Iterative Reconstruction of Whole Accelerator Phase Spaces for Intraoperative Radiation Therapy (IORT) from Measured Dose Data

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Abstract–**Monte Carlo (MC) methods are a very powerful tool to compute dose in radiotherapy, as all effects that need to be considered, such as material inhomogeneities, back-scatter from large bones, and beam hardening can be properly modeled. Their most important caveat, however, besides computation time, is that they need a realistic and reliable description of the electron and/or photon beam that delivers the dose, and this is not usually available. In this respect, Monte Carlo (MC) methods have been an invaluable tool for realistic modeling of medical therapy accelerators, including electron linear accelerators (LINAC) used in Intra-operative Radiation Therapy (IORT). The purpose of this work is to obtain the radiation beam properties (or phase-space fro the beam or PHSP) at phantom surface based on a set of dose measurements, without the need for a detailed simulation of the accelerator head and/or applicator.**

An iterative reconstruction algorithm (EM-ML), commonly used in tomographic image reconstruction, has been employed to optimize iteratively all aspects of the PHSP, such as energy spectra, particle type and fluency, and angle of particle emission, required by the MC dose calculation code Dose Planning Method (DPM). Phase space files for IORT have been derived for different energies and applicator diameters, which yield dose in good agreement with the measurements.

I. Introduction

Intraoperative Radiation Therapy (IORT) refers to the radiation treatment that delivers a high dose of radiation directly to the tumor bed or residual tumor during the surgical procedure, immediately after the resection, with minimal exposure of surrounding tissues which are displaced or shielded with attenuation plates to protect organs at risk. These plates can be made of different materials, and the correct material (or combination of materials) has to be chosen in order to achieve the desired attenuation, while avoiding excessive backscattered radiation. However, hitherto, treatment planning in IORT is limited to the consultation of graphs and charts containing isodose curves measured under standard conditions with no patient specific dose calculation.

The entry into the field of IORT of mobile electron accelerators that can be used in existing operating rooms (OR) with reduced shielding requirements makes the cost and logistics of setting up an IORT program much easier [1] and therefore provides a stimulus to the field, as the patient is spared the patient the additional complications of being transferred from the operating theatre to the radiotherapy. Examples of mobile linacs are Mobetron (Intraop Medical Incorporated, Santa Clara, CA, USA) and Novac7 (Hitesys, Aprilia, Italy).

The Monte Carlo (MC) methods represent the most powerful tools to compute the dose, as all effects that need to be considered, such as material inhomogeneities, back-scatter and beam hardening effects can be properly modeled into the Monte Carlo. Indeed, with the development of computer technology, the MC method is becoming an accurate and practical approach in the clinic for electron and photon dose calculations. However, the most important caveat of MC dose computation codes, besides computation time, is that they need a realistic and reliable description of the electron and/or photon beam that delivers the dose and this requires complex simulations of the whole system [2], including a detailed description of the accelerator head and other elements (applicators, collimators, etc), which is in many situations not available.

Existing codes have been shown suitable for modeling realistic electron beams from medical linear accelerators, including those used in IORT [3], provided a detailed description of the LINAC head is available. The detailed information of the energy, angular and spatial distribution of the particles in the electron (or photon) beam is encoded in a phase-space (PHSP) file that will be fed to the MC code used to evaluate the dose deposited in a patient or phantom. Further adjustment of the PHSP so generated is done to reproduce some experimental dose measurements in reference media (water, air).

