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# New Techniques in Diagnostic X-ray Imaging: a Simulation Tool and Experimental Findings

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**Abstract**

Absorption X-ray imaging is a well-established technique. However it is still a challenging task in its search for a compromise between the need for high spatial resolution and high contrast and the request to keep the dose delivered to the patient within acceptable values. New imaging techniques are under investigation, like the use of new X-ray sources, phase contrast imaging or K-edge imaging. Monte Carlo or analytic simulations are often the best way to test and predict the effectiveness of these techniques. A new simulation tool for X-ray imaging will be presented together with some applications to the characterization of new X-ray sources, in-line phase contrast effect and angiographic K-edge imaging. Simulation results will be compared also with experimental data


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*Keywords:*Monte Carlo simulations, phase contrast imaging, K-edge imaging

## 1. Introduction

In conventional absorption radiography X-rays are used to image the patient. The source is an X-ray tube and the spectral distribution is polychromatic, so the image formation is related to the integral of the absorption of all the spectral components of the beam. New techniques have been developed to go beyond conventional radiography. As

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a few examples are:

- Monochromatic imaging: in some applications, the use of a monochromatic beam can enhance the image quality and/or reduce the dose delivered to the patient. Examples may be mammography (Oliva *et al.*, 2009a), where signal-to noise ratio (SNR) and dose are significantly energy-dependent, or computed tomography (CT) (Alvarez *et al.*, 1976), where the use of polychromatic beam introduces beam-hardening artifacts.
- Phase contrast imaging: Conventional absorption radiography only takes into account differences in the imaginary part of refraction index. However it is also possible to image variations of the real part of the refraction index. In biological samples the visibility of details having a faint absorption contrast may be enhanced by phase contrast imaging techniques (Golosio *et al.*, 2008).
- K-edge imaging: In K-edge subtraction imaging (Peterzol *et al.*, 2005) two simultaneous images are acquired using two monochromatic X-ray beams at two different energies above and below the K-edge of a given element. The image of the element distribution is determined by subtracting the two images.

Simulation (Monte Carlo and/or analytical) tools are often a very useful tool to define/predict optimal working condition for these new modalities as a function of imaging specific application and patient/phantom characteristics.

## 2. Monte Carlo simulations

XRMC (Bottigli *et al.*, 2004; Golosio *et al.*, 2013) is a versatile program that is useful for the simulation of a wide range of X-ray imaging and spectroscopy experiments (Oliva *et al.*, 2009a; Golosio *et al.*, 2008; Brunetti *et al.*, 2013; Cesareo *et al.*, 2013; Piga *et al.*, 2013).
The main characteristics of the XRMC code are described below:

- Programming language: C++
- Operating systems: Linux, Mac OS X, Windows
- Licensing provisions: GNU General Public License version 3
- It enables the simulation of monochromatic and polychromatic X-ray sources, with polarized or unpolarized radiation.
- Single-element detectors or two-dimensional pixel detectors can be used in the simulations, with several acquisition options.
  Three dimensional complex-shape detectors are planned for future releases.
- The sample is modeled by combining convex three-dimensional objects demarcated by quadric surfaces, such as planes, cylinders and ellipsoids.
  In future releases also voxel-based object are planned.
- The Monte Carlo approach makes XRMC able to accurately simulate X-ray photon transport and interactions with matter up to any order of interaction.
- Interaction processes:
  - photoelectric absorption
  - fluorescence emission
  - elastic scattering
  - inelastic scattering

(computed using the xraylib software library (Brunetti *et al.*, 2004; Schoonjans *et al.*, 2011), which is currently the most complete and up-to-date software library for X-ray parameters).

- The use of variance reduction techniques makes XRMC able to significantly reduce the simulation time.
- A tool for analytical simulation of inline phase contrast effects is included in the package

In this paper we will show some applications of the XRMC code:

- Definitions of working parameters of a Thomson backscattering source for absorption mammography
- Evaluation of phase contrast imaging capabilities for this kind of sources
- Preparation of experimental characterization of these sources and predictions of image quality
- The application to the definition of working parameters for new k-edge angio-tomographic system will also be discussed.

## 2. Simulations for Thomson scattering sources

Thomson scattering (TS), i.e. the collision of a high brightness electron beam with a high power laser pulse (Esarey *et al.*, 1993) is a possible way to generate X-rays. The produced radiation is quasi-monochromatic after proper collimation of the radiated photon beam and the mean energy of the beam can be tuned. The fluence rate can be compatible with the requirements of radiography. Hence TS sources represent an appealing alternative to conventional X-ray tubes.

