A MONTE CARLO APPROACH TO IMAGING AND DOSE SIMULATIONS IN REALISTIC PHANTOMS USING COMPACT X-RAY SOURCE

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Abstract

X-ray emitters are amongst the most widely used tools in medicine. Based on compact electron beams, they are utilised for a range of applications, including medical imaging and cancer treatment. The optimisation of a specific X-ray source relies on detailed simulation studies into the achievable resolution and intensity distribution. Monte Carlo (MC) codes are widely used in the medical community for dose estimation to patients and the environment. They are also ideally suited for simulating 3D intensity distributions in realistic environments. This demands accurate and reliable physical models capable of handling all components of the expected radiation field. In this paper the capabilities of the FLUKA MC code to simulate complex X-ray sources are presented. Advanced phantoms, based on imported DICOM format, are used to evaluate the dose to relevant areas, including the patient, individual organs and the treatment room. It is also shown how they can provide a good basis to reproduce radiography images by scoring photon fluencies.

INTRODUCTION

The diversity of the various X-ray sources have made them quite popular for imaging techniques, such as radiography, Computed Tomography (CT), radioscopy etc. and are utilised in a growing number of applications mainly in the medical field but also in material science and in industry.

Working on the design of a new X-ray imaging system, or on the optimisation of a pre-existing one, one has to face a range of difficult decisions related to the components (i.e. X-ray emitter, detector). The parameters of the equipment (i.e. voltage and current of the X-ray tube, geometrical position, time of exposure) have to be properly optimised usually through lengthy and costly experimental procedures. More often than not the only solution is to resort to trial and error that in reality proves impractical when trying to exhaustively characterise the quantities that affect the final image quality.

Simulations [1] provide a powerful complementary method of study of the suitability and performance of the imaging device components. Moreover, with the MC approach, quantities such as patient dose to sensitive body parts (i.e. brain) or image noise due to metallic implants, can be investigated in a small amount of time and at reasonable costs. This paper showcase the capabilities of the FLUKA MC code in modelling complex realistic scenarios, including the production of x-rays, their effect on a realistic anthropomorphic phantom and the reproduction of radiography images.

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SIMULATION TOOLS

For the purposes of this study we have focused on the use of the Monte Carlo code FLUKA [2, 3] and its advanced graphical user interface Flair [4, 5]. The combination of the two offers a complete package catering fully to the needs of X-ray imaging simulations.

FLUKA

FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, utilised in a wide range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc. FLUKA is capable of simulating with high accuracy the interaction and propagation in matter of about 60 different particles, including photons and electrons from 1 keV (X-ray) to thousands of TeV as well as polarised photons (e.g. synchrotron radiation) and optical photons. Furthermore, it has the capability of accurately scoring radiation relevant quantities such as energy deposition, dose, and particle fluencies, making it an ideal tool for simulating X-ray imaging devices.

Flair

Flair is an advance user-friendly graphical interface for FLUKA. It offers the capability of handling all aspects of FLUKA simulations, from constructing an input file, error checking, geometry debugging to modifying, compiling, and executing user written routines. Furthermore it provides tools for online status monitoring of the simulations, for the processing of the results, and for generations of plots. In addition, by employing a custom 2D/3D fully functional graphical editor [5] and debugger for building geometries it offers real-time 3D rendering of complex geometries as well as a fully customizable dynamic layer toolkit enabling the user to create sophisticated illustrations, of the simulation parameters and results, superimposed on the geometry. The use of the program greatly shortens the time required to complete the simulations, even by beginners, by offering a shallower learning curve. Lastly, an important recent development [6] embedded in the code the capabilities of importing, visualising, processing and converting DICOM [7] files to FLUKA compatible input. With the use of realistic phantoms the simulation results become even more relevant providing specific feedback to the imaging system designer.

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SIMULATION SET-UP

The two main ingredients of a FLUKA simulation, are the characterisation of the source of the radiation and the geometry model description. In order to characterise the X-ray source, one might need to start by simulating the electrons impinging on a target, while for imaging and dose simulations the importation of the geometry from DICOM images is needed.

X-ray Source

The most common X-ray sources are either X-ray tubes (bremsstrahlung) or isotope sources. While the simulations of the latter are quite straight forward and minimum information is required to model (e.g. type, radioactivity, shape, geometry), the simulation of the former can be quite demanding. In order to make accurate predictions of the cathode X-ray tube sources, a plethora of information is required, such as the cathode material, the voltage, the electron current and shape (e.g. spot size), the material of any filters or windows and the collimators geometry.

