Radiation Measurements 86 (2016) 16–23

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Experimental and Monte Carlo absolute characterization of a medical electron beam using a magnetic spectrometer

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HIGHLIGHTS

- We report on the characterization of the electron beam from a Varian 21Ex accelerator.
- The direct electrons' energy distribution at 9 MeV was measured in the isocenter.
- A magnetic spectrometer and image plates were used for absolute measurements.
- Water depth dose curve measurements and Monte Carlo simulations are confronted.
- The dose contribution at z_{max} due to direct electrons is estimated about 55–60%.

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
18 December 2015
Accepted 4 January 2016
Available online 7 January 2016

Keywords:
Electron spectrometer
Position sensitive detectors
Monte Carlo methods
Accelerators
Radiation control

ABSTRACT

The knowledge of the absolute energy distributions of the particles emitted from a clinical accelerator is important for the evaluation of Monte Carlo simulations developed for treatment planning. In this paper, an original approach is presented which allows to measure the absolute energy distribution of the electron beam delivered by a Varian 21Ex medical accelerator. The electron beam was characterized at the isocenter with calibrated image plates covering the exit window of a magnetic spectrometer. The characteristics of the electron beam emitted from an effective source have been inferred from the measurements using the Geant4 Monte Carlo code. The contribution of direct electrons to the absolute depth-dose curve in a water phantom is estimated.

1. Introduction

Electron beams with energies ranging from 4 to 25 MeV are widely used in radiotherapy treatments (Mayles et al., 2007). Their aim is to deposit sufficient amounts of energy inside tumors to induce critical cell damages while sparing as much as possible the surrounding healthy tissues. The stability of clinical beam characteristics is essential for treatment plannings. The control of beam quality is performed via depth-dose measurements in water tanks with calibrated ionisation chambers according to IAEA codes of practice (IAEA, 1987, 1995, 1997, 2000). These very accurate measurements are nevertheless time consuming and are only performed monthly during dedicated irradiation time slots.

In parallel, Monte Carlo simulations have been developed for detailed characterization of the energy and angular distributions of the primary and secondary electrons as well as the contaminant photons emitted from the accelerator head and the applicators (Ding and Rogers, 1995; Ma et al., 1997; Faddegon and Blevis, 2000; Faddegon et al., 2009a; Pimpinella et al., 2007; Shimozato et al., 2013; Faddegon et al., 2009b; O'Shea et al., 2011; Sawkey and Faddegon, 2009; Jiang et al., 2000). With these spectral fluences, the relative dose distributions in water phantoms can be accurately calculated. These Monte Carlo simulations are generally validated

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http://dx.doi.org/10.1016/j.radmeas.2016.01.003
1350-4487/

by comparison with measured total absorbed dose profiles. The knowledge of the electron energy distribution and their contribution to the depth-dose curves is of great importance for beam monitoring and for further constraining such simulations.

However, direct measurements of the energies and angular distributions or the absolute fluences emitted of electrons coming from medical accelerators are very difficult tasks. Few measurements have been performed in the past and only relative spectra are published (Deasy et al., 1996; Kok and Welleweerd, 1999; Chvetsov and Sandison, 2002; Zaini et al., 1997; Fuochi et al., 2010). Monte Carlo simulations show that the particle fluences in the isocenter of the machine contain two main components (Ding and Rogers, 1995; Ma et al., 1997). The first one corresponds to electrons exiting the accelerator head and directly impinging on the isocenter plane without having hit any collimator or applicator (called here direct electron component). The second part of the spectra is due to scattered electrons and photons. The simulations show that more than 95% of electrons at the most probable energy in the isocenter are direct electrons. We have therefore focused our attention on these electrons.

In this paper, we propose an original approach in which the contribution of direct electrons to the depth-dose curve can be obtained in Monte Carlo simulations constrained by experimental data. The energy distribution of the direct electrons impinging on the isocenter plane was measured using a spectrometer associated to a position sensitive detector. The electron source absolute spectral fluence was inferred from the spectrometer data using the Monte Carlo code Geant4 and was used to estimate the contribution of the direct electrons to the depth-dose curve in a water phantom.

2. Material and methods

2.1. Accelerator characteristics

Measurements were carried out at the Institut Bergonié of Bordeaux with a Varian 21Ex electron accelerator. This irradiator offers a choice of five electron energies (6, 9, 12, 16 and 20 MeV) and five applicators (6 x 6, 10 x 10, 15 x 15, 20 x 20 and 25 $\times$ 25 cm^2). The absolute delivered dose is related to the number of accelerator Monitor Units (MU) in a calibration procedure performed differently by each clinic. In the case of the electron beams used at the Institut Bergonié, the Monitor Unit is defined with a 15 $\times$ 15 cm^2 electron beam field size and a water phantom the surface of which is located in the isocenter plane at a surface-to-source distance of 1 m. The accelerator intensity is adjusted so that an irradiation of 1 MU leads to a deposited dose of 1 cGy at the depth of the maximum absorbed dose in the phantom. Such a calibration procedure was performed before our experiment.

