Fluence profiles and energy spectral distributions of 100, 110, and 125 kVp photon beams: results of Monte Carlo simulations for a Varian OBI 1.4 CBCT

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Abstract. Cone Beam Computed Tomography (CBCT) imaging for daily patient localization has gained enormous popularity as one of Image Guided Radiation Therapy (IGRT) methods in recent years. This is largely due to the need of higher precision and accuracy in conformal beam delivery technique which is known as Intensity Modulated Radiation Therapy (IMRT). The success of this IMRT method is mainly determined by the treatment planning systems. The aim of this research is to provide detailed characteristics of incident photon beams for different beam energies from a Varian OBI 1.4 CBCT. The detailed characteristics consists of energy spectral distributions and fluence profiles. This information is critical to the future development of accurate treatment planning systems. BEAMnrc as one of EGSnrc Monte Carlo user code, has been used to simulate 100, 110, and 125 kVp photon beams from x-ray tube of a Varian OBI 1.4 CBCT. The details of each particle's complete history including where it has been and where it has interacted is stored in a phase space (phsp) data file. The phsp files are analyzed to obtain fluence profiles and energy spectral distributions.

1. Introduction
During the past decade, radiation therapy as one of main cancer treatment has experienced an extremely rapid development. Nowadays, IMRT (Intensity Modulated Radiation Therapy) occurs as a new promising radiation therapy technique. IMRT enables precise conformation of the radiation dose to the cancer volume. Besides, it has the potential to significantly reduce long-term morbidity and improve local control. IMRT uses multiple small radiation beams to precisely irradiate a cancer. In addition to conform to the cancer volume, the radiation intensity of each IMRT beam is divided into small segments and modulated throughout the treatment by the MLC (Multi-Leaf Collimator) attached to the linear accelerator. With multiple modulated radiation segments, the radiation dose is tuned to focus on cancer and spare surrounding healthy tissue as much as possible, therefore the possibility of radiation-induce side effects is significantly lowered.

Due to its complexity, IMRT requires proper and optimal treatment planning, because even a small error in treatment planning can lead to negative consequences. The uncertainty of the patient and cancer position is one of some factors that influence IMRT treatment plans. In order to overcome the challenges, IGRT (Image Guided Radiation Therapy) is proposed. IGRT is a combination of imaging procedures in the treatment room with modern radiation techniques which aims to generate accurate data about patient and cancer positions as well as the changes of their position.
A broad range of IGRT modalities is now widely available such as portal imaging, radiography, fluoroscopy, and CT (Computed Tomography). However, the most commonly used IGRT modality is CBCT (Cone Beam Computed Tomography). This is mainly due to CBCT can be integrated with conventional linear accelerator. CBCT uses cone-shaped X-ray beam to obtain complete view of the patient. The obtained imaging data is then reconstructed to show various viewing angles, depth variation, and particular tissue thickness in the patient’s body. Image reconstruction techniques in CBCT is very different with conventional CT. X-ray beam from CBCT has to cover the entire target being imaged and also the flat panel detector to produce a good image quality. Thus, it is necessary to have the knowledge of beam characteristics including spectral distribution and fluence profiles of the X-ray beam.

Based on the above background, the objective of this research is to provide the detailed characteristics of incident X-ray beams from CBCT system which consists of spectral distributions and fluence profiles using EGSnrc Monte Carlo user code. The type of CBCT system that becomes the object in this research is Varian OBI (On Board Imager) 1.4 CBCT.

2. Materials
Monte Carlo simulations of particle transport processes are a faithful simulation of physical reality: particles are “born” according to distributions describing the source, they travel certain distances, determined by a probability distribution depending on the total interaction cross section, to the site of a collision and scatter into another energy and/or direction according to the corresponding differential cross section, possibly producing new particles that have to be transported as well. This procedure is continued until all particles are absorbed or leave the geometry under consideration. Quantities of interest can be calculated by averaging over a given set of Monte Carlo particle “histories” (also referred to as “showers” or “cases”). From mathematical points of view each particle “history” is one point in a d-dimensional space (the dimensionality depends on the number of interactions) and the averaging procedure corresponds to a d-dimensional Monte Carlo integration [1].

