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Dosimetric and bremsstrahlung performance of a single convergent beam for teletherapy device

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ABSTRACT

The present work investigates preliminary feasibility and characteristics of a new type of radiation therapy modality based on a single convergent beam of photons. The proposal consists of the design of a device capable of generating convergent X-ray beams useful for radiotherapy. The main goal is to achieve high concentrated dose delivery. The first step is an analytical approach in order to characterize the dosimetric performance of the hypothetical convergent photon beam. Then, the validated FLUKA Monte Carlo main code is used to perform complete radiation transport to account also for scattering effects. The proposed method for producing convergent X-rays is mainly based on the bremsstrahlung effect. Hence the operating principle of the proposed device is described in terms of bremsstrahlung production. The work is mainly devoted characterizing the effect on the bremsstrahlung yield due to accessories present in the device, like anode material and geometry, filtration and collimation systems among others.

The results obtained for in-depth dose distributions, by means of analytical and stochastic approaches, confirm the presence of a high dose concentration around the irradiated target, as expected. Moreover, it is shown how this spot of high dose concentration depends upon the relevant physical properties of the produced convergent photon beam.

In summary, the proposed design for producing single convergent X-rays attained satisfactory performance for achieving high dose concentration around small targets depending on beam spot size that may be used for some applications in radiotherapy, like radiosurgery.

1. Introduction

Teletherapy modalities have been typically implemented in clinics by linear accelerators or cobalt units for some time. Both these techniques use photon beams, which are produced with an inherent divergent nature. Then, high dose concentrations are usually achieved by superposition of several incident fields in order to minimize radiation to healthy tissues and organs. Modern methodologies like intensity modulated radiotherapy (IMRT) [1,2] attempt to deliver higher radiation dose levels with improved capability for tumor targeting while doses delivered to surrounding critical structures are kept as low as possible [2,3].

Recent technological developments like Cyber-knife [4], True-Beam [5] or tomotherapy [6] are capable of attaining high-dose gradients to achieve dose escalation within the irradiation volume. The complexity of these kinds of technologies and specially their cost might constitute a drawback for large-scale worldwide implementation. Hence, it appears suitable to consider a photon beam of inherent convergent characteristics that could attain similar or even better dosimetric performance for treatment requiring high dose concentration [7,8]. The main characteristics of such a technology have been already well described and specific details are available in literature [9]. The present work is focused on the most relevant features of the bremsstrahlung yield corresponding to the specific setup of this new strategy for radiation delivery by means of convergent X-ray beams. The main characteristics of the proposed device, some of the accessories and a preliminary prototype for the device are described in detail in the corresponding patent and previous works [9,10]. In this context, the present work refers to the characteristics of the bremsstrahlung yield that constitutes the convergent beam.

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2. Materials and methods

The proposal for generating convergent X-ray beams is mainly based on a suitable manipulation of the electron beam produced by clinical linear accelerators that typically operate with energies larger than 6 MeV. The starting point consists of achieving perpendicular incidence of the electron beam in a relatively thin ($\leqslant$3 mm) spherical tungsten shell (20 cm in diameter, approximately) that constitutes the target. As a consequence of the impact of electrons, bremsstrahlung radiation is generated and is directed mainly forward. Then, the desired convergent effect should be observed [9,10]. This effect is produced, because of the properties of bremsstrahlung angular distribution causing the majority of radiation emissions to travel directly to the focal spot located at the centre of the spherical shell. This issue must be checked for different energies of the electron beam, and, naturally, for different prototype designs. However, it might be expected that the effect is less likely for the lowest energies, due to inherent properties of bremsstrahlung production.

Once bremsstrahlung is generated, the convergence of the photon beam must still be improved. Some accessories, like collimation and filter systems, are included in the prototype for this purpose.

The whole procedure can be summarized as follows: the electron beam is produced by the standard linear accelerator, thus making it possible to achieve energies in the megavoltage range. The electron beam interacts with a bending/splitting system consisting of an electron-dispersive sheet and/or electromagnetic deflector that guides the electron beam with the aim of attaining a normal impact on the target (shell anode) by means of electrostatic and/or magnetic devices. Photons emerge from the anode shell pointing in the same direction of incident electrons. They then pass through a filter and, finally, a curved multiple-collimation system acts as an ulterior accessory for improving beam convergence.

Moreover, it is clear that such a device has the capability of generating single convergent beams using the entire target for electron impact or limiting the process to a specific region. The effect of limiting the region of impact may affect mainly the dosimetric performance outputs, like entrance-to-peak dose ratio.

