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Challenges of dosimetry of ultra-short pulsed very high energy electron beams

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ABSTRACT

Very high energy electrons (VHEE) in the range from 100 to 250 MeV have the potential of becoming an alternative modality in radiotherapy because of their improved dosimetric properties compared with 6–20 MV photons generated by clinical linear accelerators (LINACs). VHEE beams have characteristics unlike any other beams currently used for radiotherapy: femtosecond to picosecond duration electron bunches, which leads to very high dose per pulse, and energies that exceed that currently used in clinical applications. Dosimetry with conventional online detectors, such as ionization chambers or diodes, is a challenge due to non-negligible ion recombination effects taking place in the sensitive volumes of these detectors. FLUKA and Geant4 Monte Carlo (MC) codes have been employed to study the temporal and spectral evolution of ultrashort VHEE beams in a water phantom. These results are complemented by ion recombination measurements employing an IBA CC04 ionization chamber for a 165 MeV VHEE beam. For comparison, ion recombination has also been measured using the same chamber with a conventional 20 MeV electron beam. This work demonstrates that the IBA CC04 ionization chamber exhibits significant ion recombination and is therefore not suitable for dosimetry of ultrashort pulsed VHEE beams applying conventional correction factors. Further study is required to investigate the applicability of ion chambers in VHEE dosimetry.

1. Introduction

Scanning very high energy electron (VHEE) beams is an emerging modality that has potential of becoming a new cost effective [1] radiotherapy treatment technique, with further development of laser plasma accelerator technology [2]. Currently VHEE beams are only available in research facilities in Europe [3,4] and North America [5], where there are several undergoing experimental activities. Previous theoretical studies using the PENELOPE Monte Carlo (MC) code [6] have shown the potential of employing 150–250 MeV electron beams in radiotherapy. The effective range of such beams can exceed 40 cm and, moreover, lateral scattering of such energetic electrons in tissue is sufficiently small for intensity modulated treatment of deep seated tumours to be considered [7,8]. Furthermore, the potential clinical advantage of electron beams with energies exceeding 100 MeV have been studied for lung cancer [9] and prostate cancer treatment [10]. These studies conclude that electron beams with energies above 100 MeV can achieve a very good dose conformation, comparable with, or even exceeding, those of current photon modalities, while offering significantly improved dose sparing of healthy tissue [11]. More recently, Bazalova-Carter et al. [12] developed a treatment planning workflow for MC dose calculation and treatment planning optimization for VHEE radiotherapy. Additionally, it has been demonstrated that 100 MeV VHEE dose distributions for a paediatric brain case outperformed clinical volumetric modulated arc therapy (VMAT) plan. Furthermore, for the studied patient cases, VHEE dose to all critical organs was up to 70% lower than the clinical 6 MV VMAT dose [12].

With the emerging VHEE modality in radiation treatment, there is an increasing need for accurate dosimetry of these unconventional beams. Previous work [13] demonstrated applicability of

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Gafchromic films for accurate dosimetry of VHEEs. However, this detector requires post-irradiation processing. The ionization chamber is considered as the most practical and is the most widely used type of dosimeter for accurate measurement of the output from clinical radiotherapy beams. Currently, ion chamber calibration, performed usually by standard laboratories, is not available for VHEE beams. The IAEA TRS 398 and IPEM codes of practices apply to electron beams from clinical accelerators with energies from 3 to 50 MeV [14] and 4 to 25 MeV [15], correspondingly. The VHEE beams are unlike any other existing radiotherapy beams. The radiation pulses have very short durations (femto- or pico- seconds, compared with microsecond pulses for radiotherapy beams generated with LINACs). Charge recombination may be a potential problem because of this. The electron energy range above 100 MeV is considerably higher than the electron energies for which established detectors have been calibrated (4–22 MeV typically). Extrapolation to high energies is therefore a challenge. This work reports ionization chamber measurements of a VHEE beam. Additionally, temporal and spectral evolution of ultrashort VHEE beams in a water phantom have been studied using Monte Carlo tools.

2. Materials and methods

2.1. Monte Carlo simulations of VHEE beams

The VHEE bunch is ultra-short, ranging from picosecond down to femtosecond in pulse duration, which is more than 10^6–10^8 times shorter than conventional clinical LINAs, producing microsecond duration electron bunches [16]. The ultrashort duration of VHEEs will govern the selection of detectors to carry out dosimetry with these unconventional beams. To illustrate the evolution of spectral and temporal profiles of ultrashort VHEE pulses a 150 MeV electron beam has been modelled using two MC toolkits, FLUKA [17] and GEANT4 [18]. The applicability of the MC model implemented in the FLUKA code has previously been validated against measurements in water phantoms [13]. Geant4 code has already been used for VHEE dose calculations [19]. The Geant4 calculations, presented in this work, were validated by the FLUKA model.

