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Original paper

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

Anna Subiel [a,*], Vadim Moskvin [b], Gregor H. Welsh [c], Silvia Cipiccia [c,e], David Reboredo [c], Colleen DesRosiers [d], Dino A. Jaroszynski [c,*]

[a] National Physical Laboratory, Medical Radiation Science, Teddington TW11 0LW, UK
[b] St. Jude Children's Research Hospital, Memphis, TN 38105, USA
[c] Department of Physics, Scottish Universities Physics Alliance, University of Strathclyde, Glasgow G4 0NG, UK
[d] Department of Radiation Oncology, Indiana University School of Medicine, Indianapolis, IN 46202, USA
[e] Diamond Light Source, Harwell Science and Innovation Campus, Fermi Avenue, Didcot OX11 0DE, UK

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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

* Corresponding authors.
E-mail addresses: anna.subiel@npl.co.uk (A. Subiel), d.a.jaroszynski@strath.ac.uk (D.A. Jaroszynski).

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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·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]:

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

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 10×10 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

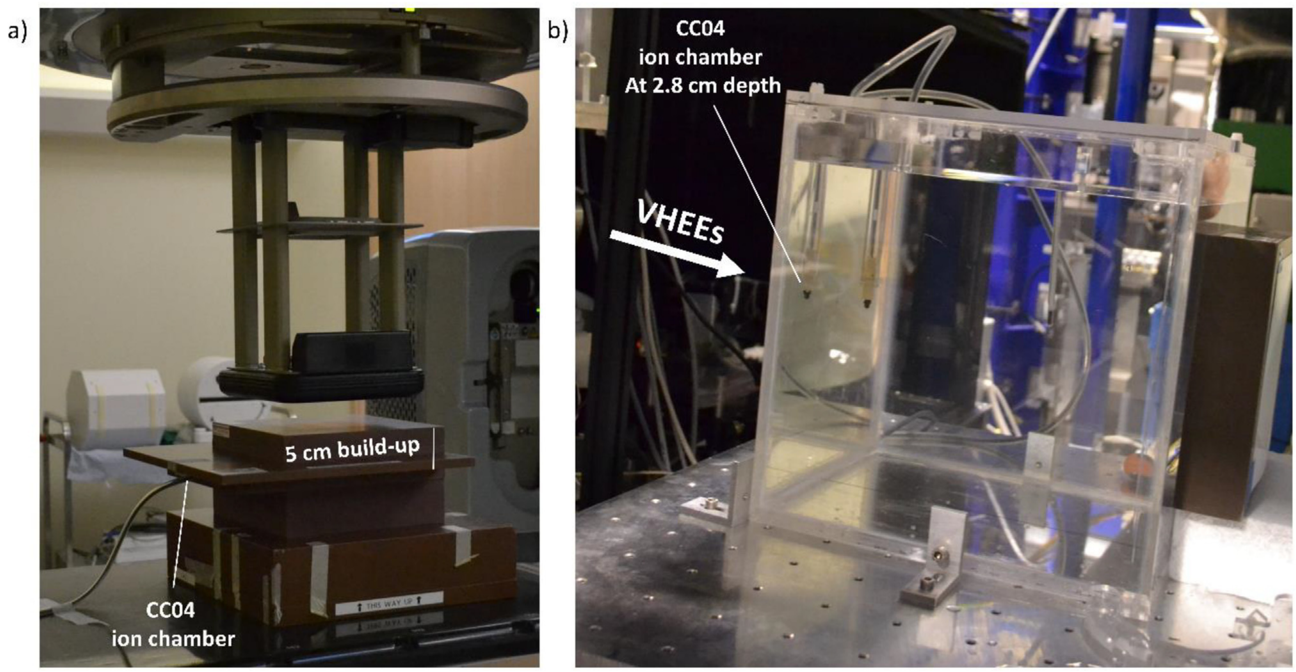

Fig. 1. Setup for ion chamber recombination measurements with (a) 20 MeV electrons and (b) VHEE beam.

out in a 30 × 30 × 30 cm^3 water phantom, placed 41 cm after the exit window. Ion chamber is positioned at a depth of 2.8 cm (Fig. 1(b)). The field size of the beam at the plane of measurement was 0.9 cm FWHM (full width at half maximum). The energy of the electron beam for this irradiation was set to 165 MeV with 0.5% FWHM energy spread. The root mean square (rms) electron bunch length duration was 0.87 ps.

Table 1
The energy downshift of the 150 MeV incident electron beam at various depths in the water tank.

