Cardiac C-Arm CT

SNR Enhancement by Combining Multiple Retrospectively Motion Corrected FDK-Like Reconstructions

M. Prümmer[1], L. Wigström[2,3], R. Fahrig[2], G. Lauritsch[4], J. Hornegger[1]

[1]Institute of Pattern Recognition, FA University Erlangen-Nuremberg, Germany
[2]Department of Radiology, Stanford University, USA
[3]Center for Medical Image Science and Visualization, Linköping University, Sweden
[4]Siemens AG, Medical Solutions, Forchheim, Germany
Email: pruemmer@informatik.uni-erlangen.de

Abstract. Cardiac C-arm CT is a promising technique that enables 3D cardiac image acquisition and real-time fluoroscopy on the same system. Retrospective ECG gating techniques have already been adapted from clinical cardiac CT that allow 3D reconstruction using retrospectively gated projection images of a multi-sweep C-arm CT scan according to the desired cardiac phase. However, it is known that retrospective gating of projection data does not provide an optimal signal-to-noise-ratio (SNR) since the measured projection data is only partially considered during the reconstruction. In this work we introduce a new reconstruction technique for cardiac C-arm CT that provides increased SNR by including additional corrected and resampled filtered back-projections (FBP) from temporal windows outside of the targeted reconstruction phase. We take advantage of several motion corrected FDK-like reconstructions of the subject to increase SNR. In the presented results, using in vivo data from an animal model, the SNR could be increased by approximately 30 percent.

1 Introduction

The combination of real-time projection imaging with 3D imaging modalities in the interventional suite is becoming more important as procedures increase in complexity. One such combination, x-ray fluoroscopy with cardiac C-arm CT, is under development. Retrospectively ECG gated FDK [1] reconstructions (RG-FDK) provide promising image quality for cardiac C-arm CT as shown by Lauritsch et al. [2]. Image presentation during a procedure often requires new imaging algorithms for segmentation and image registration, and such algorithms have stringent need for high image quality including signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). In cardiac C-arm CT, the retrospective selection of projection images whose ECG time is closest to the cardiac phase that is desired for reconstruction considers only $\frac{1}{N_s}$ of the measured projection data of an e.g. $N_s \times 4s$ multi-sweep scan, which does not maximize the potential SNR of the 3D reconstructions. In this work we introduce a technique that allows use of all projection images from a multi-sweep scan and therefore can provide enhanced SNR in the reconstructed volume. A similar approach for respiratory motion correction and SNR enhancement was introduced by Li et al. [3]. The approach we introduce is a trade-off between the spatial resolution provided by a retrospectively ECG gated FDK reconstruction using only a selected subset of all acquired projection images and a reconstruction that uses all measured projection data (and therefore has good SNR) but may exhibit reduced spatial resolution due to approximations applied during the temporally dependent spatial motion correction.

2 Methods

Let P be the set that contains all acquired projection images of a multi-sweep scan, then P^t is a subset of P that provides the retrospectively selected projection images of cardiac phase t (defined in percent between subsequent R-peaks); for each projection angle one projection image is selected that is closest to the cardiac phase t. P^t_β denotes the *β-th* projection image where the index β is ordered according to an increasing projection angle of a short-scan projection data set P^t. The cardiac phase of a projection image is denoted by $\tau(P^t_\beta)$. The *effective cardiac phase* (ECP) of a reconstruction using the set of images P^t is

$$\tau_E(t) = \frac{1}{|P^t|} \sum_{\beta=1}^{|P^t|} \tau(P^t_\beta) \tag{1}$$

As mentioned above we have a trade-off between spatial resolution and SNR enhancement due to an approximate motion correction scheme. A RG-FDK volume of the desired cardiac phase t_r is reconstructed to provide a baseline of spatial resolution where the projection images are retrospectively selected such that the observed ECP $\tau_E(t)$ is closest to t_r. This volume is denoted by $f^{RG}_{t_r}(\boldsymbol{x})$ and $\boldsymbol{x}$ is a 3D grid of the reconstructed volume intensities. It can be seen as a first sample from multiple volume reconstructions that are later combined to enhance SNR. However, during the reconstruction of $f^{RG}_{t_r}(\boldsymbol{x})$ only $\frac{1}{N_s}$ of the projection data is used. To make use of the remaining unused projection data, we apply retrospective motion correction.

