Implementations of statistical reconstruction algorithm for CT scanners with flying focal spot

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ABSTRACT

This paper presents some practical realizations of image reconstruction methods for spiral cone-beam tomography scanners in which an X-ray tube with a flying focal spot is used. These methods are related to the original formulated 3D statistical model-based iterative reconstruction approach for tomography with flying focal spot. The conception proposed here is based on principles of a statistical model-based iterative reconstruction (MBIR) methodology, where the reconstruction problem is formulated as a shift-invariant system (a continuous-to-continuous data model). We adopted nutating reconstruction-based approaches, i.e. the advanced single slice rebinning methodology (usually applied in CT scanners with X-ray tubes with a flying focal spot), and a procedure compliant with the FDK scheme. We showed that our methods significantly improve the quality of obtained images compared to the traditional FBP algorithms. Consequently, it can allow for a reduction in the x-ray dose absorbed by a patient. Additionally, we show that our approach can be competitive in terms of the time of calculations, especially if we consider commercially used statistical reconstruction systems.

Keywords: Spiral computed tomography, flying focal spot, statistical iterative reconstruction algorithm

1. INTRODUCTION

Despite the long history of medical computed tomography, the search for new designs of CT scanners still continues, and at the beginning of the XXIth century, one such new design was the spiral scanner with an X-ray tube with a flying focal spot.[1] The intention of this new technique was to increase the sampling density of the integral lines in the reconstruction planes, and the density of simultaneously acquired slices in the longitudinal direction. Of course, this technique is realized in multidetector row CT (MDCT) scanners but there it allows for view-by-view deflections of the focal spot in the rotational α-direction (αFFS) and/or in the longitudinal z-direction (zFFS). Thanks to this, it is possible to improve the quality of the reconstructed images, mainly throughout decreasing the influence of the aliasing effect in the reconstruction plane and in the z-direction, and additionally, causing a reduction of the so-called windmill artifacts. Obviously, implementation of the FFS entailed the necessity of formulating new reconstruction methods that allow for the use of measurements obtained from scanners equipped with this technique. In practice, manufacturers decided primarily to modify the adaptive multiple plane reconstruction (AMPR) method for this purpose. The AMPR conception belongs to the class of so-called nutating reconstruction methods, and is a development of the advanced single slice rebinning (ASSR) algorithm.[2] Generally, nutating methods have several serious drawbacks, among others, there is a problem with obtaining equi-spaced resolution of the slices in z-direction, due to the constant change in the position of successive reconstruction planes. Another big problem is its limited ability to suppress noise, caused by the linear form of the filters that are used during signal processing in those methods. This means that it cannot be considered for CT systems that aim to reduce the dose of X-ray radiation absorbed by patients during examinations. Recent research in the area of X-ray computed tomography, including our own investigations, is

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mostly focused on this challenge, because of the extremely harmful effect that CT examinations have on human health. On the other hand, nowadays, the most interesting research directions in the area of CT are statistical reconstruction approaches, especially those belonging to the model-based iterative reconstruction (MBIR) class of methods,[3] and some commercial solutions have been developed, which conduct the reconstruction process in an iterative way, which aims to suppress noise in the obtained images. Unfortunately, the MBIR methods used commercially (the iterative coordinate descent (ICD) algorithm[4] have some serious drawbacks, namely, the calculation complexity of the problem is approximately proportional to I^4, where I is the image resolution, and the iterative reconstruction procedure based on this conception necessitates simultaneous calculations for all the voxels in the range of the reconstructed 3D image. Moreover, the size of the forward model matrix $\mathbf{A}$ is extremely large and it has to be calculated online. The reconstruction problem used there is also extremely ill-conditioned.[5] The methodology mentioned above is classified as a method based on the discrete-to discrete (D-D) data model. All those drawbacks can be reduced by using an approach that is formulated based on a continuous-to-continuous (C-C) data model. It should be underlined, that our conception has some significant advantages over that based on the D-D model. First of all, in our method, the forward model is formulated as a shift invariant system, which allows for the use of FFT algorithms in the most computationally demanding elements of the reconstruction algorithm (realization of the 2D convolutions in the frequency domain). Furthermore, we can pre-calculate the model matrix (coefficients), i.e. we establish it before the algorithm is started. Additionally, the reconstruction process can be carried out in only one plane in 2D space, which greatly simplifies the reconstruction problem, and it is possible to obtain every slice of the body separately. Our approach also outperforms the D-D method already at the level of problem formulation, regarding the better condition number.[5] Finally, the presented here concept using the statistical reconstruction approach developed by us, can be in easy way used for spiral CT scanners with a flying focal spot technique.

