# Arion: a realistic projection simulator for optimizing laboratory and industrial micro-CT

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## Abstract

Optimal scanning conditions in a X-ray Computed Tomography scan are determined by the source and detector of the CT-scanner and composition, size and density of the sample. Because all these components have an energy-dependent behaviour, optimizing a CT scan is not straightforward. In order to ease this process a GPU-accelerated realistic projection simulator, Arion, is developed.

Arion allows the user to simulate realistic radiographic projections for a certain geometry while taking into account the polychromatic behaviour of X-ray tube, detector and sample. This allows the user to produce realistic CT datasets that can be used to optimize the scanning conditions for a certain sample.

## Introduction

The ‘Ghent University Centre for X-ray Tomography’ (UGCT; www.ugct.ugent.be) is a research facility that develops both hardware and software for high resolution computed tomography (CT). The available hardware consists of 4 state-of-the-art micro-CT scanners (Masschaele et al., 2007; Dierick et al., 2014) and is used for a wide range of research applications. In order to increase the quality of the scans and simultaneously reduce scan time and thus cost of X-ray CT, the scanner parameters need to be optimized.

A CT scan results in a reconstructed, voxelized 3D volume. Each voxel in this volume contains a calculated grey value which represents the linear attenuation coefficient for the materials present in that voxel. This linear attenuation coefficient is the product of a local density and the measured mass attenuation coefficient in that voxel with the latter being dependent on both sample composition and the detected X-ray spectrum. This reconstructed attenuation coefficient will thus be dependent on initial spectrum, sample shape and composition and detector sensitivity. To optimize a CT scan, the polychromatic behaviour of all these components must be known in order to simulate the radiographic images as accurately as possible.

At UGCT a method to determine this polychromatic behaviour of source and detector as well as a programme, called Arion, to simulate these realistic images for a CT-scanner were developed (Dhaene et al., 2015). Arion can be used to determine the optimal scanning conditions for a specific setup, geometry and sample. The method section describes the functionalities of Arion and the parameters used to determine an optimal scanning setup. The results section shows a validation done at the HECTOR scanner (Masschaele et al., 2013) present at UGCT and an example to optimize the scanning condition for visualizing water inside a butter sample.

## Methods

Arion is a realistic projection simulator that takes the polychromatic behaviour of the source, sample and detector into account. This behaviour is modelled as described by

Dhaene et al. (2015) by performing Monte Carlo (MC) simulations using BEAMnrc (www.nrc-cnrc.gc.ca/eng/solutions/advisory/beamindex.html). Both source and detector are simulated separately by using a model for their geometric design, which is given as input parameter in the MC simulations. This results in a simulated spectrum emitted by the modelled X-ray tube at a given voltage and simulated energy-dependent behaviour and efficiency of the detector. Both source and detector simulations produce datafiles that are used by Arion. This simulated data is preferred over semi-empirical data as they are significantly more accurate, since they take into account the secondary effects due to the actual construction of the X-ray tubes and detectors present at the UGCT. Further, Arion uses a ray-tracing technique to calculate the projection images.

The polychromaticity of the setup is simulated in Arion by dividing the spectrum in energy bins and in each of these energy bins, the contribution to the radiographic projection is calculated. During this calculation, each bin is treated as it was monochromatic. Further, the noise in each energy bin is calculated assuming Poisson statistics where $\sigma_{N_i} = \sqrt{N_i}$. $i$ represents the energy bin, $N_i$ is the number of detected photons in that energy bin and $\sigma_{N_i}$ is the error on the number of photons in that energy bin. These detected photons can be converted into a detected energy based on the data from the Monte Carlo simulations. Also the error on the total deposited energy can be calculated by assuming gaussian error propagation. This can be assumed when the number of photons is larger than 20, which is certainly the case in X-ray CT.

