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Short Communication

Verification of real-time dosimetry of ultra-high dose rate beams at AQURE FLASH RT on the sample surface

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Abstract

Introduction: FLASH radiotherapy involves delivering a dose of ultra-high-dose-rate ionising radiation (>40 Gy/s) in less than 200 ms, resulting in sparing healthy tissue and effectively destroying cancerous tissue. This article presents a preliminary verification of the feasibility of using real-time internal dosimetry at the sample surface to measure doses generated by the AQURE FLASH RT accelerator dedicated to FLASH radiotherapy studies.

Material and Methods: The AQURE FLASH RT emits a 6 and 9 MeV electron beam with a dose rate higher than 40 Gy/s. The real-time dosimetry system to measure doses on the sample surface was implemented into the accelerator and consists of inductive sensors in which the moving electron charge induces a voltage in the secondary toroidal winding. The internal dosimetric system was preliminarily calibrated for single pulse irradiations using passive dosimetry methods, i.e. film and alanine dosimetry.

Results: The study showed that there was no effect of the tested dosimetry system on the beam (PDD and beam profile). The linearity of the system's response to successive pulses was tested and found to be <2% only for irradiation with two or more pulses. Therefore, a single pulse calibration of the system was performed to verify the applicability of the system for single pulse irradiation. The measurement results showed that the differences between the results obtained by the different methods were less than 2% for triode grid voltages below 30 V.

Conclusion: The results confirmed the possibility of using the real-time dosimetry system to measure doses on the sample surface delivered by ultra-high dose rate beams at the AQURE FLASH RT accelerator. The system has been tested and validated over the full range of dose rates emitted by the accelerator to measure a dose in a single pulse. The results of the dosimetric measurements confirmed that the system did not affect the beam parameters.

Keywords: ultra-high dose rate; FLASH; FLASH radiotherapy; real-time dosimetry.

Introduction

FLASH radiotherapy involves the use of high dose rates of ionising radiation. It allows to save healthy tissues with a high level of destruction of cancer tissues.[1]. To notice this saving effect, a high dose of radiation using a beam of ultra-high dose rates should be delivered to a target in a very short time.[2] The first time the FLASH effect was noticed in the 60s of the twentieth century when it was shown that non-cancerous mammalian cells irradiated at ultra-high dose rates had greater viability than those irradiated at conventional dose rates.[3] However, the real flowering of interest in this subject occurred only after 2014 when it was shown that irradiation of the chest of mice with a single fraction of 17 Gy at conventional dose strengths (0.03 Gy/s) caused "moderate" and "severe" areas of pulmonary fibrosis 36 weeks after irradiation while when mice received the same dose at high dose rates (40-60 Gy/s), induction of pulmonary fibrosis was significantly reduced. At that time, this effect was again assessed and called the FLASH effect.[4]

The devices dedicated to FLASH radiation should meet the parameters of FLASH radiotherapy, i.e. generate a high dose in a short time (< 200 ms) with a dose rate of more than 40 Gy/s. Currently, research on the FLASH technique has been conducted with helium ion, carbon ion, proton, photon and electron beams.[5] The introduction of electron beams for clinical

Authors' contribution: A – Research concept and design. B – Collection and/or assembly of data. C – Data analysis and interpretation. D – Writing the article. E –Critical revision of the article. F – Final approval of the article.

use in radiotherapy with ultra-high dose rates seems to be the least complicated due to the device size, compactness and availability of electron accelerators and the preclinical and clinical studies performed so far. The use of FLASH beams for intraoperative radiotherapy also seems interesting.[6]

The most commonly used reference dosimetry method for measuring ultra-high dose rate beams are passive methods, e.g. film, alanine or TLD dosimetry.[7,8] The ionisation chambers used in both reference and real-time dosimetric measurements in medical accelerators exhibit an ion recombination effect, making their response dependent on the dose rate.[7,9] However, when it comes to beam monitoring and real-time measurement in an accelerator dedicated to FLASH radiotherapy, beam current measurements are applicable.[10] This type of solution has been proposed by an Intra Op device – The Mobetron FLASH – which has developed an accelerator for intraoperative therapy with the possibility of generating an ultra-high dose rate beam.[11]