2.1 Retrospective motion correction

As shown by Prümmer et al. [4] increased temporal resolution can be achieved by computing a 4D motion vector field $\boldsymbol{U}(t)$ (MVF) of the subjects' individual heart motion using image registration as introduced by Modersitzki [5]. The 3D MVF $\boldsymbol{u}_t := \boldsymbol{U}_{t_r}(t)$ describes the relative 3D deformation of each voxel between a selected *reference cardiac phase* t_r (RCP) that is desired for a reconstruction with enhanced SNR, and cardiac phase t. The MVF is combined with an FDK-like algorithm [4] that allows a temporally dependent spatial warping of the filtered-backprojections $\tilde{P}^t_{\beta_i}(\boldsymbol{x})$. Since we apply a voxel-driven back-projection the FBPs are defined on the 3D grid $\boldsymbol{x}$. The integral in the FDK-like algorithm [1], that we call FDK-4D, over all discrete β_i can be written as the sum

$$\tilde{f}_{t_r}(\boldsymbol{x}) = \sum_{i=1}^{|P^{t_r}|} \tilde{P}^t_{\beta_i}(\boldsymbol{x} - \boldsymbol{u}_{\tau(P^t_{\beta_i})}) \tag{2}$$

of the temporally dependent spatially warped FBPs according to the MVF. This allows the use of additional projection images during the reconstruction that would, due to their cardiac phase, otherwise introduce motion artifacts.

2.2 Multiple volume reconstruction

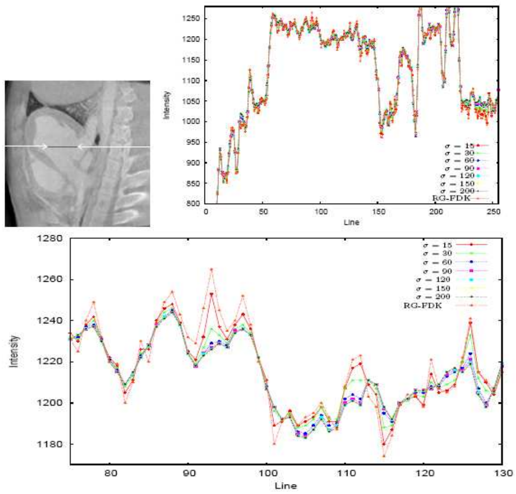
Since we correct for motion we can create several e.g. N_m arbitrary subsets P^l of projection images for a short-scan, that are not retrospectively gated. For each of the N_m subsets a motion corrected volume $\tilde{f}^l_{t_r}(\boldsymbol{x})$ according to (2) is reconstructed using FDK-4D. The selection strategy of the projection data implies that each measured projection image of a multi-sweep scan is contained in at least one of the subsets P^l. The multiple volume reconstructions are then voxel-wise combined using a 1D Gaussian window $G^{\mu_{\boldsymbol{x}}}_\sigma(i)$ where the mean $\mu_{\boldsymbol{x}} := f^{RG}_{t_r}(\boldsymbol{x})$ is defined by the voxel intensity of the RG-FDK reconstruction f^{RG}, i is the intensity and standard deviation σ. The SNR enhanced reconstruction f^{SNR} using the proposed algorithm, that we call Multiple-Volume-FDK (MV-FDK), is then given by

$$f^{SNR}_{t_r}(\boldsymbol{x}) = \frac{1}{1 + \sum\limits_{l=1}^{N_m} G^{\mu_{\boldsymbol{x}}}_\sigma(\tilde{f}^l_{t_r}(\boldsymbol{x}))} \left(\sum_{l=1}^{N_m} G^{\mu_{\boldsymbol{x}}}_\sigma(\tilde{f}^l_{t_r}(\boldsymbol{x}))\tilde{f}^l_{t_r}(\boldsymbol{x}) + f^{RG}_{t_r}(\boldsymbol{x}) \right) \tag{3}$$

3 Results

To investigate improvement of image quality using the MV-FDK algorithm, a series of ten RG-FDK reconstructions (using 191 retrospective selected projections for the reconstruction) was performed. These initial reconstructions were used to compute the MVF relative to the cardiac phase $t_r = 80$. Using the FDK-4D algorithm six motion corrected volumes, each of which using a partially distinct set of projection images, were reconstructed such that all 1146 acquired and (according to their phase distance to $t_r = 80$) spatially warped projection images were considered during MV-FDK reconstruction. Different standard deviations σ for the Gaussian weighting between the multiple reconstructions where investigated as shown in Figure 1. The MV-FDK reconstructions are compared against the RG-FDK reconstruction. The between the arrows measured SNR (defined as the ratio of the mean intensity value to the standard deviation) is $(\sigma, SNR) = (15, 66.07), (30, 73.58), (60, 74.45), (90, 74.14), (120, 73.94), (150, 73.73), (200, 73.73), (RG - FDK, 57.7)$ (see Fig. 1). An example of representative image quality of a RG-FDK reconstruction in comparison with an MV-FDK reconstruction is shown in Figure 2.