Incident beam energy	Peak of electron spectra in water		
	At 3.5 cm depth	At 9.5 cm depth	At 17.5 cm depth
150 MeV	145 MeV	131 MeV	112 MeV

3. Results

3.1. VHEE pulse duration and energy spectra

Fig. 2 presents Geant4 computed evolution of electron and bremsstrahlung spectra of a 150 MeV electron beam propagating through water. The shift of the maximum energy at depths in water is given in Table 1. Already at 3.5 cm depth the peak energy in water drops to 145 MeV. At 9.5 cm and 17.5 cm the energy downshifts by 20 and 40 MeV, respectively, with respect to the incoming 150 MeV monoenergetic electron beam.

The broadening of the energy spectrum implies a longer bunch length. From the distribution of the time of flight of the electron beam, the bunch length duration has been estimated for various positions along the beam propagation path in air and water phantom. Table 2 shows the temporal lengthening of a 1 fs electron bunch after 100 cm of propagation in air and at 1 cm, 10 cm, 20 cm and 30 cm depth in water.

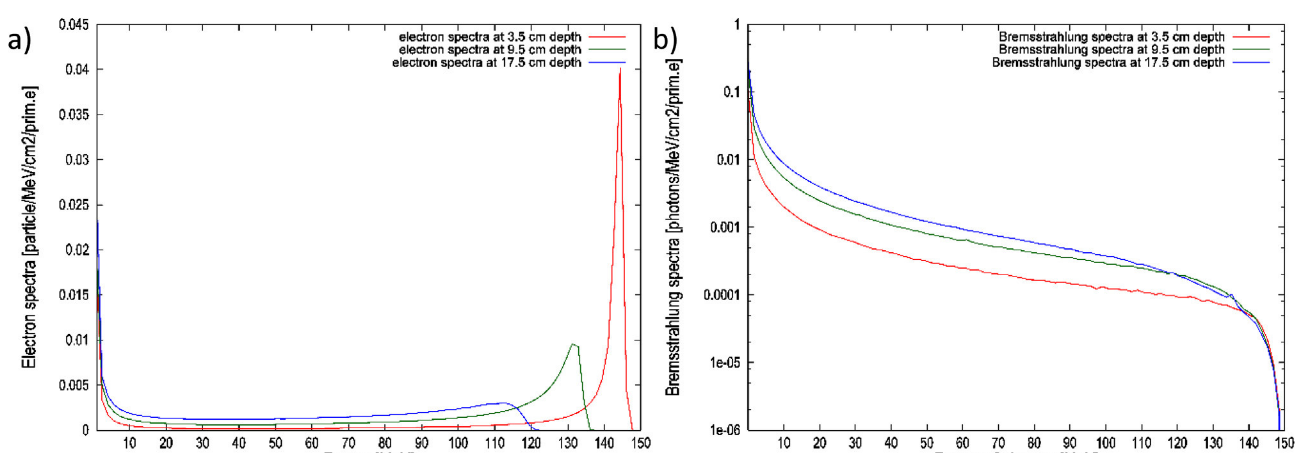

Fig. 2. Evolution of (a) electron and (b) Bremsstrahlung spectra with increasing propagation depth in a water phantom for 150 MeV monoenergetic electron beam.

Table 2
Temporal evolution of 150 MeV electron bunch along propagation path (initial bunch duration is 1 fs).

Propagation distance	Evaluated bunch length
100 cm of air	~1.1 *fs*
100 cm of air and 1 cm of water	~5.0 *fs*
100 cm of air and 10 cm of water	~100 *fs*
100 cm of air and 20 cm of water	~0.25 *ps*
100 cm of air and 30 cm of water	~1.0 *ps*

3.2. Ion chamber measurements

All of the reported dosimetry measurements [6,13,26] with VHEE has been carried out using radiochromic films. However, this detector requires post-irradiation processing and data analysis. We have, therefore, explored the applicability of ion chambers for VHEE dosimetry by measuring ion recombination employing TVA technique.

3.2.1. Ion recombination for a 20 MeV electron beam

Readings with IBA CC04 chamber were taken at 300 V (recommended operational voltage), 150 V and 100 V. The mean values of collected charge and associated standard deviations (SD) for 20 MeV electron beam are given in Table 3.

Ion recombination factor (f_{ion}), calculated from Eq. (1), is 1.0100 and 1.0094 for voltage ratio of 2 and 3, respectively.

3.2.2. Ion recombination for a 165 MeV VHEE beam

The charge density of a VHEE beam has been estimated. 65 pC electron bunch with 1 ps temporal pulse duration and 1 cm FWHM beam size yields approximately 1.3×10^{-3} C/m^3 electron charge density, which is at the upper limit of the charge density range investigated by Boag [22], where the two-voltage technique still applies.

