Modelling of X-ray tube spot size and heel effect in Arion

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Keywords: Computed tomography; Simulation; Polychromatic; X-rays

Abstract

X-rays produced in X-ray tubes originate from a focal spot on the target material. This spot is not infinitely small, but has a finite size. This finite size of the spot will affect the radiographic projections taken during X-ray Compted tomography. In order to simulate correct radiographic projections, this finite spot size needs to be taken into account during the simulations. This can be done by modelling a two dimensional profile of the spot and use this model to convolve the simulated radiographic projections simulated with an infinitely small spot size. A second effect, the heel effect that originates in directional X-ray tubes will also have an influence on the final projections. This effect can also be modelled and this model can be used to correct the simulated projections for this effect.

Introduction

X-ray Computed Tomography (CT) is a non-destructive technique used to produce three-dimensional images of objects, allowing the user to visualize the inside of these objects. This reconstructed object is represented by a discrete three-dimensional volume and each voxel inside this volume contains a grey value that represents a calculated linear attenuation coefficient μ. In laboratory-based X-ray CT, polychromatic sources are typically used in combination with energy-integrating detectors. Changes in the emitted spectrum or use of different detectors will thus result in different reconstructed attenuation coefficients.

To optimize the scanner settings such as high voltage and filtration for a given sample, a fast and realistic projection simulator called Arion (Dhaene *et al.*, 2015) was developed at the ‘Centre for X-ray Tomography’ of Ghent University (UGCT, www.ugct.ugent.be). This GPU-accelerated polychromatic simulator takes into account the characteristics of the setup such as emitted spectrum, detector energy response, beam filtration and the sample itself. This could also be very useful in iterative reconstruction methods where a simulated projection of a temporary solution is compared to the actually measured projection.

Arion already takes into account the above described effects caused by the polychromatic nature of the imaging process. Although this description of a virtual scanner is sufficient in most cases, sometimes it is useful to take into account other effects such as the finite spot size and the heel effect of the X-ray tube to perform the simulations. The finite spot size can result in a reduction of spatial resolution in the radiographic projection. The heel effect causes a gradient in the spectral distribution over the projection image, which may influence the above mentioned optimization.

Methods

An X-ray tube produces a primary spot, of which the size depends on the tube power, and in some tube geometries also an "unwanted" secundary spot caused by the internal structure of the X-ray tube (Boone et al., 2012). The effect of the former is usually minimized by choosing the tube settings (i.e. focussing mode and tube power)achieving a spot size that corresponds to or is smaller than the resolution one wants to achieve during the CT scan. Nevertheless, it can be interesting to use a higher tube power resulting in a spot size that gives rise to a worse resolution because at the same time the higher power increases the image statistics and thus reduces the noise in the data. The secondary focal spot on the other hand has a fixed size. Unless a hardware correction is made, as described in Boone et al., the effect of the secondary spot is always present in the radiographic projections.

The effect of a finite spot, both primary and secondary, can be implemented by performing the following convolution:

$$I'(x', y') = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} I(x' - x, y' - y) F(x, y)\, dx\, dy,$$

in which $I(x' - x, y' - y)$ represents the original simulated projection that was performed with the infinite small spot size and $F(x, y)$ is a normalized two-dimensional profile of the finite spot. x and y represent the coordinates in the detector plane. For an infinitely small spot, F is represented by a Dirac delta function and I and I' will be the same.

The primary spot on HECTOR (Masschaele et al., 2013) was modeled by taking radiographs of an Al Sphere of 6mm diameter at a tube voltage of 100kV with different tube powers. A tube power of 10W was used to achieve a spot size that was smaller than the ‘resolution’ of the radiograph which represents a radiograph with an infinitely small spot. Further, radiographs at the same tube voltage with a power of 100W and 200W were taken that represents radiographs with a finite spot size larger than the resolution of the radiographies.

A correction for the secondary spot present in the transmission tube described by Boone et al. requires information about the profile of the spot. This information is obtained by performing a Monte Carlo (MC) simulation of the tube with BEAMnrc (www.nrc-cnrc.gc.ca/eng/solutions/advisory/beamindex-.html). The inner structure of the tube was modeled and given as input to the MC simulations. During the simulations accelerated electrons impinge on the tungsten target and interactions can be traced. Photons are produced by the interactions between the electrons and the target material and detected on a 1cm x 1cm scoring plane at a distance of 5cm away from the target. Some electrons will scatter towards the molybdenum case of the inner tube. These electrons can also interact with this inner tube material and produce photons. Around 17% of the produced photons in the X-ray tube emanate from this molybdenum case, which results in a large secondary spot. The location of the production of these secondary photons can be traced in the MC simulations and thus a model of the secondary spot can be extracted from these data.

