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Original research article

Monte Carlo commissioning of radiotherapy LINAC—Introducing an improved methodology

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ABSTRACT

Purpose: Monte Carlo (MC) commissioning of medical linear accelerator (LINAC) is a time-consuming process involving a comparison between measured and simulated cross beam/lateral profiles and percentage depth doses (PDDs) for various field sizes. An agreement between these two data sets is sought by trial and error method while varying the incident electron beam parameters, such as electron beam energy or width, etc. This study aims to improve the efficiency of MC commissioning of a LINAC by assessing the feasibility of using a limited number of simulated PDDs.
Materials and methods: Using EGSnrc codes, a Varian Clinac 2100 unit has been commissioned for 6 MV photon beam, and a methodology has been proposed to identify the incident electron beam parameters in a speedier fashion. Impact of voxel size in 3-dimensions and cost functions used for comparison of the measured and simulated data have been investigated along with the role of interpolation.
Results: A voxel size of $1 \times 1 \times 0.5\ cm^3$ has been identified as suitable for accurate and fast commissioning of the LIANC. The optimum number of simulated PDDs (required for further interpolation) has been found to be five.
Conclusion: The present study suggests that PDDs alone at times can be insufficient for an unambiguous commissioning process and should be supported by including the lateral beam profiles in the process.

1. Introduction

Radiotherapy is among the preferred therapeutic modalities for cure as well as palliation of cancer patients. Technological advancements along with a rising global cancer burden have necessitated the need for further refinements in radiotherapy.[1,2] The success of any radiotherapy technique depends on several factors including the dose computation accuracy. Radiotherapy treatment planning systems (TPS) commonly employ analytical algorithms for dose calculation purposes.[3] However, Monte Carlo (MC) methods are being increasingly used for this purpose now. These methods are more accurate in modelling scatter and tissue heterogeneity[4,5] and are independent of electronic equilibrium assumption.[6] For MC based dose estimation, commissioning of a radiotherapy linear accelerator (LINAC) model is a prerequisite, where optimal incident electron beam parameters are identified, such as incident electron beam energy. This involves finding a close match between measured and simulated data i.e. percentage depth doses (PDDs) and cross beam profiles. It is a recursive trial and error approach with substantial computational time/effort involved. A number of studies have been reported on validation of MC models for radiotherapy LINACs and evaluation of different techniques to improve simulation efficiency.[7–11] Several authors have reported incident electron beam energy to be one of the important commissioning parameters.[12–17] Recently, Chang et al. presented a technique solely based on scoring PDD curves for commissioning of a LINAC.[18] Their study, though introducing the idea of interpolation of PDDs, does not include the effect of voxel size and its impact on the cost function (used for comparing the measured and simulated results).[18] This is an important parameter and if not taken into consideration, can give erroneous results as well as prolong the computational time for commissioning. We present this study to further improve the reported methodology by assessing (a) feasibility of reduced number of initial PDD simulations, (b) impact of cost function on PDD comparison, (c) effect of voxel size on cost function behaviour and, (d) whether just simulating PDDs is enough to isolate commissioning parameters.

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2. Materials and methods

2.1. Experimental measurements

Data from a Varian Clinic 2100 unit for 6 MV photons was acquired at the Institute of Nuclear Oncology and Radiotherapy (INOR) Abbottabad, Pakistan. Cross beam profiles (at d_{max}, 5, 10, 15, 20 and 25 cm depths), and PDDs were measured (at 5×5, 10×10, 20×20, 30×30 and $40 \times 40\,cm^2$ field sizes) using Compact ionization chamber (CC13^{TM}, IBA, Schwarzenbruck, DE) in a water phantom (3D Blue Phantom^{TM} of IBA with the scanning volume of 48 cm × 48 cm × 41 cm). A source to surface distance (SSD) of 100 cm was set up with normalization carried out at d_{max} at the central axis (according to the local clinical protocol).