At the Frascati National Laboratories (LNF) of INFN (Istituto Nazionale di Fisica Nucleare), in Italy, a Thomson source is under development (Alesini *et al.*, 2005).
The source will be able to provide a high flux (up to $10^{10}$ γ/s) of quasi-monochromatic photons. The mean energy of these photons can be varied from 20 keV to hundreds keV by changing the electrons energy. By means of XRMC we studied the feasibility of an application of the source to mammography, for both absorption and phase contrast imaging.
We have studied the optimal monochromatic energy to perform absorption imaging, as a function of breast composition and thickness, of lesion type and for different detector models (Oliva *et al.*, 2009a; Oliva *et al.*, 2009b; Oliva *et al.*, 2010a; Bottigli *et al.*, 2006; Di Maria *et al.*, 2009).
Table 1 summarizes these results for a 5 cm-thick breast phantom made of 50% adipose and 50% glandular tissue containing tumor-like masses of thickness 1, 2, 5 and 10 mm. Simulated detector are an ideal one (100% efficient), a digital flat panel detector based on 0.25 mm-thick amorphous selenium (aSe) and an indirect X-ray detection system that takes into account the absorption efficiency of a Gadox screen (82 μm thick).

| t (cm) | Ideal | aSe | GadOx |
|---|---|---|---|
| 2 | 14-16 | 14-16 | 14-16 |
| 4 | 18-22 | 20-21 | 18-19 |
| 6 | 22-25 | 22-23 | 20-22 |
| 8 | 24-33 | 27-28 | 22-25 |

Table 1. Optimal monochromatic energy range (depending on tumor thickness) to image a breast phantom, for different breast thicknesses (t) and different detector types. Energies are expressed in keV.

To evaluate the contribution of main parameters of a TS source we considered the effect of an energy spread and of harmonics on image quality. Results show that an energy spread of 1 keV (standard deviation) reduces image quality of less than 10%, while the reduction of image quality due to energy spread of 3 keV is between 10% and 30%.
The presence of harmonics could affect image quality more appreciably: the ratio of the intensity of the harmonic to the intensity of the fundamental should be kept below 1%.
A realistic TS spectrum was also used in the simulations, showing a reduction of image quality of only 5% (Oliva *et al.*, 2010a), with respect to the monochromatic optimal case.
For comparison, image quality reduction due to the use of a conventional X-ray spectrum was about 30-40%.
XRMC was used also to study the feasibility of inline phase contrast imaging with TS sources (Golosio *et al.*, 2009).
In order to study the possibility of phase contrast mammography using Inverse Compton Scattering (ICS) sources, we made a set of simulation of phase contrast imaging experiments on tumour-like details in breast-like tissue at varying working parameters. The simulated breast was 50% adipose tissue and 50% glandular tissue composition, with density 0.984 g/cm$^3$ and thickness 4 cm. The simulated tumour was a spherical object, diameter variable between 0.2 mm and 5 mm, glandular tissue composition, density 1.044 g/cm$^3$.

The basic parameters of the simulated experimental setup are as follows:

- mean energy E between 16 and 26 keV;
- energy bandwidth ΔE between 0 and 8 keV;
- Mean Glandular Dose 1.5 mGy;
- source linear size (Full Width at Half Maximum, FWHM) 13 μm;
- source–detector distance $z_2$=10 m;
- source–object distance $z_1$ between 1 and 8 m;
- detector Point Spread Function (PSF) between 20 and 120 μm (FWHM).

The optimal energy to perform phase contrast imaging is different from the optimal one for absorption imaging. Phase contrast imaging is generally optimized at higher energies (4-6 keV more than optimal energies for absorption imaging).

The presence of an energy spread does not have a relevant effect on phase contrast: there is only a small variation of visibility as a function of source energy spread.

Considering a fixed source-detector distance of 10 m, it can be observed that the visibility shows a maximum when the object is placed at about 2–3m from the source. At smaller distance, the size of the projection of the source distribution on the detector plays an important role. On the other hand, when the object is very close to the detector, the spatial frequency of the interference patterns due to phase contrast becomes relatively high, and they are suppressed by the convolution with the detector PSF.

XRMC was also used to characterize and predict phase contrast imaging capabilities of the inverse Compton source available at the Accelerator Test Facility at Brookhaven National Laboratory (Golosio *et al.*, 2012; Oliva *et al.*, 2010b).

By means of the Monte Carlo code the optimal experimental setup was defined and phase contrast effect on a polymethyl methacrylate (PMMA) wire was quantitatively estimated.

In figure 1 the visibility of the phase contrast effect (defined as the ratio of peak intensity over background intensity) is shown as a function of source-object distance, for fixed source detector distance. The maximum visibility was at about 140 cm from the source and the object was placed at that distance.