Another feature of Arion is the flexibility in defining a scan geometry. Three types of scan geometry are implemented in the GUI of the programme. These are circular, helical and conveyer belt geometry. Circular and helical geometry are usually used in a research environment because they provide information about the whole angular range, from 0° to 360°. A conveyer belt setup is included to investigate more industrial setups were there is often a restriction on the scan time and thus on the number of projections and angular range of the scan. Further, Arion uses a GPU-implemented code which reduces the simulation time for a complete realistic CT scan to the order of a few minutes

A validation of Arion for HECTOR is presented. This is done by scanning two samples: a cylindrical phantom of polyoxymethylene (POM) and an aluminum (Al) sphere. Both samples were scanned at HECTOR over a whole range of energies ranging from 30kV up to 210kV (in intervals of 30kV). In addition, a virtual representation of these samples was made and Arion was used to simulate radiographic projections of these phantoms. These projections were generated emulating the the same conditions as the real scans. This implies the same number of projections and flatfields, the same tube voltage and power and the same integration time of the detector. This was done in order to verify the predicted noise levels in the simulated versus the real datasets.

Finally, as an example, optimal settings to discriminate water nodules inside a butter sample were obtained. Water and fat have a composition that behaves very similar under X-ray CT conditions. This makes it a challenging problem in X-ray CT. A virtual butter sample containing water fractions was generated and simulations were performed over a range of tube voltages. This way, an optimal setting in terms of geometry, voltage and filtration can be derived. Arion can thus be used to predict signal to noise ratios of materials in the sample, which are defined as

$$SNR = \frac{\mu}{\sigma_\mu},$$

in which $\mu$ is the reconstructed attenuation coefficient in the 3D volume and $\sigma_\mu$ is the error on this value. Similarly, a contrast-to-noise ratio

$$CNR = \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_{\mu_1}^2 + \sigma_{\mu_2}^2}}$$

can be defined. This is an indication in how well two materials can be distinguished in a reconstructed volume.

Reconstructions of the datasets presented below were performed using Octopus (www.octopusreconstruction.com) (Vlassenbroeck et al., 2007), a softwarepackage developed at UGCT, using the algorithm of Feldkamp, Davis and Kress (FDK) (Feldkamp et al., 1984).

## Results and discussion

As mentioned before, real scans of an Al sphere and POM cylinder were acquired on HECTOR at a tube voltage from 30kV up to 210kV. Simulations were performed for these scans by using virtual phantoms for both samples. Both real and simulated scans were reconstructed and a line profile at similar places in the real and simulated reconstructed 3D volumes are given in figure 1 (POM) and figure 2 (Al) for the datasets acquired at a tube voltage of 60kV and 120kV. At the other voltages (not shown here) a similar behaviour was found. Both the reconstructed attenuation coefficients and noise for the Al and POM samples are well predicted by Arion over the whole range of energies. The noise level in the simulations is a little higher than the noise in the real scans. This probably originates in the fact that there is a slight smoothening of the real projection images due to the Modular Transfer Function (MTF) of the detector which is supposed to be ideal in Arion.