2.2. MC simulations

MC simulations were carried out in two phases; (a) modelling the LINAC head with BEAMnrc[19] and (b) scoring the PDDs and lateral beam profiles in a 3D phantom using DOSXYZnrc.[20] LINAC head was modelled according to the vendor's specifications and the incident electron beam was modelled using source 19 in BEAMnrc which is an elliptical beam source having a Gaussian radial intensity distribution and FWHM of 0.1 cm (for further details of source 19, please refer to section 4.12, in the BEAMnrc manual).[21] In BEAMnrc 1 million initial histories were simulated and a phase space file was scored at 55 cm from the target for electron beam energies of 5.5, 5.7, 5.9, 6.1, 6.3, 6.5 and 6.7 MeV using a field size of $20 \times 20\,cm^2$. This field size is neither too large (excessive computational time) nor too small. Directional Bremsstrahlung Splitting (DBS) was used for improving simulation efficiency with splitting radius of 15 cm and splitting number 1000. The global values of Electron cut off (ECUT) and Photon cut off (PCUT) were set to 0.7 and 0.01 MeV with default EGSnrc settings.

Using DOSXYZnrc, PDDs were scored in a 3D water phantom for four different voxel sizes ($1 \times 1 \times 1\,cm^3$, $2 \times 2 \times 0.5\,cm^3$, $2 \times 2 \times 1\,cm^3$ and $3 \times 3 \times 0.5\,cm^3$). In each case, 2 billion histories were simulated such that resultant statistical uncertainty in the MC results was within 1%. Range rejection was used with a limiting value of 0.511 MeV. DBS values were identical to those set in BEAMnrc simulations with the medium outside the phantom taken as uniform air. All MC simulations were carried out on an Intel Core i3 desktop system (with 4 GB RAM).

2.3. Data processing and analysis

For each voxel size, the set of seven PDDs was processed in MATLAB (version 7.10.0, The MathWorks, Natick, MA) as follows:

1 A total of 240 PDDs were generated from 7 simulated PDDs (simulated for electron beam energies of 5.5, 5.7, 5.9, 6.1, 6.3, 6.5 and 6.7 MeV) using cubic spline interpolation with an interpolation interval of 0.005 MeV.
2 For further speeding up the commissioning process, interpolated PDDs were also generated by using only 6, 5 and 4 originally simulated PDDs.
3 These interpolated PDDs were compared with the measured data using two different cost functions i.e. Chi square (χ^2) method and Mean Absolute Error (MAE) as given by the following Eqs. (1) and (2), respectively. Both of these cost functions are used to find the best fit between simulated and measured (true) value.[15]

$$\chi 2 = \sum_{i=1}^{n} \frac{(D_{calc} - D_{meas})_i^2}{n} \quad (1)$$

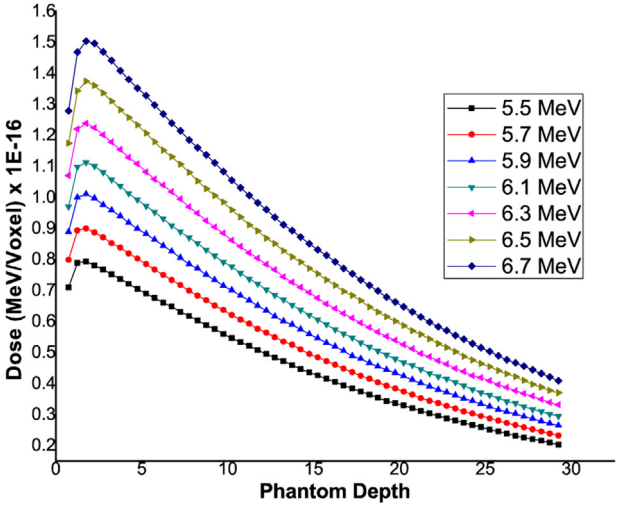

Fig. 1. The 7 original PDDs (5.5, 5.7, 5.9, 6.1, 6.3, 6.5 and 6.7 MeV) simulated for $2 \times 2 \times 0.5\,cm^3$ voxel size. The statistical uncertainty in Monte Carlo simulations was within 1%.

$$MAE = \frac{\sum_{i=1}^{n} | (D_{calc} - D_{meas}) |}{n} \quad (2)$$

Where D_{calc} and D_{meas} are the calculated (simulated or interpolated) and measured dose values at total number of n points.

4 The minima of the above described cost functions give the best fit of simulated and measured dose and helps to extract the optimum incident electron beam energy.
5 As a final validation, lateral dose profiles were scored at the optimal incident beam energy and compared with the measured data.

