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    Methods: The simulation is based on the evaluation of
    the Beer-Lambert law and of the Klein-Nishina equation. The
    algorithm is fully determinist and has been fully implemented on
    GPU to achieve clinically acceptable efficiency. A full resolution
    simulation is performed for primary radiation. A much lower image
    resolution is used for Compton scattering as it adds a low frequency
    pattern over the projection image. Each voxel of the CT dataset is
    considered as a secondary source. The number of photons that reach
    each voxel is evaluated. Then, for each secondary source, a projection
    image is computed and integrated in the final image. The photon energy
    between each secondary source and each pixel is also computed.
    An interlaced sampling mode is also proposed to further reduce
    the computation time without sacrificing numerical accuracy. Finally,
    the speed and accuracy are assessed.
    Results: We show that the computations can be fully implemented on
    the GPU with an original under-sampling method to produce clinically
    acceptable results. For example, a simulation can be achieved in less
    than 7 seconds whilst the maximum relative error remains below 5% and
    the average relative error below 1.4%. At full resolution, a speed-up
    by factor  $\sim 12X$  is achieved for the GPU implementation with our
    interlaced-mode by comparison with our multi-threaded CPU
    implementation using 8 threads in parallel.
    Conclusions: DRR calculation with scatter is
    computationally intensive. The use of GPU can achieve clinically
    acceptable efficiency. A Compton fluence map can be computed in a few
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GPU accelerated DRR computation with scatter

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Purpose

We propose a fast software library implemented on graphics processing unit (GPU) to compute digitally reconstructed radiographs (DRRs). It takes into account first order Compton scattering.

Methods

The simulation is based on the evaluation of the Beer-Lambert law and of the Klein-Nishina equation. The algorithm is fully deterministic and has been fully implemented on GPU to achieve clinically acceptable efficiency. A full resolution simulation is performed for primary radiation. A much lower image resolution is used for Compton scattering as it adds a low frequency pattern over the projection image. Each voxel of the CT dataset is considered as a secondary source. The number of photons that reach each voxel is evaluated. Then, for each secondary source, a projection image is computed and integrated in the final image. The photon energy between each secondary source and each pixel is also computed. An interlaced sampling mode is also proposed to further reduce the computation time without sacrificing numerical accuracy. Finally, the speed and accuracy are assessed.

Results

We show that the computations can be fully implemented on the GPU with an original under-sampling method to produce clinically acceptable results. For example, a simulation can be achieved in less than 7 seconds whilst the maximum relative error remains below 5% and the average relative error below 1.4%. At full resolution, a speed-up by factor 12X is achieved for the GPU implementation with our interlaced-mode by comparison with our multi-threaded CPU implementation using 8 threads in parallel.

Conclusions

DRR calculation with scatter is computationally intensive. The use of GPU can achieve clinically acceptable efficiency. A Compton fluence map can be computed in a few seconds using under-sampling, whilst keeping numerical inaccuracies relatively low. This work can be used for CBCT reconstruction to reduce scatter artifacts.



GPU Accelerated Digitally Reconstructed Radiograph Computation with Scatter

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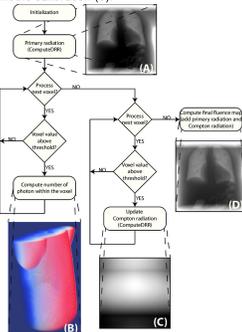
We propose a fast software library to simulate **realistic X-ray images** from computed tomography (CT) data. It takes into account first order **Compton scattering**, *i.e.* the main physical process that decreases the image quality in the range of energies used in diagnostic X-ray imaging. It can be used to produce **more realistic digitally reconstructed radiographs (DRRs)**. The simulation method is **fully deterministic** and we show that it can be implemented on **graphics processor units (GPUs)** with an under-sampling method to achieve **clinically acceptable efficiency**. For example, a simulation can be achieved in **less than 7 seconds** whilst the **maximum relative error remains below 5%** and the **average relative error below 1.4%**.