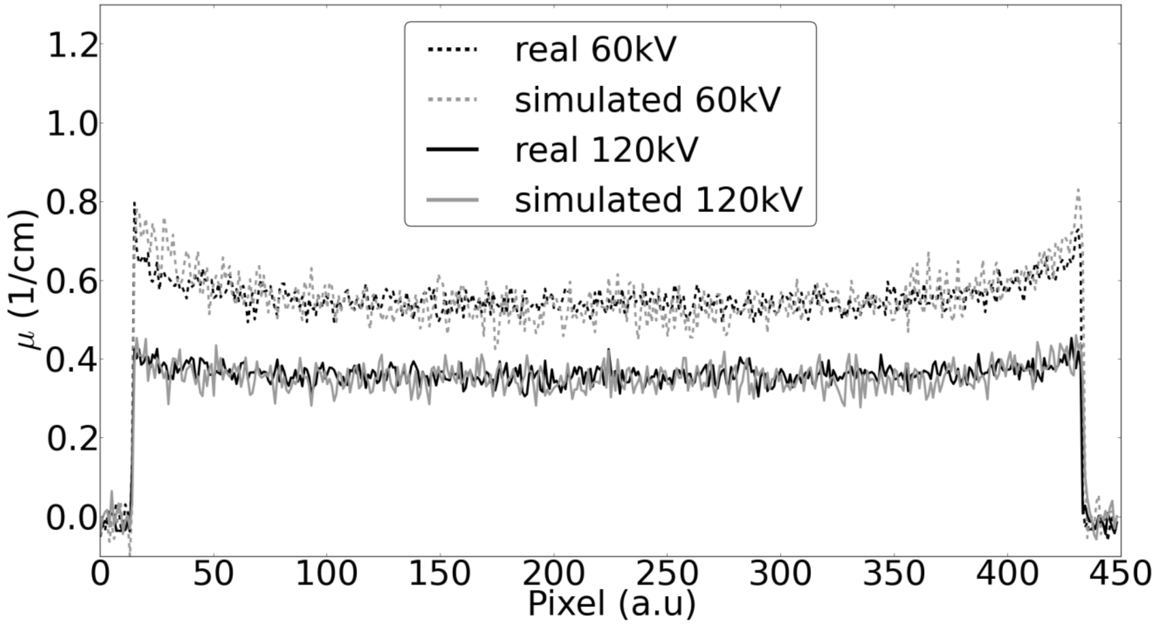

***Fig. 1.*** *Line profile of a reconstructed slice of the POM cylinder. Line profiles of the real and simulated data are compared at a tube voltage of 60kV and 120kV.*

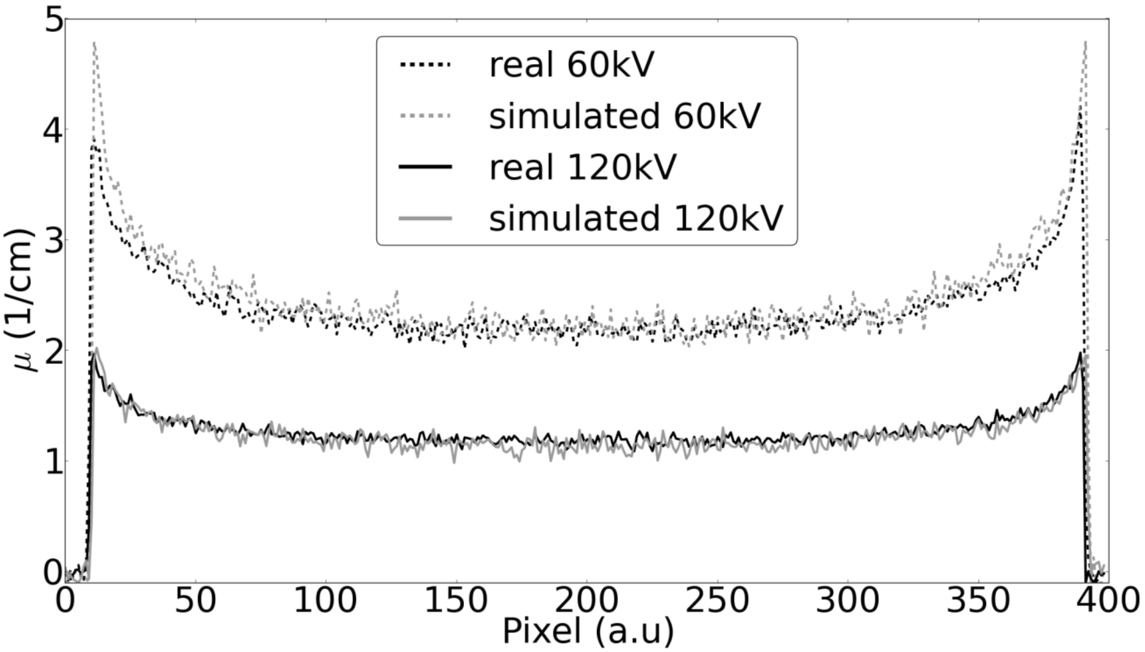

***Fig. 2.*** *Line profile of a reconstructed slice of the Aluminum sphere. Line profiles of the real and simulated data are compared at a tube voltage of 60kV and 120kV.*

Further, Arion was used to scan a virtual butter phantom which contains air and water bubbles (figure 3a). Figure 3b and 3c show reconstructed slices of a simulated dataset at 30kV and 120kV for HECTOR. Figure 4 shows a real scan of a butter sample at HECTOR at the same tube voltages. In both simulated and real reconstructed slices the CNR of water and butter is higher in the 30kV slice than in the 120kV slice. Consequently, the segmentation of water is easier in the 30kV slice than in the 120kV slice. This confirms the usability of Arion to predict the optimal scanning conditions for a certain sample.