Once the above details are entered in the FLUKA input it is possible to fully simulate the interactions of electrons and through the use of specialised FLUKA routines, such as MGDRAW or USRMED (both allow you to record particle phase space information at e.g. interaction point or surface crossing), to dump the X-ray spectrum produced. The X-rays can then be sampled directly as a source using a dedicated source routine.

Figure 1 shows the output X-ray spectrum produced by 60keV electrons impinging in 100 µm thick Gold foil with and without Aluminium filters of thicknesses up to 0.5mm. One can identify the characteristic X-rays of Gold and the bremsstrahlung spectrum up to the electron energy. Using this approach one can tune the filter thickness and material of the X-ray generator so that only the bremsstrahlung X-rays survive after the filter, which can be seen for the case of 0.5mm thickness, while less than that is not effective enough.

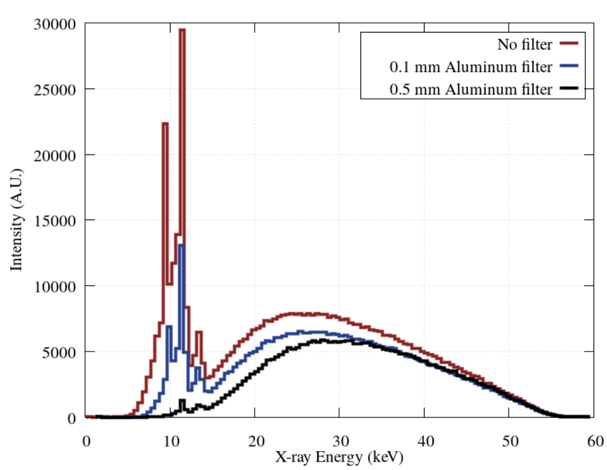

Figure 1: X-ray spectrum produced by 60 keV electrons impinging on 100 µm Gold foil with and without the addition of Aluminium filter.

Realistic Phantom Geometry

Thanks to the newly added capabilities [6] of Flair it is possible to import various DICOM format phantoms that are far more realistic than typical test phantoms most commonly used in medical simulations. The importation is done by grouping the so-called Hounsfield Units (HU), typically found in DICOM images, into groups of voxels and assigning "organ" regions with the same material. These specific ranges of HU values share the same material (based on the Schneider [8] parametrization) and during transport an additional scaling factor is applied on the density for the nuclear and for the electronic processes, based on the real HU value.

Figure 2, shows the visualisation of voxel density of various imported phantoms done with the use of Flair's graphical editor. By filtering according to the density of the voxels found in the DICOM files, one can distinguish between bone, flesh, air, supports, etc. Furthermore, depending on the resolution that the user is interested in, one can import different files with different voxel sizes. In Figure 2, the voxel volume of the full body image is 2.8 10^3 mm^3, of the head image is 2 10^{-2} mm^3 and of the series of teeth and jaw of 8 10^{-3} mm^3, showcasing the flexibility of the tool.

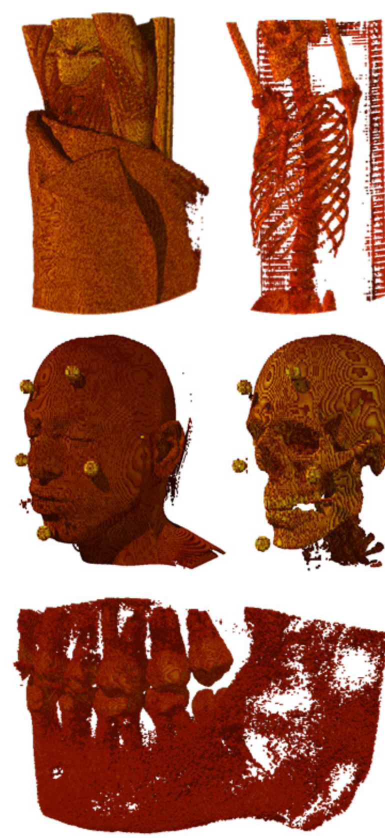

Figure 2: Visualisations using flair's graphical editor of realistic phantoms imported by DICOM files of various resolutions. Bone structured revealed by filtering the image according to voxel density.