3. Results and discussion

Fig. 1 shows the 7 original PDDs (5.5, 5.7, 5.9, 6.1, 6.3, 6.5 and 6.7 MeV) simulated for $2 \times 2 \times 0.5\,cm^3$ voxel size. Similar PDDs have been obtained for the other three voxel sizes but not shown here. These PDDs constitute the original simulated data that was further used in interpolation as described in the materials and method section. It is evident from Fig. 1 that the absorbed dose per voxel increases as the incident electron beam energy increases due to improved bremsstrahlung production efficiency in the target of LINAC head. Thus, increased flux of these photons would cause higher dose in a water phantom. This difference in dose increases with the incident electron energy in the build-up region up to d_{max} (almost doubles for 6.7 MeV compared to 5.5 MeV) and then decreases with depth. These results are in accordance with the study of Mohammed et al.[7]

Figs. 2 and 3 present the results of χ^2 and MAE cost functions vs. incident electron beam energy for PDD data acquired in different voxel sizes of (a) $1 \times 1 \times 1\,cm^3$ (b) $2 \times 2 \times 0.5\,cm^3$ (c) $2 \times 2 \times 1\,cm^3$ (d) $3 \times 3 \times 0.5\,cm^3$. Build-up region has not been included in the analysis due to large deviations. These large deviations are because of a higher depth-dose gradient near the surface, as explained by Konefał et al.[22] For each voxel size the measured data was compared with the interpolated PDDs and cost functions were calculated employing Eqs. (1) and (2). For each set of measurements, 4 curves have been plotted indicating the number of simulated PDDs that have been used to generate the interpolated PDDs.

It is evident from Figs. 2 and 3 that most of the minima are falling between 5.7 and 6.2 MeV for both cost functions. Furthermore, these results show that a cost function does influence the value of minima. Therefore, it is important to select a cost func-

