribution at 28 cm SSD

EXPERIMENTAL RESULT

The set-up of experimental platform is shown in Fig. 4, which is the same with the MC model shown in Fig. 2. The dose was measured by calibrated EBT-3 films, and the radiation duration was calculated from the recorded pulse number and the system repetition rate 700 Hz. Measured results are shown in Figs. 5. The flatness is 14 % in the rectangular field. The max dose at 2 cm depth water phantom was 12.2 ± 0.6 Gy, and the recorded pulse number was 66. Thus, the max dose rate with flattening filter was 129 Gy/s at 28 cm SSD.

CONCLUSION

An ultrahigh dose rate MV-level X-ray radiation platform for FLASH-RT research based on a normal conducting linear accelerator is presented in this work. A 4 cm × 3 cm small filed is developed with an aluminum flattening filter and a tungsten collimator for FLASH-RT researches on small animals. In MC simulation, the max dose at the center decreases to 77.8 % while the flatness is improved to 12 % from 25 % when adding a filter on the top of the collimator. Since high dose rate is difficult to achieve in X-ray FLASH-RT, FFF therapeutic mode should be considered in the future application. The measured dose rate was 129 Gy/s at 28 cm SSD and the flatness was 14 % after flatenning. The first stage FLASH preclinical research in mice has been finish at the UHDR X-ray platform.

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