Material and Methods

AQURE FLASH RT

The AQURE FLASH RT is an advanced accelerator designed to deliver ultra-high dose rate beams with energies of 6 and 9 MeV, achieving dose rates of up to 600 Gy/s and 900 Gy/s, respectively. This device is based on the AQURE accelerator, originally developed for intraoperative radiotherapy.[12] Its mobile design allows for movement in any direction, with flexible head positioning at various angles. Additionally, the system is adaptable to research-specific parameters. Key beam characteristics, such as pulse duration, pulse repeatability, and Source-to-Sample Distance (SSD), can be adjusted and customized to meet the specific requirements of ongoing studies. Adjusting the parameters of the accelerator components affects various beam parameters, including dose rate, with the grid voltage of the triode being the most significant influence. The AQURE FLASH RT generate electron fields in a range of diameter from 4 to 10 cm, with symmetry and flatness according to IEC standards for medical accelerators.[13,14] In this study, all dosimetric measurements were performed using a steel applicator with a diameter of 5 cm on SSD = 25 cm.

Internal real-time dosimetry system

The AQURE FLASH RT accelerator has been equipped with an internal pulsed-mode beam measurement system that utilises inductive sensors. In this system, the movement of electron beams induces a voltage in a secondary toroidal winding. This voltage is then transmitted to an amplification circuit, followed by a conversion from an analogue to a digital signal. The user interface processes the digital signal from the internal dosimetry system and provides real-time feedback on the dose delivered to the sample surface during each pulse based on a pre-established calibration curve. **Figure 1** illustrates a schematic of the integrated dosimetry system along with the geometry used for calibration irradiations.

To verify the feasibility of this type of measurement system, calibrations were performed on the first coil only, together with the analogue and digital circuits. This coil is positioned directly behind the output of the accelerating structure, allowing it to measure the beam current before any shaping by the electron beam forming and collimation system.

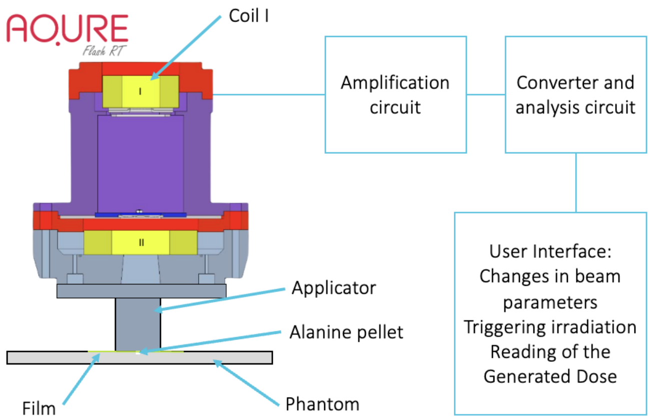

Figure 1. Schematic of the internal real-time dosimetry system and the geometry of dose measurements on the surface of the sample (phantom) by alanine and film dosimetry for calibration.

Calibration measurements by film and alanine dosimetry

The calibration of the internal real-time dosimetry system implemented in the AQURE FLASH RT accelerator was performed by two methods: alanine and film dosimetry. Both the alanine pellet and piece of film were placed in the middle of the electron field limited by an applicator to a diameter of 5 cm at SSD = 25 cm on the surface of the PMMA phantom. The geometry of calibration measurements is shown in **Figure 1**. The alanine measurements were performed by the accredited Laboratory for Measurements of Technological Doses at the Institute of Nuclear Chemistry and Technology in Warsaw, Poland.[15] To obtain results of film dosimetry, Gafchromic films type EBT-XD were used and scanned 24 hours after irradiation. To obtain and analyse results, PTW Film analysis software was used. Using alanine dosimetry, the dose was determined with an overall uncertainty of 4.8%, while the uncertainty of the measurement using radiochromic films was estimated at 4%.