A complete scan of an Al sphere was performed at the scanner described in Masschaele et al. (2007). This scanner uses the transmission tube described by Boone et al. in which the above described secondary spot is produced. For the same scan two simulations were performed with Arion, one with and one without the correction for the secondary spot. These real and two simulated datasets were reconstructed by using Octopus (www.octopusreconstruction.com) (Vlassenbroeck et al., 2007), a software package developed at the UGCT.

Monte Carlo simulations with BEAMnrc can also be used to model the heel effect in a directional tube. In these tubes both the intensity and spectrum depend on the direction in which the X-rays escape from the target material as the probability for absorption depends on the distance the photons travel within the anode material. Due to the geometry of the electron beam on the anode, this distance depends on the direction of emission. This behaviour was modeled by using the results of the MC simulations performed for the X-ray tube present at HECTOR. The model can be used to correct the radiographic images obtained by Arion for a heel effect of a directional tube.

Results

Figure 1 shows a real projection of an Al sphere (diameter 6mm) taken at HECTOR at 100W and 100kV, a projection with the same parameters acquired by a simulation performed with Arion by supposing an infinite small spot and a simulated projection where a correction for the finite spot size is executed.

Fig. 1. *Real projection of an Al sphere taken at HECTOR (right), simulated projection without (left) and with (middle) spot correction.*

The simulated profile of the spot of the transmission tube is shown in figure 2. Figure 3 shows a radial intensity profile for the secundary spot only. The geometry of the spot is assumed to be cylindrically symmetric and the normalized intensity is expressed in function of the distance to the central axis of the tube. This model was used to correct the simulated data from Arion. Figure 4 shows a line profile of a reconstructed slice of the scanned Al sphere. A comparison between the real scan, the simulated scan without secondary spot correction and the simulated scan with secondary spot correction is shown.

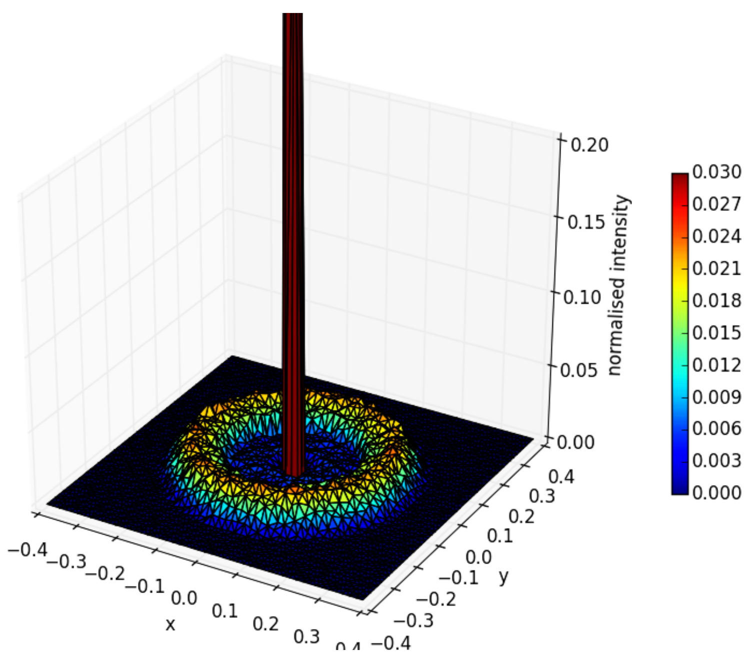

Fig. 2. *3D profile of the spot of the transmission tub on the target. The primary spot is visible on the central axis while the torus around this axis represents the secondary spot.*