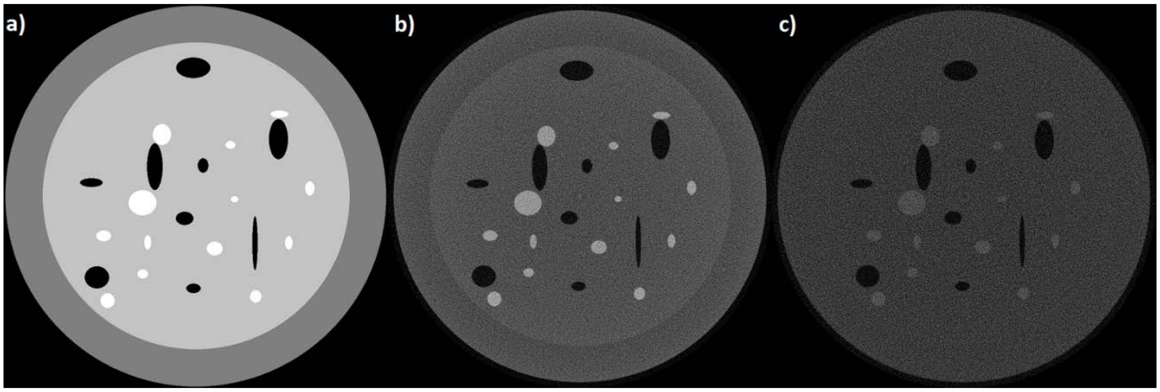

***Fig. 3.*** *A virtual phantom of a plastic cylinder containing butter (left). Inside the phantom there is air (black) and water (white). A reconstructed slice of a simulated dataset, using the phantom, is shown at 30kV (center) and 120kV (right).*

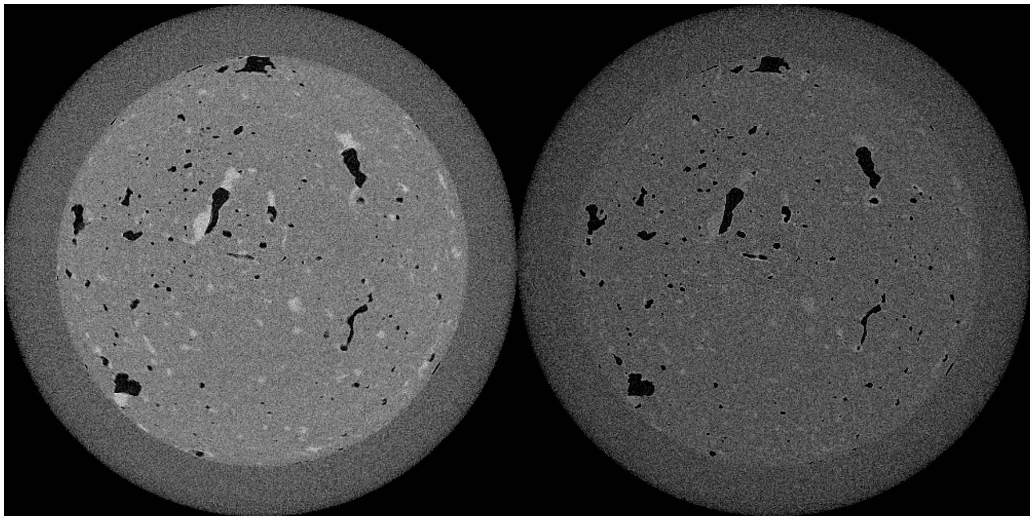

***Fig. 4.*** *A virtual phantom of a plastic cylinder containing butter (left). Inside the phantom there is air (black) and water (white). A reconstructed slice of a simulated dataset, using the phantom, is shown at 30kV (left) and 120kV (right).*

## Conclusion

Simulated and real scans performed at HECTOR for the Al and POM samples are in good agreement with each other over the whole voltage range of HECTOR. From this it can be concluded that simulations performed with Arion reliably predict both reconstructed attenuation coefficients and noise levels in real datasets. The example of optimizing water and fat contrast in a butter sample also confirms this statement. Nevertheless, secondary contributions such as the MTF of the detector can be implemented in Arion in the future to reduce the difference between real and simulated datasets even more.

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