Evaluation of the absorbed dose in X-ray microtomography

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Abstract

It is widely known that a sample receives a radiation absorbed dose during a CT-scan. Although this can have unwanted effects on the sample such as discolouration, little can be found in literature about the absorbed dose in micro-CT applications (except for small animal micro-CT). This research aims to validate the accuracy of dose simulations to be able to predict the dose before scanning the sample. Both Monte Carlo simulations with BEAMnrc and simulations with the in-house developed Setup Optimizer are compared with measurements with an ionisation chamber. The simulations nearly always underestimate the experimental values with a maximal deviation of 40%. In contrast the dose reduction after a layer of material obtained with the simulation programmes is relatively accurate.

Introduction

A drawback of X-ray imaging is the deposition of a radiation absorbed dose in the object being imaged. For medical applications, it is important to quantify this dose, because it can be harmful to the patients' health. In comparison to medical scans, micro-CT scans have a much higher resolution, which typically gives rise to a higher dose in the scanned object. Next to a higher resolution, micro-CT scanners have more degrees of freedom than medical CT scanners. In medical CT, the scan geometry is nearly always the same. The patient is placed between an X-ray source and a detector, which rotate simultaneously around the patient. The typical degrees of freedom are the tube voltage, tube power, collimation and filtration. In most micro-CT applications, the sample rotates between the source and detector. In modern systems, both the source to object distance (SOD) and source to detector distance (SDD) can be varied independently and are additional degrees of freedom, as well as the scan time, the type of source and the type of detector. Furthermore, micro-CT can be used in a large number of research domains, and the objects under investigation can vary strongly in size and composition. Both the extra degrees of freedom and the variety of samples make standardized dosimetry tests very difficult to define and perform.

Due to the differences between micro-CT and medical CT, the standardized dosimetry calculations and measurements of medical applications cannot be applied in micro-CT scans. For practically all micro-CT scan applications (except for small animal micro-CT scanners) very little information is available in literature about dose deposition in the samples. Sometimes, for non-living samples such as metal objects, the dose is less important, because the limited dose involved in laboratory-based micro-CT will not affect the sample. However, some samples are radiation sensitive, such as minerals of which the colour can change due to radiation or plants which need to be examined several times during growth. Although the plants do not die, they can stop growing after a single scan (Dhondt et al, 2010). These two examples prove that it can be important to know the exact dose (or at least an estimate) that the sample under investigation will obtain during the total scan time.

The aim of this study is to examine the absorbed dose in lab-based micro-CT. This research is performed at HECTOR (Masschaele et al., 2013), one of the scanners at the 'Centre for X-ray Tomography' of Ghent University (UGCT; www.ugct.ugent.be), which is a research facility specialised in high resolution X-ray computed tomography, where several home built modular micro- and nano-CT scanners are in use.

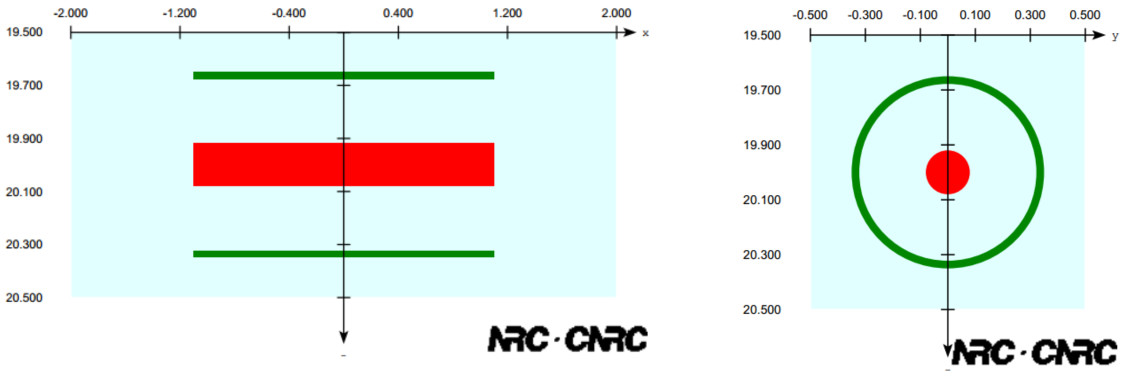
Materials & methods

In this research we have evaluated different absorbed dose simulation techniques by comparing them with experimental data. First, measurements in air were performed. Second, a bar of PMMA (a kind of transparant plastic, Fig.1a) was irradiated, while the absorbed dose was measured by placing the ionisation chamber in the drilled holes in the bar. The dose was measured using an ionisation chamber during different scan protocols. The used ionisation chamber (Fig. 1b) is a device of Capintec, with an aluminum central wire and air equivalent plastic wall. These measurements are compared with two different simulations: Monte Carlo simulations with BEAMnrc (www.nrc-cnrc.gc.ca/eng/solutions/advisory/beamindex.html) and simulations with the in-house developed Set-up Optimizer. This programme is based on the law of Lambert-Beer to determine the total attenuation through slabs (Dhaene et al, 2015).


a b

Fig. 1. *Used bar of PMMA (a) and ionisation chamber (b).*

For both measurements, in air and in PMMA, the source object distance was 200 mm. The bar was positioned in such a way that the active volume of the ionisation chamber was fixed at 200 mm of the focal spot of the X-ray source. No beam filter was used and the target current was 700 µA. The tube high voltage was varied between 20 and 240 keV. The Monte Carlo simulations were performed with a phantom representing the ionisation chamber as good as possible. The phantom is shown in Fig.2.