2. RECONSTRUCTION ALGORITHMS

Our reconstruction approach is based on the well-known maximum-likelihood (ML) estimation, where an optimization formula is consistent with the C-C data model, as follows:

$$\mu_{\min} = \arg\min_{\mu} \left(\int_{x} \int_{y} \left(\int_{\bar{x}} \int_{\bar{y}} \mu\left(\bar{x}, \bar{y}\right) \cdot h_{\Delta x, \Delta y} d\bar{x} d\bar{y} - \tilde{\mu}\left(x, y\right) \right)^{2} dxdy \right), \tag{1}$$

where $\tilde{\mu}\left(x, y\right)$ is an image obtained by way of a back-projection operation (without filtration), and the coefficients $h_{\Delta i, \Delta j}$ can be precalculated according to the following relation:

$$h_{\Delta x, \Delta y} = \int_{0}^{2\pi} int\left(\Delta x \cos\alpha + \Delta y \sin\alpha\right) d\alpha, \tag{2}$$

and $int\left(\Delta s\right)$ is a linear interpolation function.

The presence of a shift-invariant system in the optimization problem (1) implies that this system is much better conditioned than the least squares problems present in the referential approach.[5]

According to the formulated by us iterative approach to the reconstruction problem, decribed by Eqs (1)-(2), it is possible to show a practical model-based statistical method of image reconstruction, as follows:

$$\mu_{\min} = \arg\min_{\mu} \left(\sum_{i=1}^{\mathrm{I}} \sum_{j=1}^{\mathrm{I}} \left(\sum_{\bar{i}=1}^{\mathrm{I}} \sum_{\bar{j}=1}^{\mathrm{I}} \mu^{*}\left(x_{\bar{i}}, y_{\bar{j}}\right) \cdot h_{\Delta i, \Delta j} - \tilde{\mu}\left(x_{i}, y_{j}\right) \right)^{2} \right), \tag{3}$$