Monte Carlo simulations have both strengths and weaknesses compared with another simulation methods. The strengths of Monte Carlo simulations can be described below:

a. The algorithm approaches real condition of radiation transport by following the processes step by step until it reaches the lowest of radiation energy.
b. The algorithm is relatively simple, making it easier to code and debug.
c. If the algorithm is appropriate, the accuracy level is determined by the accuracy of the cross-sectional data, so that cross-sectional data can be updated without change the existing algorithm.
d. Monte Carlo simulations is a microscopic method, hence geometry of the medium does not influence the Monte Carlo algorithm. Thus, Monte Carlo simulations can be used for complex medium.

Meanwhile the weaknesses of Monte Carlo simulations consists of two things as follows:
a. Monte Carlo simulations take relatively long time for running the program.
b. For electron transport, this methods still use the condensed history algorithm and in some parts still use approximations such as stopping power for low energy and multiple scattering theory for small angles, so it contains systematic errors.

The EGS (Electron Gamma Shower) system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several hundreds of GeV. The EGS system is developed by NRCC (National Research Council of Canada). EGSnrc is the new version of the EGS system, previously named EGS4, which has been improved in their some key features. The EGS code system has been written in an extended Fortran language known as Mortran. Today many of its features are available in other languages. Nonetheless Mortran3 have been continued to use because there are so many user codes available in Mortran3 that it makes no sense to abandon it. Over the years, NRCC has developed and distributed a series of user codes for use with the EGSnrc code system for the Monte Carlo simulation of photon and electron transport. These have been widely used and their results compared to experiment in many cases. BEAMnrc and BEAMDP are two of the user codes used in this research.
2.1. **BEAMnrc**

BEAMnrc is a Monte Carlo simulation system for modelling radiotherapy sources which was developed as part of the OMEGA (Ottawa Madison Electron Gamma Algorithm) project to develop 3-D treatment planning for radiotherapy. Before compiling and running a BEAM accelerator simulation, user must specify which component modules (CMs) are to be used and in what order. Each CM can be used in a wide variety of applications and user should not restrict themselves by the names [2].

One of the design features of BEAMnrc is that each part of the accelerator or source unit is considered to be a single component module which takes up a horizontal slab portion of the accelerator. These component modules are re-usable and are all completely independent. A component module can be considered as a block which has a ‘front’ surface and a ‘back’ surface. An accelerator is built with many such blocks. Very often there is gap between two blocks. This gap is automatically filled with air by the BEAMnrc main routine, which is consistent with the case of a real accelerator. The air gap which is in front of a module, and after the ‘back’ plane of the previous module, is considered as a part of this component module [2].

2.2. **BEAMDP**

BEAMDP (BEAM Data Processor) is an interactive program, developed for the OMEGA project. BEAMDP can be used to analyze the phase-space (phsp) parameters of a radiation beam generated using BEAMnrc and to derive the data required by a multiple-source model for representation and reconstruction of the radiation beam for use in Monte Carlo radiotherapy treatment planning. BEAMDP can also be used as a general-purpose BEAM utility program to derive energy, planar fluence, mean energy, angular distributions, etc., from an existing phsp data file generated by BEAM [3].

3. **Methods**

Broadly speaking, this research is divided into two stages.

a. The first stage is a geometrical X-ray tube of OBI 1.4 CBCT modeling using BEAMnrc. The output of this simulation is some phsp data file.

b. The second stage is analyzing the phsp data file, output of BEAMnrc, using BEAMDP to obtain the X-ray spectral distributions and fluence profiles.

The X-ray tube of OBI 1.4 CBCT consists of several components: X-ray target, exit windows, pre-filter, pre-collimator, upper blades, glass, and bow tie filters. The components are then modeled on BEAMnrc by utilizing the available component modules. The CM used to design the components of
OBI 1.4 CBCT are composed of XTUBE, CONESTAK, SLABS, FLATFLIT, and JAWS. Figure 1 and figure 2 are OBI 1.4 CBCT models for full-fan and half-fan modes. In full-fan mode, the type of the used bow tie filter is a full bow tie filter, while half-fan mode uses a half bow tie filter. In order to know the spectral distributions and fluence profiles of the radiation beam, the scoring planes are placed in X-ray tube geometry model. There are three scoring planes and each are placed after target, before bow tie filter, and after bow tie filter. The tube voltage is varied with values 100 kVp, 110 kVp, and 125 kVp.