In figure 2 the simulated and experimental acquired profile of a PMMA wire is shown. The phase contrast effect is clearly visible on the borders of the wire.

The experimental results are in agreement with the simulation results within the 2% experimental error.

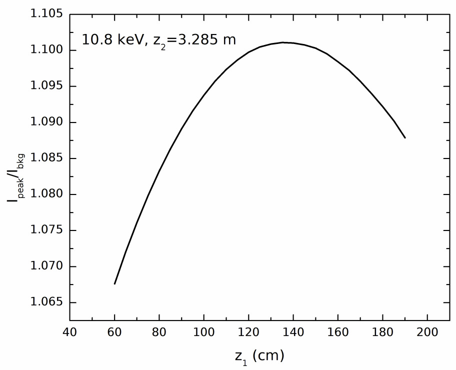


Figure 1. Optimization of the phase contrast visibility as a function of source-object distance ($z_1$) at fixed source-detector distance ($z_2$) for the BNL Inverse Compton source.

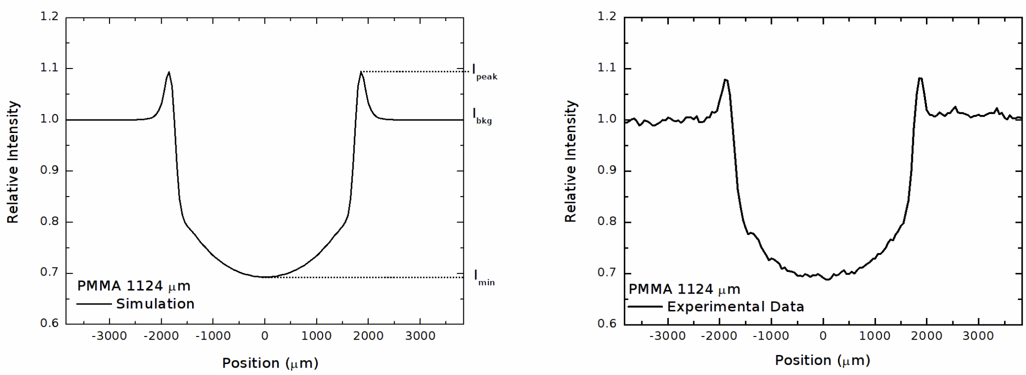


Figure 2. Comparison of simulation (left) and experimental (right) data for phase contrast imaging for a PMMA wire at the BNL Inverse Compton source.

## 4. Angiographic K-edge system

A new angiographic and angio-tomographic technique, based on the use of K-edge filters is under development at the University of Sassari. The system can provide maps of the distribution of the contrast and produce accurate images of the vessels in which the contrast agent is present.

The technique is based on the quasi-simultaneous acquisition of two images, obtained using two different filters at the exit of an X-ray tube. One of the two filters (K-edge filter) contains the same chemical element used as a contrast agent (gadolinium in our study). This filter absorbs more radiation with energy just above the K-edge energy of gadolinium than the radiation with energy just below it. The other filter (an aluminium filter) is simply used to suppress the low-energy contribution to the

spectrum. Using proper calibration curves, the two images are combined to obtain an image of the

contrast agent distribution. In the angio-tomographic application of the proposed technique two images, corresponding to the two filter types, are acquired for each viewing angle of the tomographic scan. From the two tomographic reconstructions, it is possible to obtain a three-dimensional map of the contrast agent distribution. In a preliminary study (Golosio *et al.*, 2014) we tested the technique on a sample consisting of a rat skull placed inside a container filled with water. Six small cylinders with 4.7 mm internal diameter containing the contrast medium at different concentrations were placed inside the skull. The corresponding gadolinium mass percents was evaluated to be 6.5%, 5.1%, 3.6%, 1.9%, 0.96%, and 0.49%, respectively. In the plain angiographic application of the technique, five cylinders were visible, with gadolinium concentration down to 0.96%. In the angio-tomographic application, all six cylinders were visible.

After this encouraging preliminary work, the optimization of the main parameters involved in the technique is now under investigation, both experimentally and by simulations. Optimal anodic voltage and filter thicknesses may vary depending on patient size and composition and on vessel size. Also a limit to the visibility of contrast agent concentration has to be defined as a function of these parameters.

We are currently performing experimental acquisitions using different filter thicknesses (for both Al and Gd filters) at constant anodic voltage, in order to see the dependence of image quality on these parameters.

