Physica Medica 44 (2017) 34–41

Contents lists available at ScienceDirect

Physica Medica

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

Original paper

Implementation and application of a Monte Carlo model for an *in vivo* micro computed tomography system

Peter Manser[a,*], Silvia Peter[a], Werner Volken[a], Martin A. Zulliger[b], Andres Laib[b], Bruno Koller[b], Michael K. Fix[a]

[a] *Division of Medical Radiation Physics and Department of Radiation Oncology, Inselspital, Bern University Hospital, and University of Bern, Switzerland*
[b] *SCANCO Medical AG, Switzerland*

ARTICLE INFO

Keywords:
Micro-CT
Cone beam CT
Monte Carlo
Scatter radiation

ABSTRACT

Micro computed tomography (μCT) scanners are used to create high-resolution images and to quantify properties of the scanned objects. While modern μCT scanners benefit from the cone beam geometry, they are compromised by scatter radiation. This work aims to develop a Monte Carlo (MC) model of a μCT scanner in order to characterize the scatter radiation in the detector plane.

The EGS++ framework with the MC code EGSnrc was used to simulate the particle transport through the main components of the XtremeCT (SCANCO Medical AG, Switzerland). The developed MC model was based on specific information of the manufacturer and was validated against measurements. The primary and the scatter radiation were analyzed and by implementing a dedicated tracing method, the scatter radiation was subdivided into different scatter components.

The comparisons of measured and simulated transmission values for different absorber and filter combinations result in a mean difference of 0.2% ± 1.4%, with a maximal local difference of 3.4%. The reconstructed image of the phantom based on measurements agrees well with the image reconstructed using the MC model. The local contribution of scattered radiation is up to 10% of the total radiation in the detector plane and most of the scattered particles result from interactions in the scanned object. The MC simulations show that scatter radiation contains information about the structure of the object.

In conclusion, a MC model for a μCT scanner was successfully validated and applied to analyze the characteristics of the scatter radiation for a μCT scanner.

1. Introduction

Modern computed tomography (CT) is based on either fan-beam CT or cone beam CT (CBCT) technology. Dedicated micro computed tomography (μCT) scanners are used to create high-resolution images and to measure physical properties (e.g. bone mineral density) of the objects examined [1]. One example of μCT applications is the *in vivo* clinical assessment of bone structure and architecture in order to determine the fracture risk, which is related to osteoporosis [2]. Such a cone beam micro-CT (CBμCT) system is the XtremeCT (SCANCO Medical AG, Switzerland), which has been developed and designed for the clinical characterization of density and structure parameters by 3D-scanning of the distal tibia and the radius bone of humans.

Compared with fan-beam CT, the CBCT has a great advantage in terms of acquisition time and it is used in radiation therapy [3,4] as well as in quantitative μCT [5,6]. However, it is well known that CBCT imaging is strongly limited by effects related to scatter, which is more pronounced in CBCT than in fan-beam CT [7]. Scatter radiation leads to reduced image quality such as cupping artifacts and streaking artifacts or has impacts on the information about physical properties of the objects observed. While scatter correction methods for CBCT in radiation therapy can be realized by adding anti-scattering grids [8], this approach is not appropriate for CBμCT applications due to the small pixel sizes of the corresponding detectors. As a consequence, detailed knowledge about the scatter contribution is of interest in order to understand the impact of the scatter on these effects.

Investigating the scatter radiation by using measurements is very difficult and limited to special situations, which do not represent realistic cases. Another common approach is the use of Monte Carlo (MC) simulations that are generally used to simulate the particle transport through matter. In radiation therapy, MC simulations are used for beam characterization of particles leaving the head of a treatment machine

* Corresponding author at: Division of Medical Radiation Physics, Inselspital and University of Bern, Freiburgstrasse, CH-3010 Bern, Switzerland.
E-mail address: peter.manser@insel.ch (P. Manser).

https://doi.org/10.1016/j.ejmp.2017.11.005
Received 10 June 2017; Received in revised form 5 October 2017; Accepted 4 November 2017
Available online 16 November 2017
1120-1797/

[9–12], for dose calculation in MC treatment planning [13–16], and for different kinds of dosimetric investigations [17–19]. The MC method is also a powerful tool for investigating the scatter radiation in diagnostic radiology. While there are a number of MC investigations in the literature on CBCT for radiation therapy, only a few publications are available for CBμCT [20]. In addition, to our knowledge, no MC based study on the scatter radiation of the XtremeCT is currently found in the literature.

In this work, the XtremeCT is modeled using MC methods. For this purpose, the main components of the XtremeCT are implemented in the MC framework and an accurate beam model is generated in order to overcome the phase space file related limitations such as efficiency or flexibility issues. The resulting MC model is validated using transmission measurements. As an application, the scatter radiation is investigated by means of a method that was developed to separate the different scatter components. It will be seen that mainly the phantom scatter is of greatest importance. This information is important in order to understand the origin of scatter contribution to the image signal, which in turn provides the basis for scatter correction algorithms.

2. Materials and methods

2.1. Monte Carlo implementation of the XtremeCT

The XtremeCT is implemented in the EGS++ MC code, which is the C++ framework of the well accepted EGSnrc MC code [21–24]. For all MC simulations in this work, the EGSnrc version V4 was used and the applied MC settings for the radiation transport are summarized in Table 1. It is worth mentioning that due to the energy range observed in this study, the Rayleigh scattering has to be taken into account [20] and there is a need to set the transport cutoffs as low as possible. In addition, photoelectron angular sampling, atomic relaxations, and spin effects were considered in the MC simulations.