4. Results and Discussion

4.1. X-Ray Spectral Distribution and Fluence Profile after Target

Based on the spectral distribution shown in figure 3, it can be seen that there are nine peaks representing the characteristic X-ray spectrum. This characteristic X-ray spectrum is the result of the interaction between the electron and the target in OBI 1.4 CBCT X-ray tube. The obtained peak value can then be compared with the value of the online edition of "Kaye and Laby: Tables of Physical & Chemical Constants", provided by National Physical Laboratory (NPL), United Kingdom (table 1). The comparison shows that the energy value of the X-ray characteristics produced by the simulation tends to be the same. In addition, the X-ray spectral distribution also shows that the X-ray spectral energy for the 100 kVp, 110 kVp, and 125 kVp has a maximum value of 100 keV, 110 keV, and 125 keV respectively. Moreover, a review of the X-ray fluence distribution or the X-ray fluence profile after the target informs that the resulting radiation beam is not a parallel beam but a cone beam.

![X-Ray Spectral Distribution After Target](image1)

![X-Ray Fluence Profile After Target](image2)

**Figure 3.** X-ray spectral distribution after target.

**Figure 4.** X-ray fluence profile after target.

| No. | Peak Energy Value of X-Ray Spectral Distribution (keV) in Each Different Tube Voltage | Peak Energy Value of X-Ray Spectral Distribution (keV) from NPL Measurement |
|-----|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
|     | 100 kVp | 110 kVp | 125 kVp | 100 kVp | 110 kVp | 125 kVp | 100 kVp | 110 kVp | 125 kVp |
| 1   | 1.75    | 1.65    | 1.88    | 1.77    | 1.78    | 1.84    |
| 2   | 7.35    | 7.98    | 7.81    | 8.34    | 8.40    |
| 3   | 9.25    | 9.08    | 9.06    | 9.53    | 9.67    |
| 4   | 20.30   | 20.10   | 20.30   | 20.07   | 20.20   |
| 5   | 22.80   | 22.80   | 22.80   | 22.70   | 22.72   | 23.17   |
| 6   | 57.80   | 58.00   | 57.80   | 57.98   |
4.2. X-Ray Spectral Distribution and Fluence Profile before Bow Tie Filter

Figure 5 above shows the X-ray spectral distribution before the bow tie filter. This distribution illustrates the X-ray spectral distribution that has passed through exit windows, pre-filter, pre-collimator, upper blades, and glass. By comparing with the spectral distribution after target, it is known that there is a reduction of low-energy X-ray. In this area the minimum energy value of X-ray is approximately 0.02 MeV. Meanwhile the fluence profile before bow tie filter in figure 6 shows that the resulting cone beam diameter in this area is about 8 cm. The diameter of X-ray beam corresponds to the size of the patient that can be covered by CBCT imaging.

4.3. X-Ray Spectral Distribution and Fluence Profile after Bow Tie Filter

Figure 7 and 8 are the X-ray spectral distributions after bow tie filter for full-fan and half-fan modes. Basically bow tie filter serves to reduce skin dose, reduce X-ray scattering, improve image quality, and reduce charged particles trapped in the detector. By comparing with the X-ray spectral distribution
before bow tie filter, it can be seen that there happens again a reduction in low-energy photons where there is more reduction in full-fan mode. Meanwhile, the analysis of the X-ray fluence profile after bow tie filter for both modes gives information that the resulting beam diameter is reduced by the presence of a bow tie filter, with a smaller beam diameter in full-fan mode. This is related to the fact that full-fan mode commonly used for head imaging. While half-fan mode with larger beam diameter is generally used for pelvic imaging.

![Figure 9. X-ray fluence profile after bow tie filter for full-fan mode.](image1)

![Figure 10. X-ray fluence profile after bow tie filter for half-fan mode.](image2)

5. Conclusion
It has been presented beam characteristics from Varian OBI 1.4 CBCT for three variation of the tube voltage, including 100, 110, and 125 kVp. The obtained beam characteristics data provided useful and needed information that can be used for determination of radiation exposure and calculation of imaging dose resulting by Varian OBI 1.4 CBCT in a treatment planning system. Besides, this study has demonstrated that the Monte Carlo simulation could provide details of the X-ray beam characteristics data which can be used for commissioning an X-ray beam in a radiotherapy treatment planning system.

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