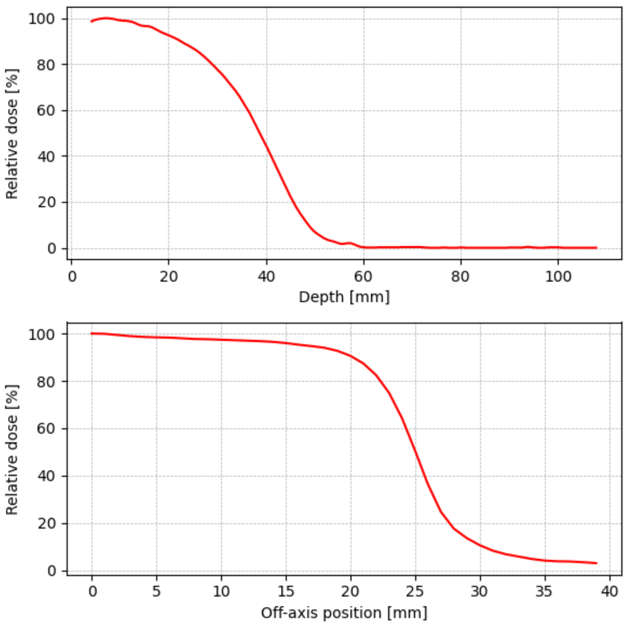

Figure 2. PDD and profile of the 9 MeV ultra-high dose rate electron beam (1500 Gy/s) generated by AQURE FLASH RT.

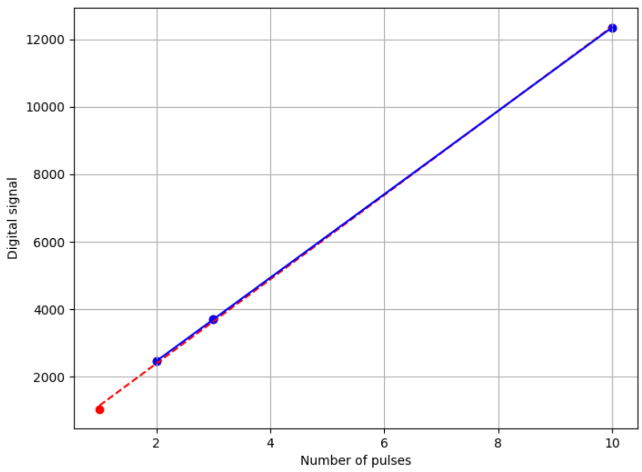

Figure 3. The linearity of the response of the internal real-time dosimetry system to the radiation pulses for the first and subsequent pulses (red) and the linearity for two or more pulses (blue).

Results

The impact of the internal real-time dosimetry system on the electron beam parameters was examined, revealing no effect of the measurement system on the dose depth distribution or profiles of the FLASH beam. **Figure 2** shows the PDD (Percentage depth dose curve) and beam profile of the 9 MeV beam used to calibrate the real-time dosimetry system. The flatness of the measured beam was 1.69%, and the symmetry was 3.21 % according to IEC standards for medical accelerators.

The linearity of the internal dosimetry system's response was evaluated to assess its proportionality to consecutive pulses. The analysis revealed that the maximum deviation from linearity in the system's response to two or more consecutive pulses is 0.2%, as shown in **Figure 3**. For comparison, according to the IEC-60977 standard for medical accelerators, the acceptable deviation in proportionality should be below 2%. The linearity analysis of the response of the internal dosimetry system showed agreement of less than 2% except for a single pulse (>2%).

To verify whether the internal real-time dosimetry system can correctly measure doses from a single pulse – i.e., beyond the linear response range of the system – a single-pulse calibration was conducted. Calibration measurements were performed simultaneously using alanine and film dosimetry depending on the opening of the grid on the triode voltage from 0 to 40 V with a step of 5 V, which increased the dose rate, i.e. the dose in the pulse. Each measurement point was repeated three times. Then, quadratic functions were fitted to the obtained results (see **Figure 4**), which were adjusted with the model fit quality index to the data (R) for alanine $R_A = 0.98$ and for the films $R_F = 0.99$.

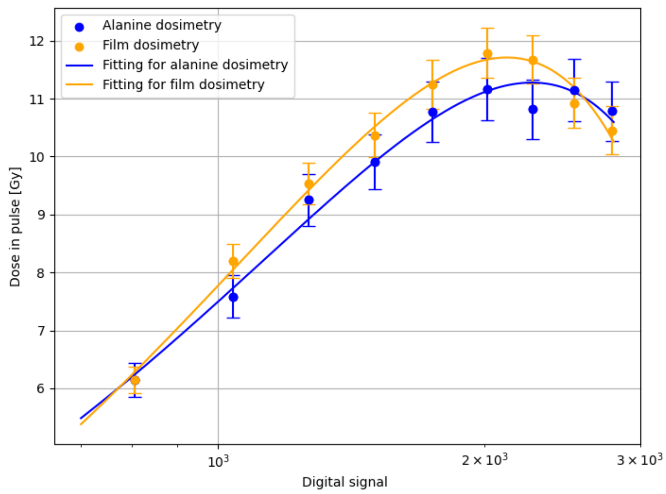

Figure 4. Calibration curves of the internal real-time dose measurement system on the sample surface determined by alanine and film dosimetry. Digital signal (in arbitrary units) corresponds to the current intensity induced by the electron beam.