2.1.1. Evolution of the temporal profile of 150 MeV VHEE beams

The pulse lengthens when the electron bunch interacts with matter. GEANT4 5.9.5 has been used to evaluate bunch stretching time of flight (TOF) of a VHEE. A $30 \times 30 \times 30\ cm^3$ water phantom is positioned 100 cm from the source of a 150 MeV monoenergetic electron beam. The source-to-surface distance (SSD) is set to 100 cm. The electron beam is modelled as a cylinder of 50 mm radius and 0.3 μm height, corresponding to a bunch length of 1 fs, with a central axis positioned along the beam propagation direction. TOF is scored at 1 cm, 10 cm, 20 cm and 30 cm depth in water. The calculations are carried out for 5×10^6 particles. The low energy Livermore model [20] is used for these simulations and all relevant processes for photons, electron/positron interactions are switched on. Electron and photon transport thresholds are set to 10 keV.

2.1.2. Spectral profile of 150 MeV electron beams propagating through a water phantom

Calculations using FLUKA have been carried out for the energy distribution of the electrons at various depths (3.5 cm, 9.5 cm and 17.5 cm) in a water tank. The spectrum of incident 150 MeV monoenergetic VHEEs at various depths in a water tank are calculated using the USRBDX card, scoring energy of the particles crossing a probe detector. The probe detector is represented by a sphere of 1 cm radius, placed at a depth of 3.5 cm, 9.5 cm and 17.5 cm in water. Similarly, bremsstrahlung spectra have been evaluated for the same geometry. The 10^7 primary particle histories were simulated.

2.2. Ion chamber measurements

The standards laboratories provide calibration factors under standard ambient conditions. For the National Physical Laboratory, these are 20 °C, 1013.25 mbar (1013.25 hPa), and 50% humidity. All of the readings reported in this work have been corrected for non-standard ambient conditions employing IPEM recommendations [15]. IBA CC04 (SN: 108640) ion chamber in combination with Dose1 electrometer (IBA Dosimetry, Nuremberg) have been used to study ion recombination with conventional radiotherapy electron beam and VHEE beams. CC04 is a thimble-type, waterproof ion chamber which exhibits high spatial resolution due to its small volume ($0.04\ cm^3$) and is considered to be suitable for small fields measurements in high dose gradients [21]. The measurements with the CC04 chamber are recommended to be carried out at +300 V polarizing voltage. The electrometer was set up in the charge integration mode to determine the accumulated charge over the whole irradiation period. Ion recombination measurements have been carried out for 165 MeV VHEE beams at the SPARC beamline [4] and for 20 MeV electron beam generated by a Varian iX series LINAC.

2.2.1. Two voltage analysis

Theoretical correction factors can be calculated following Boag's work on experimental corrections [22–24]. Most convenient practical procedure for determining the ion recombination correction factor for a given measurement is to use the experimental two-voltage analysis (TVA) technique, which is accurate over: $(4.3{\cdot}10^{-6}$–$1.3{\cdot}10^{-3})C/(m^3{\cdot}pulse)$ range [22]. The TVA method has been used in this study to quantify ion recombination with 20 MeV and 165 MeV electron beams. Three ionization chamber readings were taken under the same irradiation conditions, one at the normal (recommended by the manufacturer of the chamber) collecting voltage (V_1, reading M_1) and two others at a lower voltage (V_2, reading M_2). The voltage potentials have been selected so that the ratio V_1/V_2 had a value of two or three. The recombination correction factor f_{ion} has been calculated from [25], as recommended by TRS 398 [14]:

$$f_{ion} = a_0 + a_1 \frac{M_1}{M_2} + a_2 \left(\frac{M_1}{M_2}\right)^2, \qquad (1)$$

where the coefficients, a_i, (j= 0,1 and 2) are 2.337, −3.636 and 2.299 for voltage ratio of 2 and 1.198, −0.8753 and 0.6773 for voltage ratio of 3, respectively. All of these parameters are given in Table A.1 consistent with the IPEM code of practice for electron dosimetry [15]. Measurements at each polarizing voltage were acquired three times and the mean value was used for further analysis.

2.2.2. Ion recombination measurements with 20 MeV and VHEE beam

For ion recombination measurements in the 20 MeV electron beam, the IBA CC04 chamber was placed in a standard grade solid water phantom (Gammex, Middleton, WI) with 5 cm of build-up and 20 cm thickness of solid water to provide adequate backscattering conditions (Fig. 1(a)). The chamber was irradiated with a 20 MeV electron beam with Varian iX series LINAC at SSD of 100 cm with a $10 \times 10\ cm^2$ field size.

Ion recombination measurements with VHEE beam have been carried out at the SPARC LINAC. A 3 mm thick Perspex window was used to interface the beamline with open air, in which the dosimetric setup was placed. VHEE measurements were carried

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