The XtremeCT is a peripheral quantitative CBμCT device, which is able to reconstruct 3D images with isotropic voxels of 82 μm. As shown schematically in Fig. 1, the main components of the XtremeCT are implemented in the MC code according to the manufacturer's specifications in terms of geometry, material properties and source description. These components include a filter (either aluminum-copper or titanium), shielding blocks, the collimator, the shielding ring and the detector. The source used for the MC simulation of the XtremeCT was approximated by an extended source with a double 2D Gaussian distribution at the location of the X-ray tube target based on the information from the manufacturer. Thereby, the size of the initial cone beam defined by the collimator was $22 \times 220\,\text{mm}^2$ in the detector plane, which is located at about 500 mm from the source. From this 2D Gaussian distribution the starting point of the particle was sampled for the MC simulations. An additional point was sampled from a homogeneous distribution located in the plane directly below the beryllium window. The connected line between this point and the starting point was used to determine the initial direction of the starting particle. Since the scatter radiation is strongly dependent on the incident energy spectrum, this spectrum was determined from the phase space file generated in a pre-simulation of the X-ray tube. In this pre-simulation, the X-ray tube was simulated using the BEAMnrc MC package [23], which is also using EGSnrc for the radiation transport. The X-ray tube was implemented as a tungsten anode with an angle of 20° and a 125 μm thick beryllium window through which the photon beam emerges. The source for this pre-simulation was a circular parallel electron beam with a radius of 25 μm and an energy of 60 keV (monoenergetic). Below the beryllium window a phase space file was generated. The schematic view of the X-ray tube simulation is illustrated in the upper part of Fig. 3. A mean energy spectrum of the photons in the phase space file within the initial cone beam is determined and used as input spectrum for the MC simulation of the XtremeCT. The statistical uncertainty of the fluence and the mean energy of the spectrum are within 0.5% and 0.6%, respectively.

Table 1
Summary of the EGSnrc transport parameter values used for the Monte Carlo simulations in this work (BH = Bethe-Heitler, KM = Koch-Motz).

MC-Parameter	Value
Photon cross sections	PEGS4
Photon transport cutoff [MeV]	0.001
Pair angular sampling	Simple
Pair cross section	BH
Triplet production	Off
Bound Compton scattering	On
Radiative Compton corrections	Off
Rayleigh scattering	On
Atomic relaxations	On
Photoelectron angular sampling	On
Electron transport cutoff [MeV]	0.001
Bremsstrahlung cross sections	BH
Bremsstrahlung angular sampling	KM
Spin effects	On
Electron impact ionization	Off
Maximum electron step in cm (SMAX)	1.0E + 10
Maximum fractional energy loss/step (ESTEPE)	0.25
Maximum 1st elastic moment/step (XIMAX)	0.50
Boundary crossing algorithm	Exact
Skin-depth for boundary crossing (MFP)	3.00
Electron-step algorithm	PRESTA-II

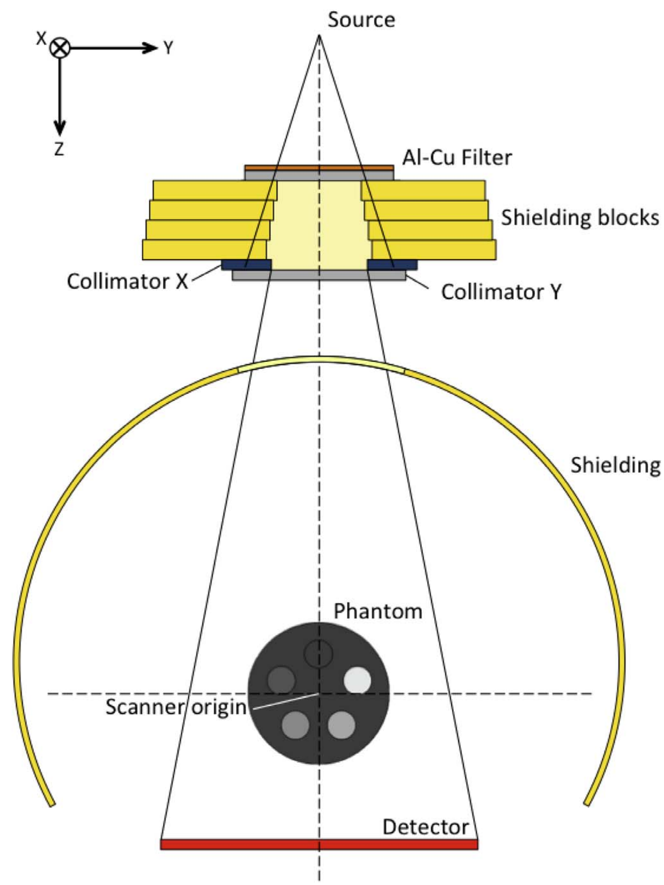

Fig. 1. Illustration of the main components of the XtremeCT as implemented in the Monte Carlo code (not on scale).

The initial photons released from the source are first filtered by aluminum-copper or titanium plates and subsequently collimated to the detector's sensitive area of $14 \times 170\,\text{mm}^2$. Additional brass shielding blocks and a cylindrically shaped brass ring are used to reduce the radiation leakage. The detector consists of a 0.3 mm thick layer of CsI with a density of $4.31\,\text{g/cm}^3$ covered by a 1 mm thick layer of