Table 1. Comparison of doses in single pulses determined using an internal real-time surface dose measurement system from alanine and film dosimetry fitting, with measured doses in single pulses obtained from alanine and film dosimetry, and the differences between determined and measured doses for various grid voltages.

Grid voltage [V]	System measured dose [Gy]	Alanine measured dose [Gy]	The difference [%]	System measured dose [Gy]	Film measured dose [Gy]	The difference [%]
7	8.01	7.86	1.91	7.41	7.56	1.98
17	10.19	10.13	0.60	9.78	9.91	1.25
27	11.26	11.05	1.89	11.01	10.93	0.66
37	10.94	10.60	3.24	11.15	10.66	4.58
39	10.77	10.14	6.20	10.57	10.98	3.74

Test measurements were also performed to verify the calibration of the internal single pulse dose measurement system on the sample surface. Doses per pulse at the sample surface were determined from the response of the dosimetry system under test, and actual doses at the sample surface were measured using alanine and film dosimetry. For measuring points with triode grid voltages below 30 V, differences in doses calculated by the system and by film and alanine dosimetry of no more than 2% were obtained. On the other hand, when the triode grid voltage was higher than 30 V, the differences were higher, up to 6.20%. The results obtained with the differences are shown in **Table 1**.

Discussion

The linearity of the response of the dosimetry system remains at the assumed level of 2% for irradiation of at least two pulses. Single pulse radiation dosimetry requires additional calibration procedures. The destructive effect of a single pulse on linearity may result from the low repeatability of a single pulse, which may be caused by the microwave power matching within the accelerator structure, which may vary significantly for a single pulse of high radiation intensity. Further analysis of this effect and the influence of other parameters affecting single pulse repeatability and stability is required.

It has been observed that when the response of the dosimetry system is above the digital signal of 2000 (see **Figure 4**), the dose in the pulse does not increase as expected. This effect may be caused by the change in energy of the ultra-high dose rate beam. When the intensity of the electron beam is increased, it is necessary to increase the value of the microwave field in the accelerating structure so that more electrons can be accelerated to the same energy. In the case described in this study, the microwave field value in the accelerating structure was constant; therefore, the maximum dose rate was observed, and no further increase in dose rate was observed despite the increase in digital signal response. At present, an integral dosimetric system can measure doses on the sample surface for a beam in the range of about 1100 Gy/s (grid voltage = 0 V) up to about 1700 Gy/s (grid voltage 30 V). It is necessary to extend the measurement range of the currents induced by the passing electron beam and to vary the microwave field to control and increase the energy of the electron beam as the dose rate increases.

Conclusions

The real-time sample surface dose measurement system presented in this paper did not interfere with the beam parameters over the entire dose rate range (the triode grid voltage ranges from 0 to 40 V, which corresponds to the dose rate range from 1100 to 1700 Gy/s), so it can be used on the AQURE FLASH RT accelerator and determine the dose at the sample surface in real-time during ultra-high dose rate beam testing.

Preliminary verification of the feasibility of real-time dosimetry of ultra-high dose beams in AQURE FLASH RT was performed for single pulses to test its applicability to single pulse irradiation. The tests performed showed a linear dependence of the beam current measurement system signal on the number of pulses (for two or more pulses) so that an integrated real-time dosimetry system measuring the dose at the sample surface can measure doses delivered in a multi-pulse manner. However, single-pulse dose delivery requires an individual method of analysis and detail. Calibration performed for single pulses showed that a real-time dosimetry system measuring the dose at the sample surface can determine the value of the deposited dose with a difference of no more than 2% up to the opening of the 30 V grid.

The next step in the procedure calibration of real-time dosimetry for ultra-high rate dose electron beams will be a verification of multi-pulse irradiation, i.e. calibration with multiple pulses and reading of doses on the surface of the sample deposited by several pulses.

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Editor's comment

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