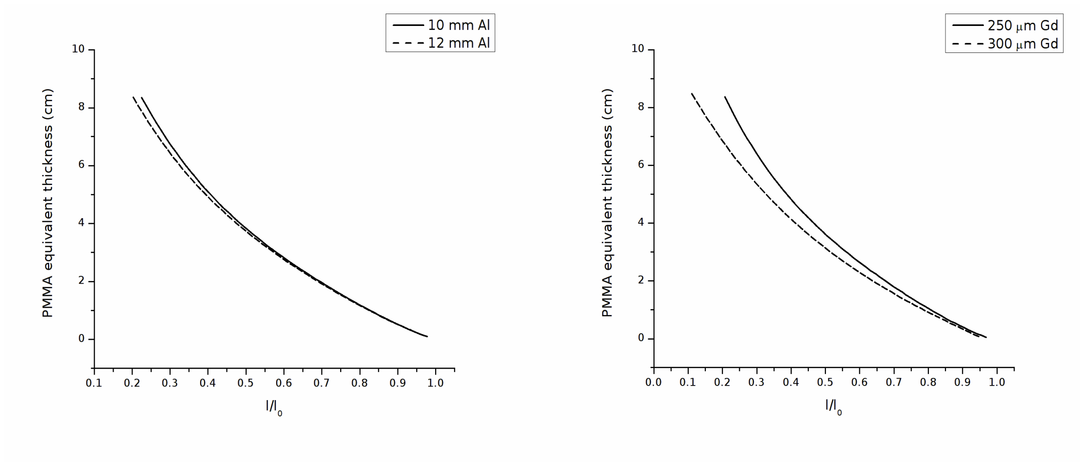


Figure 3. Calibration curves for different filter thicknesses for the aluminum (left) and the gadolinium (right) filter. Tube voltage is 80 kV.

Calibration curves for each filter have been produced by imaging 4 slabs of PMMA (each slab is 2.5mm thick) and a PMMA wedge.
For each filter, counting levels of the images are associated to the corresponding PMMA thicknesses.
The wedge is used for the low-thickness region.
These calibration curves are reported in figure 3. They are used to reconstruct the PMMA equivalent mass thickness in the images. In figure 4 a profile of the calibrated image of a PMMA cylinder having a 4cm diameter is shown.

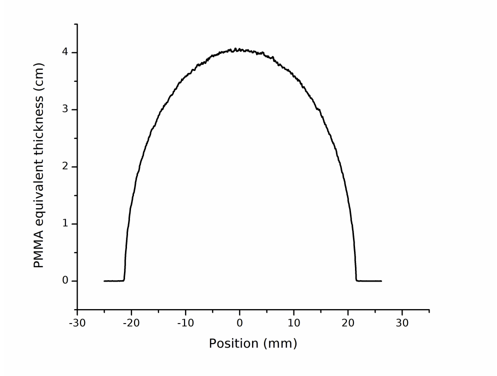


Figure 4. Profile of the reconstructed equivalent thickness of the image of a 4cm PMMA cylinder. The filtration is 10 mm of aluminum.

The two images are hence identical if only biological tissue is present along the X-ray path, while they differ if the contrast medium is present along the path
The signal in the difference of the two calibrated images is only due to the contrast medium, while biological structures are suppressed.

| | 3 mm Al | 5 mm Al | 7 mm Al |
|---|---|---|---|
| 250 μm Gd | 0.0553 | 0.0558 | 0.0560 |
| 300 μm Gd | 0.0634 | 0.0641 | 0.0646 |
| 350 μm Gd | 0.0706 | 0.0715 | 0.0721 |

Table 2. Signal-to-noise ratio as a function of different filtrations for the planar angiographic system.

A large set of simulations will be now performed in order to define the optimal working conditions (anodic voltage, filter thicknesses) for a specific phantom.
In table 2 a preliminary result on the effect of different filtrations on the signal-to-noise ratio is presented. The anodic voltage is 80 kV and the phantom is a cylinder of 40 cm diameter of tissue-equivalent material, containing a 2mm diameter cylinder filled with blood and Gd-contrast agent. Dose-area-product is kept constant at 60 Gy $cm^2$. The simulations show that, under these conditions, higher filtrations allow better SNRs.
Future activity will be devoted to better define the optimal working point, introducing also the anodic voltage as a variable and a realistic limitation to the tube current.

## 5. Conclusions

A precise simulation software is an essential tool in understanding and designing new radiographic techniques.
XRMC offers a large set of options to simulate conventional and innovative radiographic systems, providing affordable results.
Simulation results have been compared with experimental data for a non-conventional X-ray source like the TS ones, showing very good agreement.
A new angiographic and angio-tomographic technique is also presented together with preliminary experimental results and simulation data about the optimization of the technique.

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