The SPARC accelerator is a research beamline without dose monitors with the accuracy as used for clinical beams. Therefore, controlling accumulated dose at each irradiation was not possible. The number of shots and the electron charge delivered in each irradiation was recorded. To quantify the ion recombination correction factor the electrometer readings for each irradiation were normalized to the electron beam charge accumulated over whole irradiation. This value, reported in Table 4, is defined as Q' (dimensionless unit).

Ion recombination factor (f_{ion}), calculated from Eq. (1), is 1.5953 and 1.5968 for voltage ratio of 2 and 3, respectively.

Table 3
Mean collected charge (Q) measured at 300 V, 150 V and 100 V for a 20 MeV conventional electron beam.

Bias voltage [V]	Mean Q [nC]	SD of mean Q [nC]
300	1.0480	0.0010
150	1.0375	0.0028
100	1.0287	0.0015

Table 4
Mean Q' collected at 300 V, 150 V and 100 V for 165 MeV VHEE beam.

Bias voltage [V]	Mean Q'	SD of mean Q'
300	1.6990	0.0160
150	1.2670	0.0046
100	1.0300	0.0033

4. Discussion

When ultra-short duration VHEEs bunches pass through a water phantom the primary electrons lose energy (Table 1) as a result of multiple scattering, ionization and bremsstrahlung production, which leads to a broadening of the energy spectra with increasing depth in water, and is eventually dominated by bremsstrahlung photons (Fig. 2). After passing through 100 cm of air, the electron bunch is not significantly scattered and the bunch length is still close to 1 fs. Another 1 cm of propagation in water elongates the bunch to approximately 5 femtoseconds (Table 2). By the exit of the water phantom the electron bunch temporal duration has increased to 1 ps. This pulse duration is still several orders of magnitude shorter than that of a clinical linear accelerator. Based on previous work [13], the dose delivered by a VHEE beam pulse with duration 5 fs is of 12 mGy at 1.8 cm depth (see Table 2 for temporal evolution of the pulse). Thus the dose rate of the beam is the order of 10^{11} Gy/s, which leads to the conclusion that VHEEs are high-dose-per-pulse (DPP) beams.

The correction for ion recombination is the sum of two components: initial recombination and general recombination. Both depend on the chamber geometry and the collecting voltage. General recombination relies on the ion density in the cavity. Initial recombination in clinical electron beams is commonly around 0.1% for the usual cylindrical chambers and collecting voltages employed in radiotherapy [15]. General recombination is typically a small effect for continuous radiation, however for pulsed beams, such as those generated by SPRAC LINAC, it can often be significant.

The MC calculations investigating spectral and temporal duration of VHEE beam have been complemented with preliminary ion recombination measurements. The measurements allowed to calculate the CC04 ion chamber recombination factors for 20 MeV and 165 MeV electron beams. The f_{ion} for the conventional 20 MeV radiotherapy electron beam is 1.010, which is within acceptable correction range for clinical beams. The IBA CC04 chamber in the 165 MeV SPARC electron beam exhibits recombination of the order of 60%.

The TVA method, which was employed here to assess recombination in VHEE beam, applies to the SPARC generated beam in terms of beam electron density. However, the applicability of this approach has never been validated for an electron energy range outside that of radiotherapy beams. The performance for ion collection in CC04 chamber could be increased by applying higher than recommended bias voltage. This preliminary study on ion chambers applicability to VHEE dosimetry aims to highlight the effects observed, not to accurately quantify correction factors that need to be applied to detector readings.

5. Conclusions

Properties of VHEEs, such as electron bunch duration and evolution of spectral profile for the beam propagating in water, have been discussed in the context of dosimetry. Preliminary ion chamber measurements were presented. Initial results indicate that ultrashort high-dose-per-pulse VHEE beams produce significant ion recombination in the air-filled chamber cavity. Increasing applied bias voltage could reduce the ion recombination correction factor for these beams. However, this effect is so substantial that redesign of chamber to pinpoint size may be required. In order to meet requirements of contemporary radiotherapy, it is necessary to establish dosimetry with appropriate detectors enabling online dose measurements in absolute terms. However, this is a subject for additional research. Further systematic studies are required to be carried out to investigate if ion chambers can be used reliably for dosimetry of VHEE beams and to extend existing protocols to ultrashort pulsed electron beams.

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Data availability Data associated with research published in this paper is available at http://dx.doi.org/10.15129/6d260b6a-a77e-4e0e-9783-c48eef33bba9.