In this study, the accelerator parameters were set to a mean energy of 9 MeV at the isocenter of the machine. For practical reasons a 6 $\times$ 6 cm^2 applicator was used to spatially limit the electron beam. The downstream side of the 1.5 cm thick cerrobend applicator was placed at a distance of 5 cm above the isocenter.

2.2. Spectrometer measurements

The measurements of the direct electron beam were performed in ambient air with a magnetic spectrometer coupled with a position sensitive particle detector (image plate). The setup is illustrated in Fig. 1. The electron spectrometer manufactured by TE2M, France, is schematically drawn in Fig. 2. It is composed of two permanent NdFeB magnets (130 $\times$ 90 $\times$ 25 mm^3) separated by a 10 mm gap and supported by a yoke of magnetizable steel. A nearly homogeneous field of about 1.08 T is created between the two

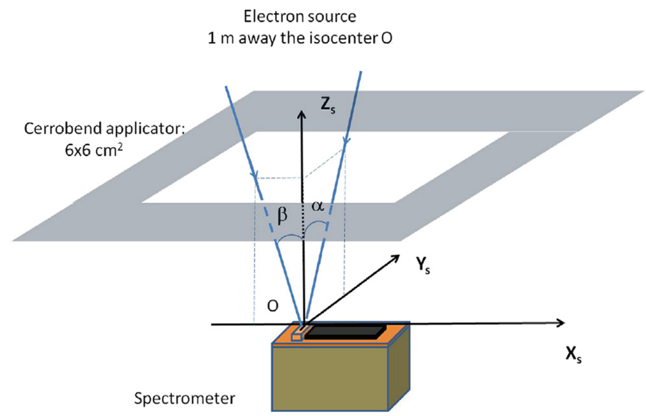

Fig. 1. Schematic view of the applicator and electron spectrometer. The O point is the accelerator isocenter. Two examples of accelerator head direction are given with blue lines. The direction between the source and the isocenter is characterized by the α angle in the y_sOz_s plane and the β angle in the x_sOz_s plane with respect to the vertical z_s axis. The two directions of the accelerator head arbitrarily define the negative values of these oriented angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

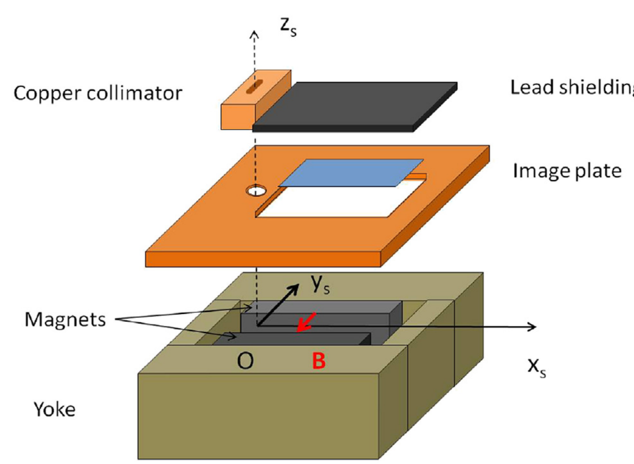

Fig. 2. Expanded drawing of the spectrometer. The electrons enter into the magnet gap by the O point placed at the accelerator isocenter. An image plate shielded by lead is used to detect the electrons deflected between the two magnets.

magnets. The entrance window of the spectrometer is defined by a 1 $\times$ 5 mm^2 aperture in a 1 cm thick copper collimator. In the Fig. 2, the electrons come from the top, then go through the copper collimator, through the spectrometer magnet and then hit the detector (image plate).

In the following we consider the reference frame (O, x_s, y_s, z_s) linked to the spectrometer. Its origin O is associated with the entry point of the electrons in the spectrometer gap and corresponds to the isocenter of the machine (Fig. 1). The x_s axis is parallel to the magnet length while the y_s axis and the magnetic field $\vec{B}$ are collinear. In this field, the electron trajectories are circular, their radius of curvature R depending on their momentum P as R (cm) = 0.309 P (MeV c^{-1}). With this setup, electrons with energies between 2 and 16 MeV can be resolved by using a position sensitive particle detector.

The magnetic field cartography was measured inside and outside the spectrometer with a Hall probe (Model PT002 from HIRST Magnetic Instruments Ltd) to ensure a realistic tracking of the electrons with Monte Carlo codes. A magnetic field leakage up to 20 cm above the origin O was measured. This leakage field is in