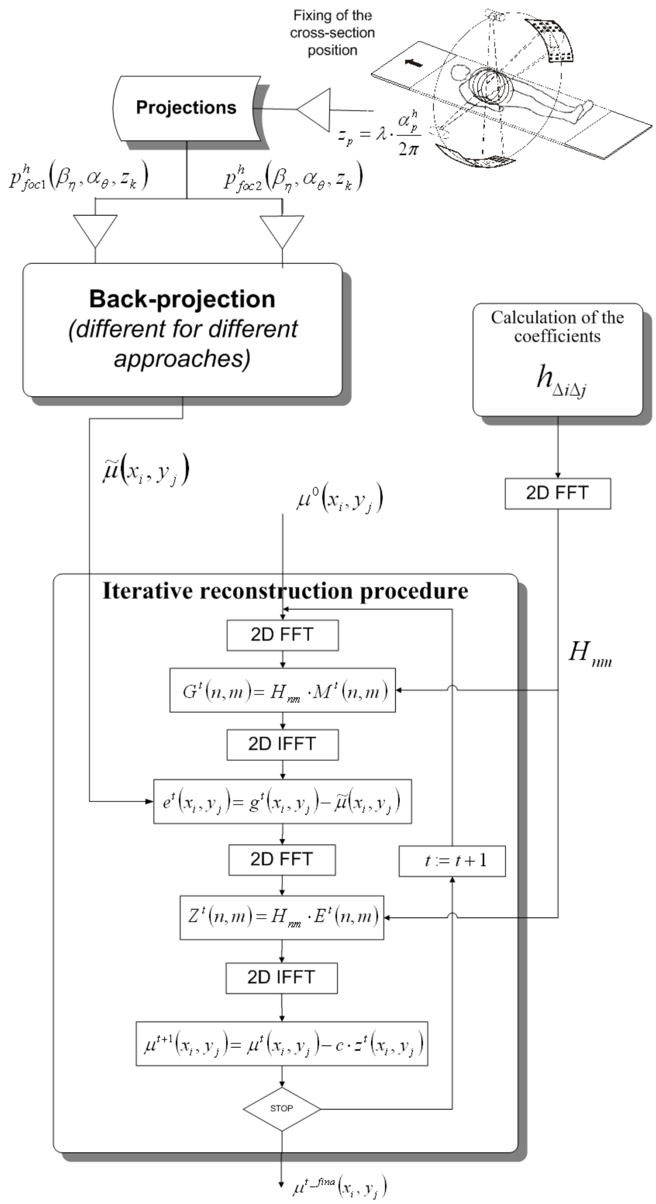

Figure 1. General statistical reconstruction algorithm for spiral cone-beam scanner with flying focal spot.

where I is a resolution of the reconstructed image, $\tilde{\mu}(i, j)$ is an image obtained by way of a back-projection operation, and coefficients $h_{\Delta i, \Delta j}$ are determined according to the following formula:

$$h_{\Delta i, \Delta j} = \frac{1}{{\Delta_s}^2} \Delta_\alpha \sum_{\psi=0}^{\Psi-1} int \left(\Delta i \cos \psi \Delta_\alpha + \Delta j \sin \psi \Delta_\alpha \right), \tag{4}$$

wherein $int(\Delta s)$ is an interpolation function used in the back-projection operation, and $\Delta_s = R_f * \tan \Delta_\beta$.

Figure 1 depicts this general algorithm after discretization and implementation of FFT which significantly accelerates the calculations.

Between all approaches to image reconstruction problem using projections obtained in the spiral scanner with flying focal spot there is only one difference: determination of the image obtained after back-projection

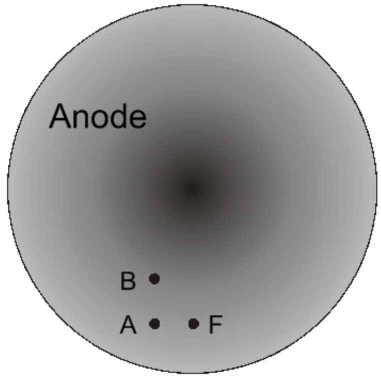

Figure 2. The movement of focal spot with flying spot technique used in our experiments.

Table 1. Combination of α-direction and z-direction deviations

Parameter/Focal spot	R^{fs}	α	$\dot{z}$
A	0	$\delta\alpha^A$	0
B	δR^B	$\delta\alpha^B$	$\delta\dot{z}^B$

operation. Up to now, we have formulated the following approaches to determine the image $\tilde{\mu}(i,j)$: method which uses spiral cone-beam projections directly, similar to FDK-type algorithms,[6] methods belonging to the class of nutating reconstruction algorithms (based on the advanced single slice rebinning) methodology, using projections from different focal spots separately,[7] and together (unpublished).

3. EXPERIMENTAL RESULTS

All our experiments were carried out using projections obtained from a Somatom Definition AS+ (helical mode) scanner with the following parameters: reference tube potential 120kVp and quality reference effective 200mAs. The geometrical parameters of this scanner are as follows: $R_{fd} = 1085.6mm$, $R_f = 595$mm, number of views per rotation $\Psi = 1152$, number of pixels in detector panel 736, detector dimensions 1.09mm $\times$ 1.28mm. During experiments, we used the spiral CT scanner with only two flying spot positions, as shown in Fig. 2.

The focus position A is involved with movement in α-direction, and the focus position B corresponds to the focal movement both in α-direction and in z direction. The deviations of the geometrical parameters are summarized in Table 1.

The size of the reconstructed image was fixed at 512×512 pixels. A discrete representation of the matrix $h_{\Delta i,\Delta j}$ was established in a computational way before the reconstruction process was started. These coefficients were fixed (transformed into the frequency domain) and used for the whole iterative reconstruction procedure. A prepared result of an FBP reconstruction algorithm was chosen as the starting point of the iterative reconstruction procedure (using projections obtained from the focal spot position A).