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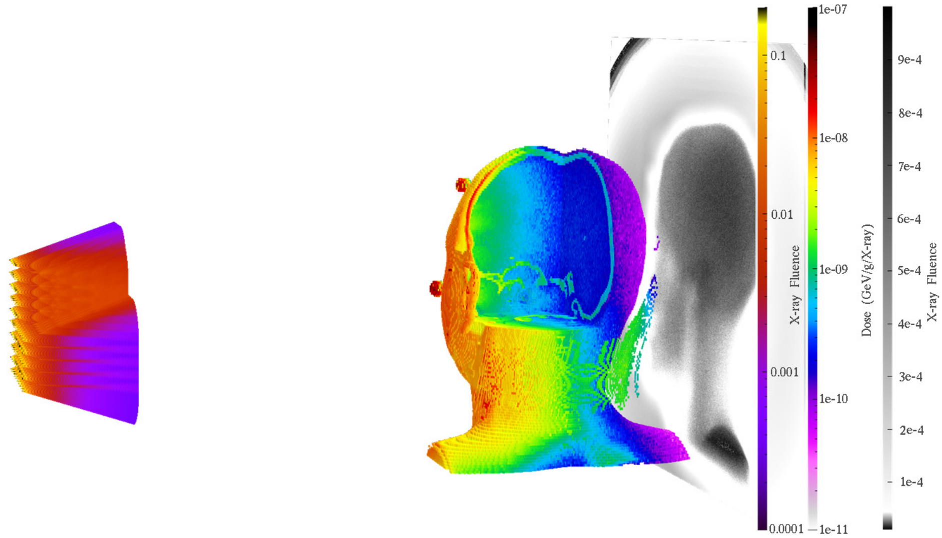

Figure 3: From left to right: Visualisation of the photon fluence by the 10 x 10 array of X-ray sources, 3d map of absorbed dose in the head phantom, image reconstruction (figure 4). The fluence is given in photons/cm^2/primary X-ray and the dose in GeV/g/primary X-ray.

SIMULATED X-RAY IMAGING

As an example of a combination of the previously mentioned capabilities, a human head phantom was used as a target of an array of 100 X-ray sources in a 10 by 10 matrix. For this example a monochromatic beam of 100 keV photons was used with an angular divergence of 30 degrees. A dose scoring FLUKA USRBIN detector is superimposed in the phantom, matching the voxel size of the imported image, and a 2000 x 2000 photon fluence 2D Cartesian USRBIN is placed behind the phantom in order to simulate a 4 megapixel detector. The first USRBIN is easily added using the flair tools, while the second one should ideally match the user's detector resolution. While it is possible at this stage to even fully implement the geometry of the detector, this is a first approach to imaging where this part is skipped and the detector's response to the photon fluence not simulated. However, such studies are routinely done by the community using FLUKA and falls fully within its capabilities.

Figure 3 illustrates the fluence of the initial array of photons (left), the 3d dose map absorbed by the phantom as well as the photon fluence image generated behind it. The results of the simulation are readily available (e.g. dose to the patient per initial photon), easily visualised (enabling the identification of the most exposed areas) and provide immediate feedback to the user in terms of image quality, beam shape/coverage, and patient dose. Quantities are given in terms of average X-ray fluencies (photons/cm^2/primary X-ray) and absorbed dose (GeV/g/primary X-ray). This provides the user with the flexibility of scaling their results to evaluate the dose to the patient by simply multiplying with the beam current and irradiation time.

Figure 4 shows the final produced X-ray image by visualising the photon fluence behind the phantom. As in figure 3 the palette is inverted at lower fluencies to allow for increased contrast at low fluence areas and for better illustration of the characteristics of the image. One can clearly distinguish the bone and flesh structure and shape while the visualisation pattern is user customisable.

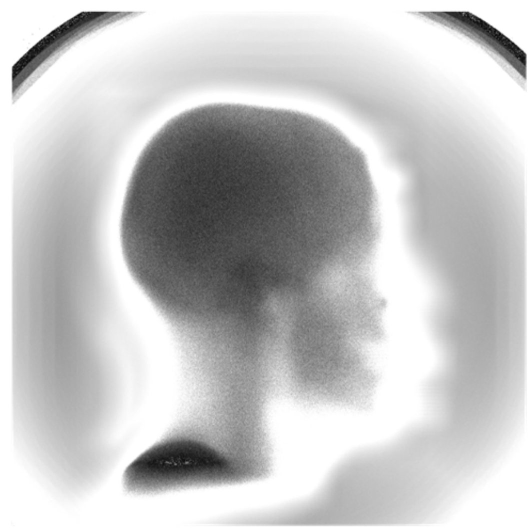

Figure 4: X-ray radiography image reconstruction by visualisation of the X-ray fluence behind the phantom.

CONCLUSION

FLUKA and Flair have proved to be a versatile complete package capable of handling all the different aspects involved in X-ray imaging techniques. This study successfully showcased the possibility of Monte-Carlo studies of the generation and optimisation of the X-ray source, the importation and handling of advanced realistic phantoms using DICOM files in combination with superimposed 3d dose maps, to the generation and quality test of the produced images based on the photon fluence detectors.

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