1. Introduction

To date, digitally reconstructed radiographs are often restricted to primary radiation computed using the Beer-Lambert law and Siddon's algorithm. Higher level of physics fidelity is, however, possible, *e.g.* using Monte Carlo trials (1), but this method is computationally too expensive for clinical applications. Analytic methods have also been proposed to take into account photon scattering (2). We exploit this deterministic approach on the GPU to produce physically realistic images.

2. Simulation Pipeline

DICOM files are directly imported and converted into material properties (density and chemical composition) using a stoichiometric calibration (3).

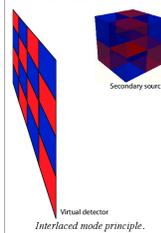


- (A) A full resolution simulation is first performed for primary radiation.
 (B) The number of photons reaching each voxel is evaluated. Each photon becomes a secondary source emitting scattered photons. A threshold is set to skip all voxels made of air.
 (C) For each valid voxel, a low resolution DRR image is computed and the resulting image is integrated into the scattering map.
 (D) The final energy fluence image is computed combining the primary radiation with the scattering image.

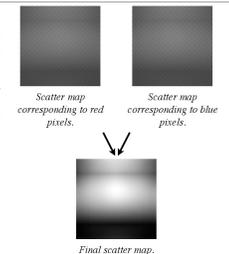
References

- (1) S. Jan et al. GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy. *Phys. Med. Biol.*, 56:881-901, 2011.
- (2) N. Freud et al. Deterministic simulation of first-order scattering in virtual X-ray imaging. *Nucl Instrum Methods Phys Res B*, 222(1-2):285-300, 2004.
- (3) W. Schneider et al. Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions. *Phys. Med. Biol.*, 45(2):459-478, 2000.

3. Interlaced Mode

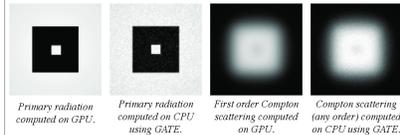


An interlaced mode is also introduced so that only half of an image is computed for each secondary source. For each red voxel, only the red pixels of the virtual detector are evaluated. The similar principle applies to the blue voxels and pixels. Holes are then filled in each temporary scatter map using bi-linear interpolation. Edges are processed as special cases. This method does not introduce aliasing and it is more advantageous than a brute-force undersampling.

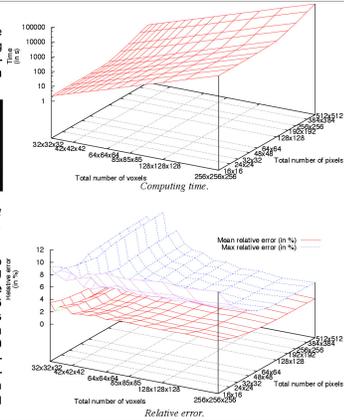


4. Results

A plate of soft tissue (size = 50×50×5 mm³, and HU = 50) with a hole (size = 10×10×5 mm³, and HU = -1000) in the middle is simulated using i) our fully deterministic method on GPU without the interlaced-mode, and ii) the Monte Carlo method implemented in GATE. Both methods provide similar results.



A batch of tests has been performed using the NCAT phantom to assess both the accuracy and the performance of the GPU implementation using a Nvidia Tesla C1060 card. A reference image (512×512 pixels) has been computed on the GPU using 256×256×256 voxels without the interlaced-mode in 48 hours. About 315 hours are required to compute the same image using parallel computing on CPU (8 threads) on a computer with two quad-core Intel Xeon E5410 processors at 2.33 GHz. 26 hours were required with the interlaced-mode on the GPU. Since it is not clinically acceptable, under-sampling has to be used. Therefore, the test images have been simulated on the GPU using our interlaced-mode with varying volume and image resolutions.



5. Conclusion

A speed-up factor of 12X is achieved between the GPU implementation with our interlaced-mode and our multi-threaded CPU implementation using 8 threads. An acceptable Compton fluence map can be computed in a few seconds (< 7sec) using under-sampling whilst keeping the numerical inaccuracy low (error max < 5%, mean error < 1.4%). This work can be used for CT and CBCT reconstruction to reduce scatter artefacts.

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Figure 1: Poster presented at AAPM Annual Meeting, Vancouver, Canada, Jul 31–Aug 4, 2011.