A crucial parameter for the practical implementation of a reconstruction method is the actual computation time of the reconstruction procedure. We have implemented our iterative reconstruction procedure using some hardware configurations, namely: a computer with 10 cores, i.e. with an Intel i9-7900X BOX/3800MHz processor (our iterative procedure was implemented at assembler level), using different GPUs (see 3). In table 2, we show time result for application which is working only on CPU which is develop in Assembler (special vector registers AVX 512 used). In turn, in table 3, we present time result for application which is working only on GPU accelerators. There are compared those accelerators. It is worth noting that it is very stable time, because deviation is extremely small and that application is very susceptible to parallelisation, because time for one iteration it is getting smaller with on more CUDA Cores assembled in GPU Accelerator.

According to an assessment of the quality of the obtained images by a radiologist, 7000 iterations are enough to provide an acceptable image for medical purposes. One can compare the results obtained by assessing the views of the reconstructed images in Figure 3, where where the quarter-dose projections were used.

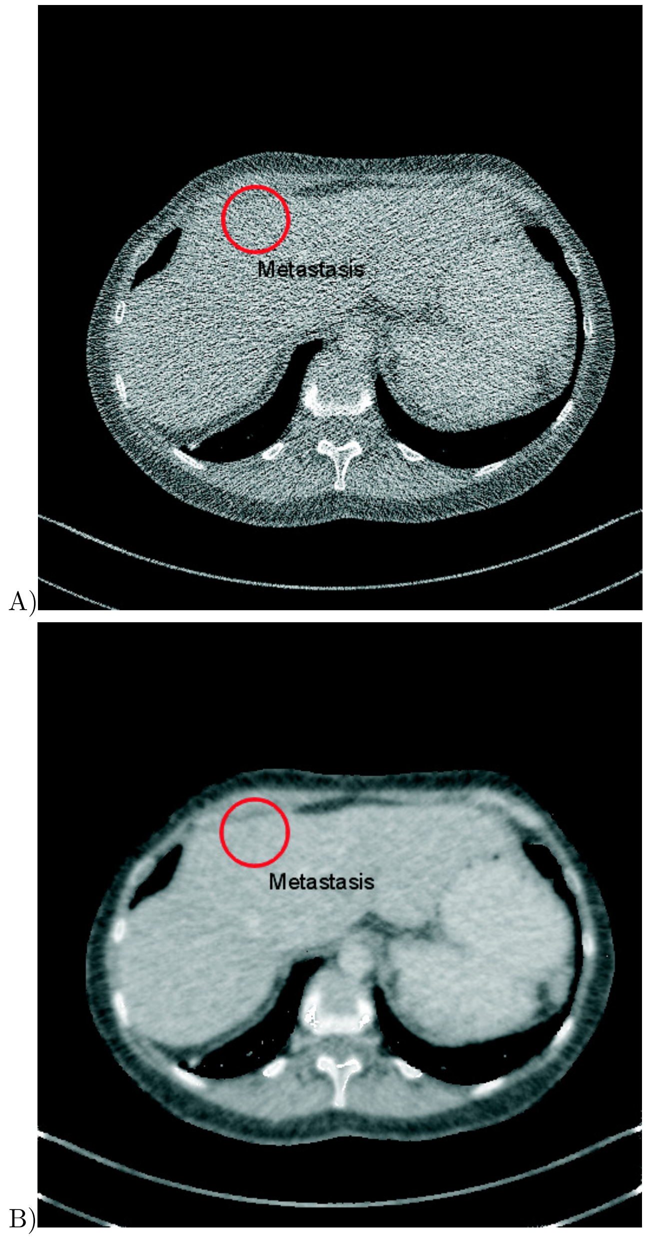

Figure 3. Obtained images (a case with relative small pathological change in the liver) using quarter-dose projections with application of: the standard FDK algorithm (focal spot position A) (A); the statistical method presented in this paper (FDK scheme with both focal spot positions) (B).