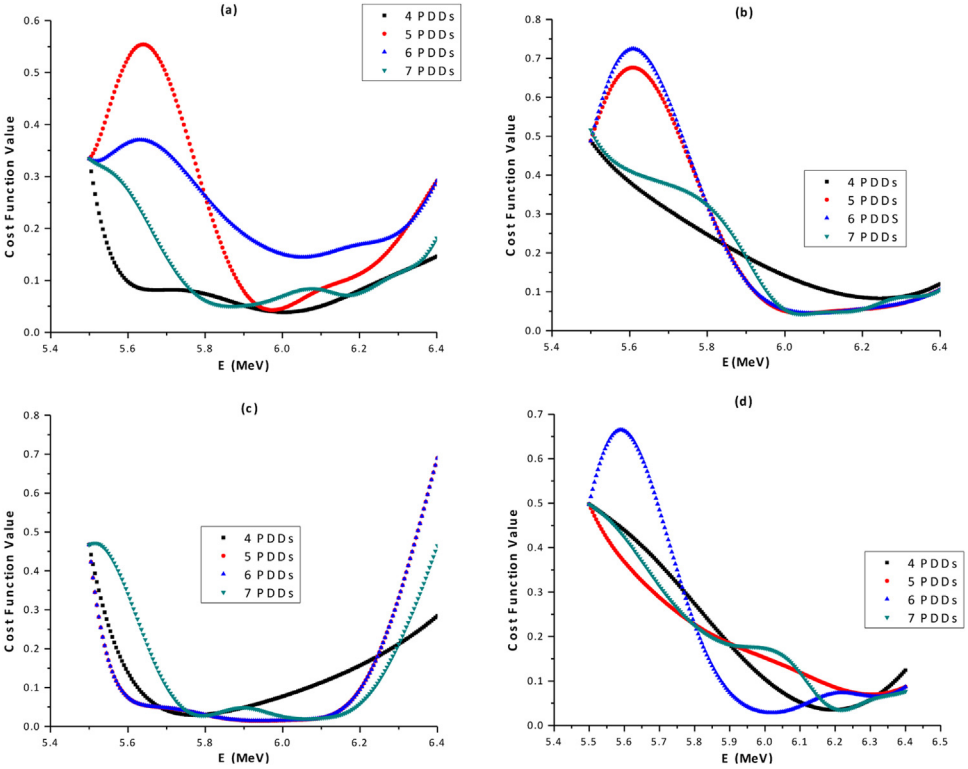

Fig. 2. Comparison of measured and simulated data using chi square method while excluding the build-up region. The measured data has been compared with simulated data generated by interpolating 7, 6, 5 and 4 originally simulated PDDs (a) $1 \times 1 \times 1\,cm^3$ (b) $2 \times 2 \times 0.5\,cm^3$ (c) $2 \times 2 \times 1\,cm^3$ (d) $3 \times 3 \times 0.5\,cm^3$. For visual clarity the range of energy axis has been selected between 5.5 and 6.4 MeV as for all cases the minima were lying in this interval.

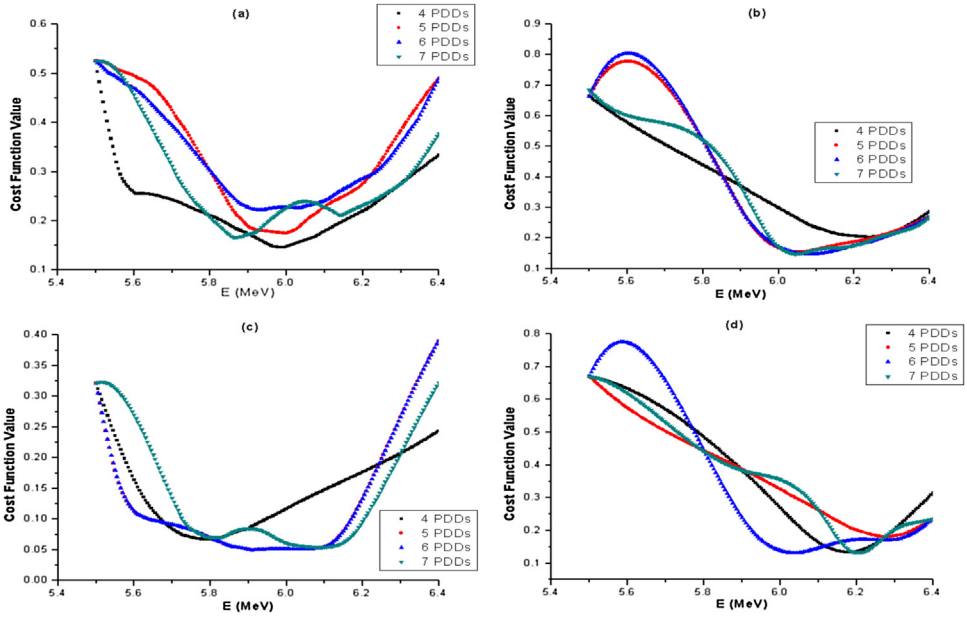

Fig. 3. Comparison of measured and simulated data using mean absolute error method while excluding the build-up region. The measured data has been compared with simulated data generated by interpolating 7, 6, 5 and 4 originally simulated PDDs (a) $1 \times 1 \times 1\,cm^3$ (b) $2 \times 2 \times 0.5\,cm^3$ (c) $2 \times 2 \times 1\,cm^3$ (d) $3 \times 3 \times 0.5\,cm^3$. For visual clarity the range of energy axis has been selected between 5.5 and 6.4 MeV as for all cases the minima were lying in this interval.

tion that is not biased and can work with a limited data set. Chi square values tend to be more biased if the number of data points is relatively few. In this case, MAE cost function is more accurate in producing the results. Alijarrah et al. have discussed several cost functions.[15]

By changing the voxel size in Z dimension, the cost function value has changed more as compared to changes in the x and y directions as evident from Figs. 2 and 3 (subplots a versus d and b versus c). Smaller z dimension provides clear and sharp minima (Figs. 2b, d, 3b and d) and, hence, more helpful to choose optimum electron beam energy. From both of the above mentioned cost functions, generally, no common minima are observed for all sets of measurements. Therefore, validation is required to be carried out using lateral beam profiles.