The emerging photon beam is emitted mainly convergently, despite the location where electrons reach the shell anode. Finally, the focus of the emerging convergent photon beam is geometrically determined by shell pieces, namely the anode, collimation grid and filtration accessories. Further details are available in previous works [9,10].

Of course, it is not possible to ensure that all photon fluence will arrive at the phantom, because of the losses in filtration and collimation systems. Therefore, it becomes crucial to characterize the bremsstrahlung yield according to the actual design of the proposed prototype. As is well-known, the angular distribution and kinetic energy of bremsstrahlung production are intrinsically coupled so that it is necessary to investigate both of these parameters simultaneously affecting bremsstrahlung yield. The key is that angular distribution probabilities become more and more closely concentrated around forward direction for higher electron kinetic energies in the megavoltage range.

Bremsstrahlung yield produced by high energy electrons striking high atomic number (Z) targets has been thoroughly investigated and is explained in detail in the basic literature [11,12] and the formulation describing the process for this convergent photon beam prototype was already presented showing that the bremsstrahlung yield, described in terms of the double differential cross section $\left(\frac{d^2\sigma_{Br}}{dEd(\cos\theta)}\right)$ is determined by [9,13]:

$$\frac{d^2\sigma_{Br}}{dEd(\cos\theta)} = \frac{Z^2}{\beta^2} \times \frac{1}{E} A(Z, T, E/T) \left[\frac{\sigma_I(1-(\cos\theta)^2) + \sigma_{II}(1+(\cos\theta)^2)}{\sigma_I(1-\beta(\cos\theta)^2)}\right] \quad (1)$$

In the above equation E is the kinetic energy of the emitted photon produced by electrons with kinetic energy T and velocity v, $A(Z, T, \kappa)$ is a parameter dependent on the target material, $\beta = v/c$ and the coefficients σ_I and σ_{II} (independent of polar angle θ) are obtained from Sommerfeld's model [13,14].

Knowing the characteristics of photon beams generated by bremsstrahlung for both divergent (standard) and convergent arrangements, it remains necessary to investigate the corresponding dosimetric outputs according to the possible options for the prototype. Thus, analytical and Monte Carlo (MC) simulations methods can be adapted for in-phantom dose distribution calculations. As a first approach, isotropic homogeneous water-equivalent medium was selected for the irradiated phantom. If required, dedicated techniques can be developed to calculate dose distribution in anthropomorphic heterogeneous phantoms.

The basic idea for the analytical approach is relatively intuitive and considers that dose concentration can be achieved by combining multiple radiation fields or using beam modulation mechanisms [9,10]. Due to continuity requirements, the absorbed dose due to primary particles calculated at depth ($D(h)$) can be approximated by [9]:

$$D(h) \approx D_0 \frac{L_0^2}{(L_0 - h)^2} e^{-\sum_{ip_i} \mu_i(E_i)\rho h} \quad (2)$$

where L_0 is the focus-surface distance, D_0 is the entrance dose, μ_i is the attenuation coefficient evaluated for the i spectral channel (E_i) of the incident beam (which probability is $p(E_i)$) and ρ is the mass density of the medium. Although expression (2) means that absorbed dose tends to infinity when the depth $h \to L_0$ this hypothetical case does not represent drawbacks or limitation in practice for typical clinical depths.

On the other hand, full radiation transport is performed by means of built-in MC subroutines developed to compute 3D absorbed dose distributions. Hence, mean absorbed dose $\langle D\rangle$ and corresponding uncertainty, typically characterized by standard deviation σ_D are calculated for each voxel according to:

$$\langle D\rangle = \frac{1}{m(i,j,k)}\left[\sum_{prim} E^{(in)}(i,j,k) - \sum_{seco} E^{(out)}(i,j,k)\right] \quad (3)$$

In the above expression (i, j, k) indicated spatial coordinates of the considered voxel of mass $m(i, j, k)$. The quantities $E^{(in)}$ (i, j, k) and $E^{(out)}$ (i, j, k) are the energy deposited in the (i, j, k) voxel due to incoming primary (*prim*) particles and the energy that leaves the voxel due to secondary radiation (*seco*), respectively.

The MC subroutines are based on the FLUKA main code [15,16], which accounts for atomic and also nuclear type interactions. The setups for simulation exactly reproduce geometrical and physical properties of the proposed prototype.

Different kinetic energy values for the electron beam were carefully investigated, paying specific attention to the range of 0.4–10 MeV (0.4, 0.6, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0 and 10.0 MeV), as might be the interest for the convergent device. MC simulations are divided into two different groups: studies for the effect of accessories on bremsstrahlung yield and those dedicated to dosimetry calculation. After preliminary tests, it was observed that 5×10^8 and 2×10^9 primary showers ensure in all investigated