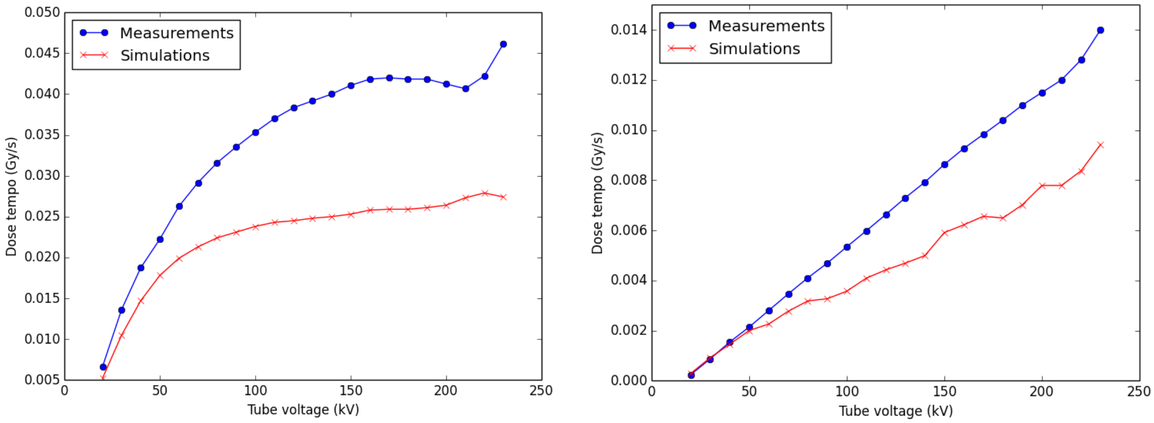


a b

Fig. 2. *The xz-view (a) and the yz-view (b) of the phantom used in BEAMnrc. Colour scheme: red = aluminum, green = air-equivalent plastic, blue = air.*

Results

The resulting absorbed dose in air as a function of tube voltage is shown in Fig.3a. The Monte Carlo simulations yield an underestimation of the actual dose with a maximum deviation of 40%. The second set of measurements is performed at a depth of 10mm in the bar of PMMA. There is a good agreement between the measurements and simulations at low energies. In contrast, for high voltages the deviation rises to 37%.



a b

Fig. 3. *The measurements and simulations of the absorbed dose in air (a) and after 10 mm PMMA (b)*

Next to the absorbed dose, also the dose reduction after traversing a slab of material can be calculated. Beside measurements and Monte Carlo simulations with BEAMnrc, two other methods are tested. The two additional methods are based on the Setup Optimizer, which is a programme developed at UGCT to calculate the beam attenuation in multiple layers of different materials. The first method is to compare the transmission of photons with and without a slab of PMMA. If 85% of the photons reaches the air sample if no PMMA is present and 40% reaches the air sample if 10mm PMMA is present, the dose reduction would roughly be 0.40/0.85 = 47% in case of a monochromatic beam. This method seems to be a too rough estimation to calculate dose reductions (Fig. 4) because we are dealing with a polychromatic beam. The other method takes into acount that the energy of the spectrum changes while traversing a sample. From the incoming and outgoing spectrum calculated by the setup optimizer the absorbed part of the spectrum can be calculated, which can be divided in a Compton-scattered part, a Rayleigh-scattered part and a photo-electric absorbed part. The absorbed dose is then due to all the photo-electrically absorbed photons and a part of the Compton scattered photons, depending on their energy. The fraction by which they contribute is a linear function of the energy. This is 1 for a photon of 0 keV and 0.4 for a photon energy of 240 keV. These values are chosen to match the experimental data and are logical. Low-energy photons are completely absorbed, while most high-energetic photons are able to leave the sample, even after scattering. The Rayleigh-scattered photons do not contribute to the dose, because they are mostly leaving the sample. Although the agreement between measurement and simulation is not sufficiently accurate to predict the absorbed dose, the dose reduction in PMMA in respect to the air is relatively good. This is clearly illustrated in Fig.4.

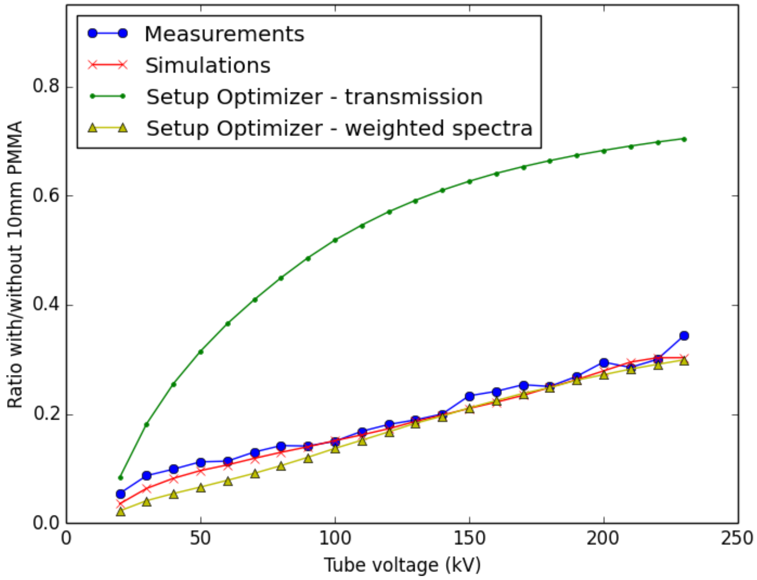


Fig. 4. *Dose rate reduction after 10 mm PMMA: 4 different methods*

Conclusion

At this moment the accuracy for fast absorbed dose estimation prior to scanning is not yet good but sufficient if only absorbed dose estimations are necessary. However, the dose reduction after traversing a slab can be more correctly estimated. Combining the dose reduction with an experimentally obtained standardized table of the absorbed dose in air at different distances with different tube settings, could result in a good dose estimation.

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