Editors' pick

Monitoring electron energies during FLASH irradiations

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What was your motivation for initiating this study?

Performance of dosimetry during ultra-high-dose-rate FLASH irradiations is far from straightforward, since most conventional real-time dosimeters (e.g. ionisation chambers) are inappropriate for this application due to saturation effects. Furthermore, when linear accelerators (linacs) are used to deliver energetic, high-current FLASH electron pulses, even small variations in beam current can cause significant changes in beam energy. In effect, the total accelerator radio frequency (RF) power is shared between the power that is transferred to the beam and the power that is lost in the accelerating waveguide. In all linacs, the available RF power is limited; increases in beam current result in reduction of beam energy and vice versa. These energy variations affect penetration of the electron beam into tissues and thus modify the dose that is delivered at depth. During FLASH irradiation, the beam current is usually maximised. It is essential that the doses that are delivered at depth are made similar to those that would be offered under conventional irradiation methods in order to avoid adverse consequences.

Our solution to this problem was to develop an extremely simple, non-saturating, non-intercepting, external beam energy monitor that could be placed close to the irradiated sample. This device provides us with a real-time readout of energy during every linac pulse. The electron pulse lasts for ~3.5μs and repeats at user-set repetition rates that range from 25Hz to 300Hz. Our energy monitor is extremely simple. It is made up of two aluminium charge collection plates that are electrically floating, coaxial, closely separated and of annular shape; these plates are complemented by two thin, grounded screens that are used for electrical screening and to isolate the charge collection plates from each other. The portion of the beam that passes through the central hole is collimated as required and irradiates the sample. The fringes of the beam, however, are picked up by the plates; the high-energy electrons are stopped at the rear plate, which is closer to the sample, while most low-energy electrons are picked up by the front plate, which is closer to the accelerator output window. The charges that are picked up by the charge collection plates are measured and processed to provide a ratiometric output that indicates beam energy that is independent of total beam charge.

The distance between the collimator and sample can be varied by up to ~95cm. This variation, in conjunction with adjustments of pulse repetition rate, number of pulses and peak electron current, gives the experimenter the ability to vary the average dose rate from <3 x 10^{-4} Gy sec^{-1} to >3 x 10^{6} Gy sec^{-1}. Furthermore, we can alter the matching of the RF source to the accelerator waveguide in our linac in order to alter the RF power to the accelerator waveguide and hence change the beam energy.

What were the main challenges that you faced during the work?

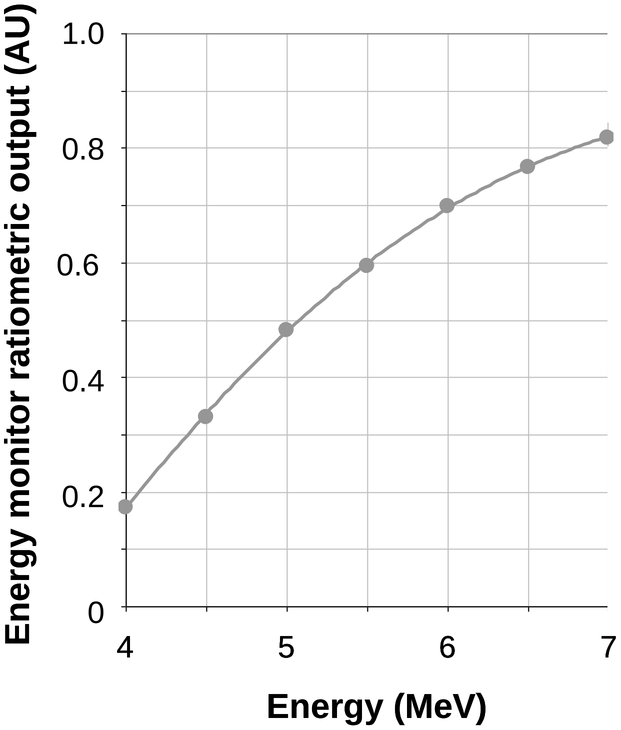
We first set up a model of the monitor in EGSnrc, which is a software toolkit, to perform Monte Carlo simulation of the transport of ionising radiation through matter. However, in order to model the monitor's energy response at different working distances, we needed to know the output beam's energy spectrum. We could not determine this directly and were forced to use an iterative approach, by first presuming a likely energy distribution and then comparing the monitor's response that was provided by the simulation with measurements of percentage depth dose, lateral beam profiles and beam charge that passed through the monitor. This proved to be the most challenging and time consuming part of the work. After we had performed numerous such iterations (>100!), we were confident that our beam was modelled correctly over a wide range of working distances and would predict the monitor's behaviour under all operating conditions. Of course, the Covid pandemic inevitably interfered with data acquisition, but the main challenge was to define our 'beam' (energy, spectrum, dimensions and distribution).

What is the most important finding of your study?

Our energy monitor was very easy to use. It enabled the performance of straightforward optimisations of accelerator parameters in order to maximise dose rate for FLASH irradiation as well as the adjustment of total power that was fed to the waveguide so that conventional dose-rate irradiations could be performed at beam energies that were comparable with those used for FLASH. Duration of experiments was significantly reduced because a real-time readout was available and quality assurance processes were similarly simplified.

We could even observe changes in energy *during* the electron pulse. The plate pulse currents could be observed if the plates were connected to a pair of 50Ω oscilloscope or digitiser inputs. This was made possible because we equalised the capacitances of each of the charge collection plates to ground and eliminated the plate-plate capacitance with the aid of the aforementioned thin screens. We achieved 10-90% rise/fall times of ~80ns, though this could be readily reduced to ~30ns if the use of long interconnection cables was eliminated by using a pair of buffer amplifiers.

The ratiometric output from our device is not linear with energy, which is why we call it an 'energy monitor' rather than an 'energy meter'. However, its sensitivity to energy changes is more than acceptable. If we assume that the ratiometric output can never exceed a value of unity, which would correspond to infinite energy, our device provides typically a 21% change in the output between 5MeV and 6MeV and a 13% change between 6MeV and 7MeV, progressively reducing at higher energies. The response of the monitor is shown in the accompanying figure.



What are the implications of this research?

The construction and installation of this extremely simple device has provided us with the confidence to compare biological responses to FLASH and to conventional irradiation. Although we have used our device with electron beams of 6MeV nominal energy, the device can be optimised easily for use with other energies. Furthermore, if we combine the energy readout from the device with an independent measure of the charge that irradiates the sample (e.g. through use of inductive or capacitive sensors), we can deduce the dose to the sample. This aspect is likely to be the subject of a future publication.

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