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The purpose of this work is to derive a complete measurement-driven phase space generation model [4,5,6] without the need of a detailed description of the accelerator head or applicator. This model extracts beam characteristics, i.e. energy spectrum, angular and radial distribution and particle type, in an iterative optimization process, to obtain the set of distributions that best explains the experimental measurements in water and air. Previous works [8] have only considered a small subset of parameters, such as the energy spectrum, for data fitting,

II. Material and Methods

We have developed a robust procedure to derive a PHSP generation model from a set of dose measurements in water, that is applied to different LINAC systems [4, 5, 6]. To this end, an iterative image reconstruction algorithm (EM-ML) [7], commonly used for tomographic image reconstruction, has been employed

A. *Algorithm Description*

In order to compute a full phase-space associated to each set of data we proceed as follows:

- Particles are represented in n-tuple that includes particle type, energy, radial position of emission and angle with respect to the applicator axis.
- Particle variables are histogrammed, so that the actual set of histories in the PHSP form a finite set.
- Each element of this set may be considered as a micro source, which fixed energy, fluency, and emission direction.
- A dose matrix is precomputed, which stores the dose in water or air from each micro source of the set.
- By the principle of linear superposition of doses, we assume that a given experimental dose in water or air $\mathbf{D_w}$ can be obtained as a linear combination of the individual dose foot prints $\mathbf{D_i}$ deposited by each of these elemental micro sources $i, i \in I$.

$$D_w = \sum_I w_i D_i$$

- By means of an iterative procedure, we fit the relative weigths w_i of each microsource, i.e. the number of particles that must populate each bin of the PHSP, so that the experimental dose is successfully reproduced by the PHSP so defined.

In this work we plan to fit PHSP to depth-dose and isodose surfaces from different LINAC systems and configurations [2, 5, 6] for which published data are available.

The final size of the dose matrix, after removing elements with vanisingly small values, is around 1 Gb. The total amount of time required for obtaining this matrix was 6 days using 32 cores of modern CPUs (Xeon, 3 GHz).

Data fit is achieved by means of a maximum likelihood expectation maximization algorithm (EM-ML), very similar to that used in tomographic image reconstruction [7]. Convergence is usually reached after 150 iterations, which takes less than two hours in 1 core of a 3 GHz CPU.

B. *Experimental data*

Experimental measured dose corresponds to the Novac7, device which has also been successfully modeled [10] with BEAMnrc [11]. This device is a mobile electron linac for IORT that produces pulsed electron beams with nominal energies from 4 to 10 MeVs, range that ensures no neutrons are produced [12], and it has been specifically designed for being employed in a conventional operating room. It is mounted in a motorized structure that can be easily displaced thanks to a caster installed in the base, and pushed very slowly towards the operating table, so as to be easily positioned with great accuracy in the treatment position. The basic system includes four types of PMMA cylindrical applicators with inner diameters 4, 6, 8 and 10 cm, wall thickness 0.5 cm and lengths 69, 67, 67 and, respectively, 87 cm. These applicators are available in two different forms: right (0°) and beveled (15°, 22.5° and 45°). The source-to-surface distance is SSD = 80 cm, except for the 10 cm diameter case in which SSD=100 cm.

C. *Materials*

The dose matrix is build using the MC code Dose Planning Method (DPM) code [9]. The following variable binning size (BS) is considered for the definition of the micro sources:

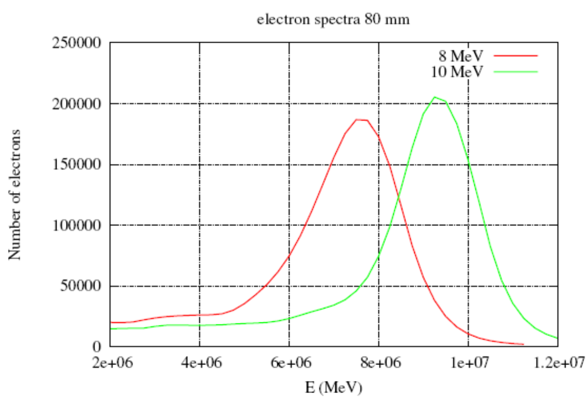
- Type of particle (e-, photon)
- Energy: ranging from 0 to 12 MeV (BS = 0.25 MeV).
- Axial Angle: ranging from 0 to 29º (BS = 1º).
- Radial position: ranging from 0 to 25 cm (BS=0.2 cm).

The applicator is right angled, i.e. bevel angle is 0º.