Fig. 1. Intensity profile plot along a line as shown in the top left image. The image shows a slice of an MV-FDK reconstruction ($6 \times 4s$ multi-sweep scan, using 1146 projection images during reconstruction). The intensity profile of the complete line is shown in the top right panel. A magnification of the intensity profile measured between both arrows is shown in the bottom panel. Each MV-FDK reconstruction is a combination of six reconstructions, that are reconstructed using several partially distinct subsets of the acquired projection data. Inside the left ventricle the intensity profile of the MV-FDK reconstruction is more homogeneous compared to the RG-FDK reconstruction



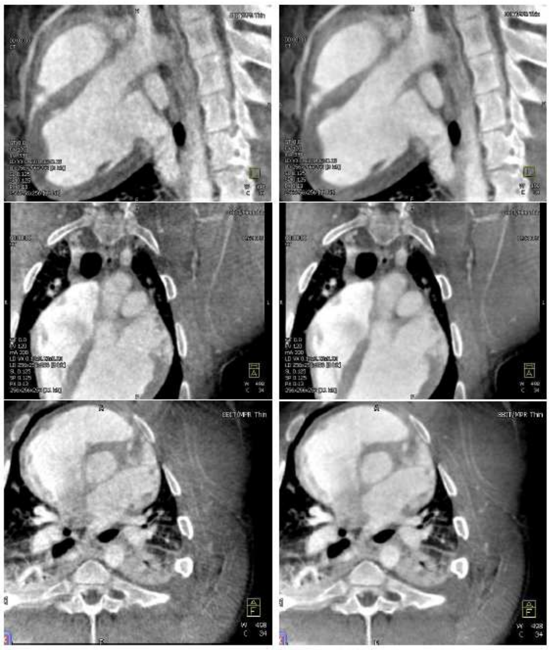
4 Conclusion and discussion

We could show that using the MV-FDK algorithm the SNR can be improved by approximately 30 percent compared to a standard RG-FDK reconstruction. The measured intensity profile inside the ventricle shows a higher SNR. Intensity variations inside high density regions like the contrast filled ventricle are decreased and the location of edges remain while only a very slight blurring is noticed such that improved segmentation results for clinical applications can be expected. In conclusion we can say that improvement of SNR by including additional corrected and resampled projections from cardiac phases outside the temporal window of the targeted reconstruction phase during reconstruction can be achieved.

5 Acknowledgments

This work was supported by Siemens AG, Medical Solutions, Forchheim, Germany, NIH grant R01 EB 003524 and by the Lucas Foundation, HipGraphics, Towson, Maryland, USA, BaCaTec and by Deutsche Forschungsgemeinschaft (DFG), SFB 603, TP C10.

Fig. 2. Column (a) shows three orthogonal multi-planar reconstructions (MPRs) of the heart from an animal model using RG-FDK where 191 retrospectively selected projection images were used ($t_r = 80$). Column (b) shows a multiple-volume FDK reconstruction considering 1146 acquired projection images from a $6 \times 4s$ scan. The standard deviation of the Gaussian kernel used for the MV-FDK reconstruction (b) was $\sigma = 60$. The MV-FDK reconstruction (b) is less noisy compared to the RG-FDK reconstruction (a) while edges in principle remain as provided by the RG-FDK approach



References

1. Feldkamp LA, Davies LC, Kress JW. Practical cone-beam algorithm. J Opt Soc Am A1 1984:612–619.
2. Lauritsch G, Boese J, Wigström L, Kemeth H, Fahrig R. Towards Cardiac C-arm Computed Tomography. IEEE Trans Med Imaging 2006;25:922–934.
3. Li T, Schreibmann E, Thorndyke B, Tillman G, Boyer A, Koong A, et al. Radiation dose reduction in four-dimensional computed tomography. Med Phys 2005;32(12):3650–3660.
4. Prümmer M, Wigström L, Hornegger J, Boese J, Lauritsch G, Strobel N, et al. Cardiac C-Arm CT: Efficient motion correction for 4D-FBP. Procs IEEE Medical Imaging Conference, San Diego, 2006, accepted for publication.
5. Modersitzki J. Numerical Methods for Image Registration. Oxford University Press, 2004.