References

[1] DesRosiers CM. An evaluation of very high energy electron beams (up to 250 MeV) in radiation therapy. Indiana, USA: Prude University; 2004.
[2] Nakajima K. Laser-driven electron beam and radiation sources for basic medical and industrial sciences. Proceedings of the Japan Academy Series B-Physical and Biological Sciences. 2015;91:223–45.
[3] SCAPA. <http://www.scapa.ac.uk/?page_id=70>; 2016 [accessed 08.12.16].
[4] SPARC. <http://www.lnf.infn.it/acceleratori/sparc/>; 2016 [accessed 28.11.16].
[5] NLCTA. <https://www6.slac.stanford.edu/blog-tags/next-linear-collider-test-accelerator-nlcta>; 2016 [accessed 08.12.16].
[6] DesRosiers C, Moskvin V, Bielajew AF, Papiez L. 150–250 MeV electron beams in radiation therapy. Phys Med Biol. 2000;45:1781–805.
[7] Fuchs T, Szymanowski H, Oelfke U, Glinec Y, Rechatin C, Faure J, et al. Treatment planning for laser-accelerated very-high energy electrons. Phys Med Biol 2009;54:3315–28.
[8] Yeboah C, Sandison GA. Optimized treatment planning for prostate cancer comparing IMPT, VHEET and 15 MV IMXT. Phys Med Biol 2002;47:2247–61.
[9] DesRosiers C, Moskvin V, Cao M, Joshi C, Langer M. Lung tumor treatment with very high energy electron beams of 150–250 Mev as compared to conventional megavoltage photon beams. International Journal of Radiation Oncology Biology Physics 2008;72. S612-S.
[10] DesRosiers C, Moskvin V, Cao M, Joshi CJ, Langer M. Laser-plasma generated very high energy electrons in radiation therapy of the prostate. Proceedings of SPIE; 2008. p. 688109.
[11] Yeboah C, Sandison GA, Moskvin V. Optimization of intensity-modulated very high energy (50–250 MeV) electron therapy. Phys Med Biol 2002;47:1285–301.
[12] Bazalova-Carter M, Qu B, Palma B, Hardemark B, Hynning E, Jensen C, et al. Treatment planning for radiotherapy with very high-energy electron beams and comparison of VHEE and VMAT plans. Med Phys 2015;42:2615–25.
[13] Subiel A, Moskvin V, Welsh GH, Cipiccia S, Reboredo D, Evans P, et al. Dosimetry of very high energy electrons (VHEE) for radiotherapy applications: using radiochromic film measurements and Monte Carlo simulations. Phys Med Biol. 2014;59:5811–29.
[14] IAEA. Absorbed dose determination in external beam radiotherapy. Vienna: IAEA; 2000.
[15] Thwaites DI, DuSautoy AR, Jordan T, McEwen MR, Nisbet A, Nahum AE, et al. The IPEM code of practice for electron dosimetry for radiotherapy beams of initial energy from 4 to 25 MeV based on an absorbed dose to water calibration. Phys Med Biol 2003;48:2929–70.
[16] Khan FM. The Physics of radiation therapy. Lippincott Williams & Wilkins; 2003.
[17] Ferrari A, Sala PR, Fasso A, Ranft J. FLUKA: a multi-particle transport code. CERN 2005–10, INFN/TC_05/11, SLAC-R-773; 2005.
[18] Butterworth KT, McMahon SJ, Currell FJ, Prise KM. Physical basis and biological mechanisms of gold nanoparticle radiosensitization. Nanoscale. 2012;4:4830–8.
[19] Lundh O, Rechatin C, Faure J, Ben-Ismail A, Lim J, De Wagter C, et al. Comparison of measured with calculated dose distribution from a 120-MeV electron beam from a laser-plasma accelerator. Med Phys 2012;39:3501–8.
[20] Geant4 User's Guide for Application Developers, Version: Geant4 9.5.5; 2012.
[21] Detectors for Relative and Absolute Dosimetry. IBA Dosimetry; 2016.
[22] Boag JW, Currant J. Current Collection and Ionic Recombination in Small Cylindrical Ionization Chambers Exposed to Pulsed Radiation. Br J Radiol 1980;53:471–8.
[23] Boag JW. The Recombination Correction for an Ionization-Chamber Exposed to Pulsed Radiation in a Swept Beam Technique. 1. Theory. Phys Med Biol 1982;27:201–11.
[24] ICRU Report 34, The dosimetry of pulsed radiation. In: Bethesda MIP, editor. ICRU Report 341982; 1982.
[25] Weinhous MS, Meli JA. Determining Pion, the correction factor for recombination losses in an ionization chamber. Med Phys 1984;11:846–9.
[26] Bazalova-Carter M, Liu M, Palma B, Dunning M, McCormick D, Hemsing E, et al. Comparison of film measurements and Monte Carlo simulations of dose delivered with very high-energy electron beams in a polystyrene phantom. Med Phys 2015;42:1606–13.