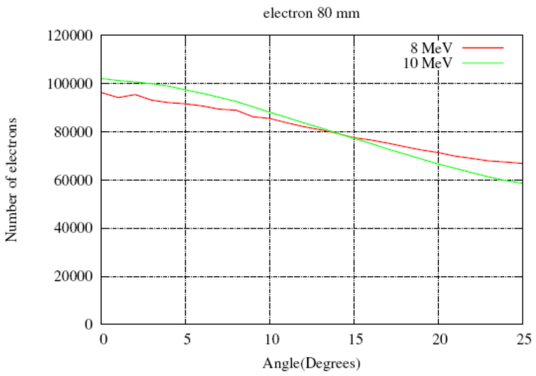
III. Results

The phase space files have been analyzed in terms of energy spectra, angular distribution, and fluency to visually asses the reasonability of the results obtained after minimization. Fig. 1 shows the energy spectra (A) and the angular (B) and radial (C) PHSP distributions obtained with 8 and 10 MeV electron beams when an applicator of 80 mm-diameter has been employed.

A)



B)



C)

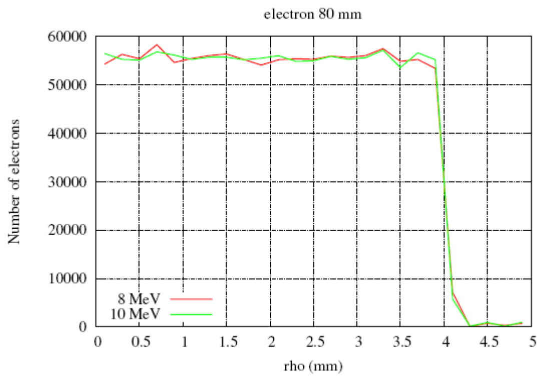


Fig.1. Energy spectra (A), angular (B) and radial (C) PHSP distributions obtained with, 8 and 10 MeV electron beams when an applicator of 80 mm of diameter has been employed.

The dose from the obtained PHSP has been compared to the experimental data. In Fig. 2, we show depth dose profiles and cross beam profiles of experimental and fitted data for 80 mm–diameter applicator and an energy electron beam of 5 MeV. We have found good agreement between experimental and fitted data.

IV. Conclusions

Calculated absorbed dose distributions which are in good agreement with measurements can be obtained from reconstructed, reasonable PHSP, and in a very short computing time. The proposed method is a new and powerful technique that can be employed to obtain PHSP files for any accelerator for radiotherapy system.

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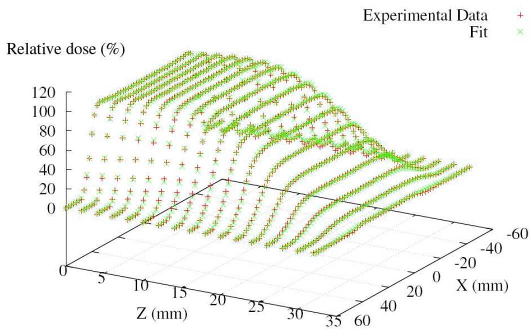

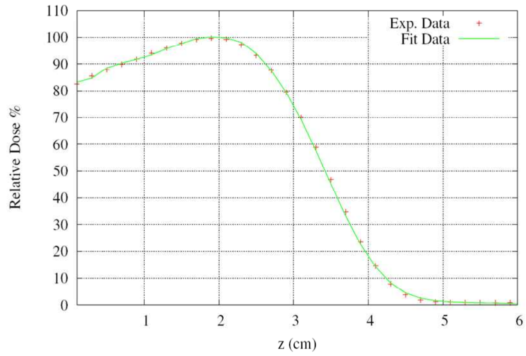

Fig.2. (Top) Comparison between dose depth profiles and cross beam profiles of experimental and fitted data for 80 cm –diameter applicator and an energy beam of 5 MeV. (Bottom) Corresponding percent depth profile (PDD).

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