Table 2. Times results of reconstruction image on multi threading CPU: Intel i9-7900X (10-cores, 20-treads). An application created in the assembler programming language with multithreading

Threads:	4	8	10	16	20
Avg. time 30000[ms]	63 724,36	33 571,42	29 836,34	30 532,14	27 905,62
Avg. time 20000[ms]	42 482,91	22 380,95	19 890,89	20 354,76	18 603,75
Avg. time 10000[ms]:	21 241,45	11 190,47	9 945,45	10 177,38	9 301,87
Time 1 iteration [ms]:	2,124145	1,119047	0,994545	1,017738	0,930187
HT effectiveness:	-	-	-	0,909468	0,935290
Median for 30000:	63 694	33 542,5	29 800	30 566	27 854
Deviation std.:	135,69	117,32	217,58	193,88	391,76

Table 3. Times results of reconstruction image on different models GPU accelerator. An application created in the CUDA programming language

GPU:	MSI GTX 1050	ASUS GTX 1080 Ti	nVidia Titan V
Avg. time 30000[ms]	2 562 175,10	49 699,71	28 858,40
Avg. time 20000[ms]	170 845,28	33 132,52	19 224,48
Avg. time 10000[ms]:	85 467,24	16 593,00	9 616,75
Time 1 iteration [ms]:	8,540583	1,656657	0,961947
Median for 30000:	256 229,55	49 703,68	28 861,24
Deviation std.:	0,160806	0,310476	0,010239

4. CONCLUSION

In this paper, it has been shown that our statistical approach, which was originally formulated for CT scanner with parallel beam geometry, can be adapted for helical scanner with flying focal spot technique. We have presented a fully feasible statistical reconstruction for cone-beam CT. Comprehensive experiments have been performed, which prove that our reconstruction method is relatively fast (thanks to the use of FFT algorithms) and gives satisfactory results with suppressed noise. It should be noted that approximately the same results were achieved for both hardware implementations: the iterative reconstruction procedure takes less than 7s, mainly thanks to the use of an FFT algorithm in the iterative reconstruction procedure and to the use of the efficient programming techniques. These are rewarding results regarding possibilities of the commercial Veo system (referential MBIR technique), where reconstruction times range between 10 to 90 minutes depending on the number of reconstructed slices.[8] It means an unacceptable delay between data acquisition and availability for interpretation for emergent indications. Additionally, all formulated by us reconstruction algorithms are very easy to implement and open to use multisource techniques regardless the kind of the focal spot movement (both z and angle flying).

REFERENCES

[1] Kachelrieß, M., Knaup, M., Penßel, C., and Kalender, W., "Flying focal spot (ffs) in cone-beam ct," *IEEE Trans. on Nuc. Sci.* **53**, 1238–1247 (2006).

[2] Kachelrieß, M., Schaller, S., Penßel, C., and Kalender, W., "Advanced single-slice rebinning in cone-beam spiral ct," *Med. Phys.* **27**, 754–773 (2000).

[3] Zhou, Y., Thibault, J.-B., Bouman, C., Hsieh, J., and Sauer, K., "Fast model-based x-ray ct reconstruction using spatially non-homogeneous icd optimization," *IEEE Tran. Im. Proc.* **20**, 161–175 (2011).

[4] Thibault, J.-B., Sauer, K., and Bouman, C., "A three-dimensional statistical approach to improved image quality for multislice helical ct," *Med. Phys.* **34**, 4526–4544 (2007).

[5] Cierniak, R. and Lorent, A., "Comparison of algebraic and analytical approaches to the formulation of the statistical model-based reconstruction problem for x-ray computed tomography," *Computerized Medical Imaging and Graphics* **52**, 19–27 (2016).

[6] Cierniak, R., Pluta, P., Waligóra, M., Szymański, Z., K. Grzanek, F. P., and Piuri, V., "A new statistical reconstruction method for the computed tomography using an x-ray tube with flying focal spot," *Journal of Artificial Intelligence and Soft Computing Research* **11**, 271–286 (2021).

[7] Cierniak, R., Pluta, P., and Kaźmierczak, A., "A practical statistical approach to the reconstruction problem using a single slice rebinning method," *Journal of Artificial Intelligence and Soft Computing Research* **10**, 137–149 (2020).

[8] Geyer, L., Schoepf, U., Meinel, F. G., Jr, J. N., Bastarrika, G., Leipsic, J., Paul, N., Rengo, M., Laghi, A., and Cecco, C. D., "State of the art: iterative ct reconstruction techniques," *Radiology* **276**, 339–357 (2015).