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Introduction

Undersampled imaging strategies with cutting edge reconstruction methods like compressed sensing, which reformulate image reconstruction as a constrained optimization problem [1,2], have the potential to deliver images with high spatial and temporal resolution. This is of great importance for application like time resolved MR angiography, because the acquisition window is limited by the passage of the contrast agent. The major drawback of these algorithms is their long reconstruction time which makes it impossible to use them in clinical practice. It was shown recently that it is possible to use the massively parallel streaming processor architecture of modern graphic processing units (GPUs) to speed up image reconstruction for parallel imaging [3]. In this work, we show that optimization problems as encountered in compressed sensing can be solved on the GPU, with computation times that allow real time imaging.

Theory

It has been shown recently that streaking artifacts from radially subsampled datasets can be removed efficiently with Total Variation (TV) penalties [2]. Our TV implementation is based on the ROF image denoising model [4]

$$\min_x \left\| x - x_0 \right\|_2^2 + \lambda TV(x), \quad (1)$$

where x_0 is the original 3D image space data set with streaking artifacts due to subsampling, x is the reconstructed stack of images and λ is a parameter that controls the amount of regularization. $TV(x)$ is the sum of the absolute values of the derivatives at all pixel positions, which can be calculated from the finite differences between neighboring pixels. The GPU implementation is based on the idea that the minimum of this functional can be found by solving the associated discretized Euler-Lagrange equation for each pixel in the data set [5]. Using this formulation, it is possible to parallelize the computation process by calculating a solution for each individual pixel in the data set. Each of these computations can be done in a different thread on the GPU. As the 3D TV constraint is evaluated in 3D, optimal performance of the algorithm is achieved when the streaking artifacts appear in a different pattern in adjacent slices. This can be achieved by using a 3D stack of stars trajectory with projection angles of adjacent slices being shifted by $\pi/(2k)$, when k is the number of projections (see Fig.1).

Methods and Results

A CE MRA dataset of the carotid arteries was acquired on a clinical 3T scanner, using a 3D FLASH sequence. Sequence parameters were TR=3.74ms, TE=1.48ms, FA=20°, Matrix Size(x,y,z)=448×352×40, voxel size(x,y,z)=0.55mm×0.55mm×0.70mm. Images were subsampled in the xy-plane retrospectively, to simulate an accelerated acquisition. 80 and 40 projections were obtained, using the proposed stack of stars trajectory with shifted projection angles. No acceleration was used in the z-direction. Reconstructed images showed significantly reduced aliasing artifacts in comparison to conventional regridding reconstructions (see Fig.2). Using a CUDA [6] implementation of the proposed algorithm on an Nvidia Gforce GTX 280 GPU, we achieved a reconstruction time of 0.24s for the whole 3D data set. In comparison, reconstruction took 9min using a Matlab (The MathWorks, Natick, MA) CPU implementation of the same algorithm. This corresponds to a speedup of 2300 with the GPU implementation.

Discussion

Our reconstructions show excellent removal of undersampling artifacts even at high acceleration factors. Vessels with their strong contrast are preserved because the L2 norm in the data fidelity term makes the removal of structures contrast dependent. While the use of our data fidelity term in image space shows excellent performance for angiography data sets because the structures of interest have a high contrast to noise ratio, the evaluation of the data fidelity term in k-space will allow the use of the algorithm for other applications. Future work will also include the investigation of the algorithm's performance when additional acceleration is used in the second phase encoding (z) direction. The GPU implementation facilitates image reconstruction times that are significantly lower than the corresponding acquisition times. Therefore, image reconstruction is no longer the time limiting step in the imaging chain. We believe that this can pave the way for these reconstruction strategies, currently promising research topics, to become powerful tools in daily clinical practice.

Acknowledgements

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References

[1] Lustig et al., MRM 58: 1182-1195 (2007), [2] Block et al., MRM 57: 1086-1098 (2007), [3] Hansen et. al., MRM 59: 463-468 (2008), [4] Rudin et al. Phys. D, 60(1-4) 259-268, 1992, [5] Pock et al., CVGPU Workshop CVPR 2008, [6] NVIDIA Corporation, NVIDIA CUDA – Programming Guide (2007)

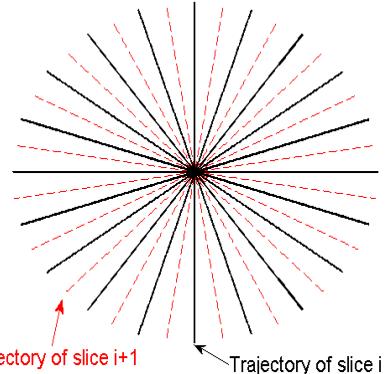


Fig. 1: 3D stack of stars trajectory with shifted projection angles.

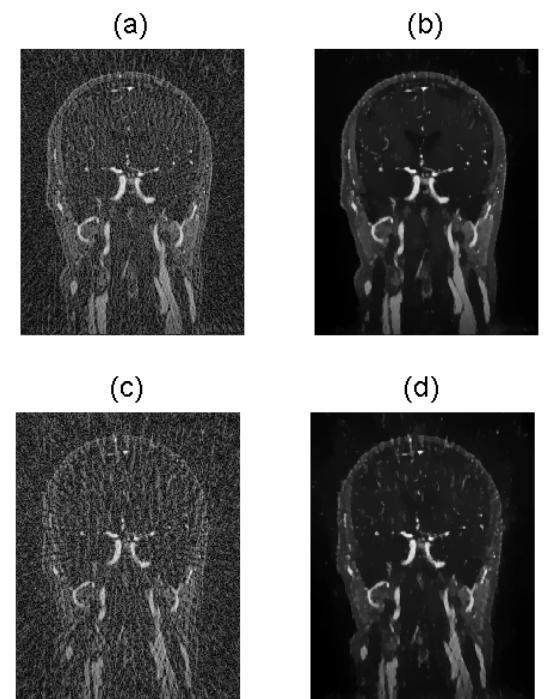


Fig. 2: CE MRA Dataset of the carotid arteries:
 (a) 80 projections, conventional reconstruction
 (b) 80 projections, proposed method
 (c) 40 projections, conventional reconstruction
 (d) 40 projections, proposed method