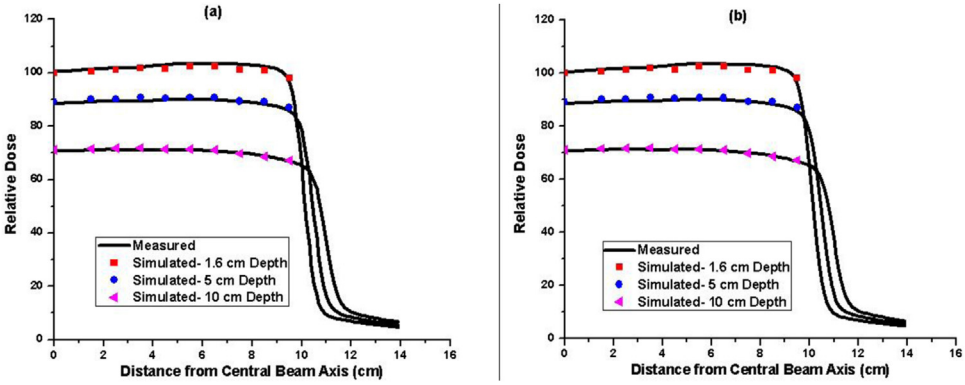

Fig. 4. Lateral dose profiles for verification of incident beam energy at 5.8 MeV with voxel size (a) $1 \times 1 \times 1\,cm^3$ (b) $2 \times 2 \times 1\,cm^3$.

Fig. 4 shows the lateral profiles scored at different depths for different voxel sizes. For optimized incident electron beam, a good match between the simulated and measured doses has been observed at three depths that is better than those reported previously.[18] The agreement between measured and simulated beam profiles is improved as the depth increases, which is consistent with the findings of Konefał et al.[22] No substantial difference in simulated beam profiles has been observed with the change of voxel dimension as obvious from Fig. 4a and 4b. It is important to mention here that the penumbra region is not considered for validation as the data in this region may lead to inaccurate selection of beam parameters.[10]

The next logical extension of these results is the minimum number of PDDs required to simulate. In this study, the effect of the initial number of PDDs has been studied by interpolating between 4, 5, 6 and 7 PDDs. The aim was to estimate the minimum number of PDDs required to be simulated while conserving the accuracy of the incident electron beam energy estimate as provided by the cost function. From the available results in Figs. 2 and 3 a quantitative relationship cannot be concluded. However, it seems prudent that selecting 5 PDDs will not make much of a difference on the results as compared to 6 or 7 PDDs.

These results suggest that there may exist scenarios where PDDs alone are not sufficient to isolate the exact electron beam incident energy. However, the use of PDDs may quickly narrow down the energy range which can be further probed using lateral profiles. To identify initial electron beam energy, the following steps may be carried out in sequence:

1 Five PDDs may be simulated around the reported energy X MeV for which the linear accelerator needs to be commissioned. For a 6 MV LINAC, as an example, a range of 5.5 MeV–6.5 MeV may be used. This range has been reported to be the most probable region in finding the desired energy. The voxel dimensions may be set at $1 \times 1 \times 0.5$ cm or even less in the Z direction.
2 MATLAB interpolation may be carried out and tens or hundreds of PDDs may be generated with a suitable interpolation step (i.e. 0.005 MeV in our case resulting in 240 interpolated PDDs).
3 Comparison of measured and simulated profiles may be carried out using a cost function say MAE.
4 If a single minimum is achieved, then that energy can be taken as the required electron beam energy at which the model has been commissioned. Otherwise, profiles will be required for the most plausible values (i.e. for all minima values) and the final decision is to be made on the quantitative comparison of the lateral dose profiles.

4. Conclusions

This study is carried out to investigate an efficient methodology for MC commissioning of a radiotherapy LINAC. It has been concluded that selection of optimum electron beam energy (electron beam tuning) is dependent on the cost function as well as the voxel size. Voxel dimensions along the depth of a water phantom are more sensitive to the cost function than to the lateral directions. Furthermore, a smaller Z dimension of a voxel provides sharper minima of the cost functions. Regarding the minimum data, 5 simulated PDDs are sufficient to generate interpolated PDDs for extracting optimum electron beam energy. PDDs can be used as a decisive tool to choose incident beam parameters. However, lateral profiles are also required in most scenarios for electron beam tuning. Relying solely on PDDs can generate serious errors and increase the time taken to commission a model.

Ethical statement

This article does not contain any studies with human participants or animals performed by any of the authors

Financial disclosure

None declared.

Conflict of interest

None declared.

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