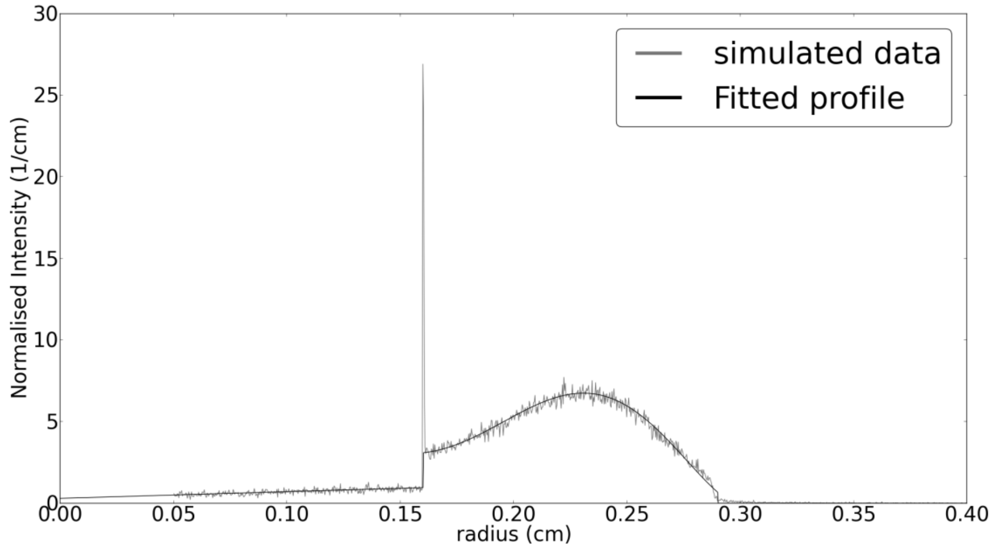

Fig. 3. *Normalised intensity of the secondary spot in function of the distance to the centre of the transmission tube. A profile is fitted to the data.*

Fig. 4. *A line profile of the real and simulated scan in a reconstructed slice of the Al sphere .*

Figure 5 shows a line profile in an open beam image taken at HECTOR and the line profile acquired in a simulation with Arion. The measured open-beam image is corrected for detector inhomogeneity by normalization with an image acquired using a transmission-type tube, where the heeling effect is not present and the X-ray beam is expected to be very homogeneous. The simulated open beam image takes into account the modelled direction of the photons emitted by the source and thus corrects for the heel effect.

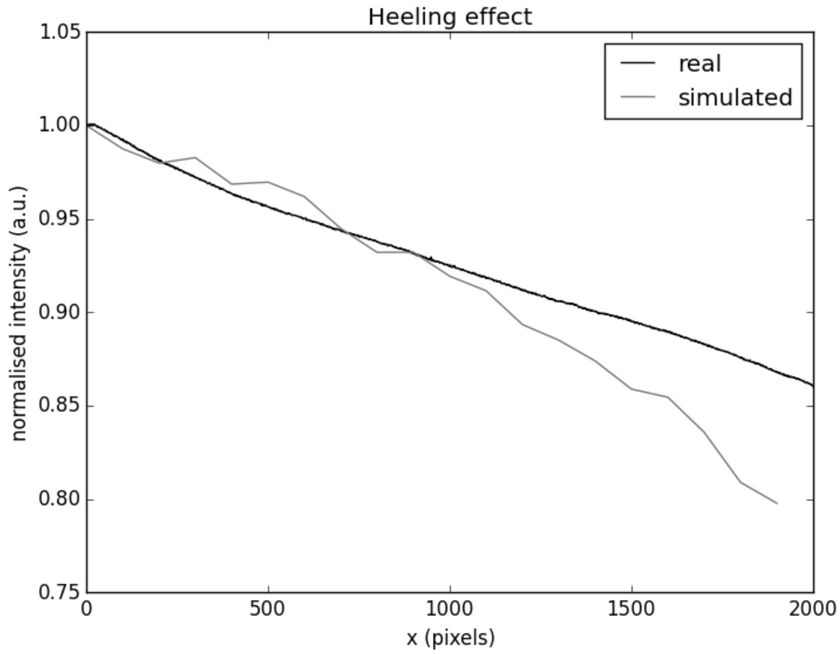

Fig. 5. *Comparison between the real and simulated line profile in an open beam image.*

Conclusion

The finite size of a spot can be modeled and used to improve the simulations performed with Arion. This is done by performing a convolution between the simulated projection with infinite small size and a profile of the finite spot. Further the heel effect in the directional tube mounted on HECTOR was studied and modelled. A maximum deviation of 15% between simulated and real data was found.

These models of the finite spot size and heel effect can help to improve image quality of the simulated scans but future research is needed to model these effects more accurately.

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