Motion Vector Field Upsampling for Improved 4D Cone-Beam CT Motion Compensation of the Thorax

S. Sauppe[1], C. M. Rank[1], M. Brehm[2], P. Paysan[2], D. Seghers[2], and M. Kachelrieß[1]

[1]Medical Physics in Radiology, German Cancer Research Center, Heidelberg, Germany

[2]Varian Medical Systems Imaging Laboratory, Baden-Dättwil, Switzerland

GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION

Research for a Life without Cancer

Introduction

Accurate information about patient motion is essential for precise radiation therapy, in particular for thoracic and abdominal cases. Motion compensation based on daily on-board CBCT images before treatment beam-on would allow us to adapt the treatment plan instantly. Especially for patients with tumors close to an organ of risk, the patient position verification has to be very precise and can be enhanced by taking motion into account based on 4D-CBCT images. But retrospectively gated image reconstructions of respiratory and / or cardiac phase-correlated projections contain severe sparse projection artifacts. We propose an adapted method of our previously published 4D motion compensation (MoCo) algorithm [1], to improve the accuracy of the estimated motion vector fields (MVFs) and thus the image quality of those CBCT scans. We propose to upsample the MVFs that had been estimated using a larger bin size, and to use the upsampled MVFs to motion compensate reconstructions performed with a smaller bin size.

Materials and Methods

To estimate the MVFs, a modified version of the Demons algorithm is used. Our proposed method is able to interpolate the original MVFs up to a factor that each projection has its own individual MVF. For validation of the MVF upsampling method we use simulated CBCT rawdata from an artificially deformed clinical 3D CT scan. Additionally clinical patient data acquired with the TrueBeam™ 4D CBCT system (Varian Medical Systems) had been used for our study. We evaluate our method for different numbers of respiratory bins, each again with different upsampling factors. Let p be the measured (projection) data, let p_r be the data corresponding to one motion phase (or time window) and let $f_r = \mathsf{X}^{-1}p_r$ be the reconstruction of these data with X^{-1} being a reconstruction algorithm that does not compensate for the motion, e.g. a filtered backprojection algorithm such as the Feldkamp algorithm that we use in this paper. We call this kind of reconstruction gating which gives us the phase–correlated Feldkamp (PCF) reconstruction. Due to the gating, the PCF images are an average of all projection sorted in each phase. Thus every motion vector field describes the average motion between the adjacent bins. The deformation of a volume $f(\boldsymbol{r})$ is then given as $Tf(\boldsymbol{r}) = f(\boldsymbol{d}(\boldsymbol{r}))$ with T being the transform operator. $T_r^{r'}$ describes the transform from one respiratory phase r into another respiratory phase r'.

To compensate for motion, MoCo applies

$$f_r^{\mathrm{MoCo}}(\boldsymbol{r}) = \sum_\rho T_\rho^r f_\rho(\boldsymbol{r})$$

Our upsampling strategy is an interpolation of the original MVFs. Assume to have MVFs available for R respiratory phases. Let the integer r count these phases. Let $\boldsymbol{d}_r(\boldsymbol{r})$ be the MVF pointing from phase r to the next respiratory phase, such that

$$f_{r+1}(\boldsymbol{r}) = f_r(\boldsymbol{d}_r(\boldsymbol{r}))$$

We are now interested in increasing the number of phases and decreasing the width of each phase bin. Mathematically, we describe this as fractional phases $r + w$ with $0 \le w < 1$ being the sub–phase. Let $g_{r+w}(\boldsymbol{r})$ be the PCF reconstruction of phase $r + w$. Note that these reconstructions are done with a smaller bin width. Thus $g_r(\boldsymbol{r}) \neq f_r(\boldsymbol{r})$. To perform MoCo on the images $g_{r+w}(\boldsymbol{r})$ we need the corresponding MVFs. Our approach, which is the simplest ansatz, is to do linear interpolation, i.e. to define $\boldsymbol{d}_{r+w}(\boldsymbol{r}) = (1-w)\boldsymbol{d}_r(\boldsymbol{r}) + w\boldsymbol{r}$ as the vector field required to jump from fractional phase $r + w$ to phase $r + 1$: $g_{r+1}(\boldsymbol{r}) = g_{r+w}(\boldsymbol{d}_{r+w}(\boldsymbol{r}))$.

Results

The typical motion blurring, which is induced by the limited temporal resolution of PCF images on the one hand and by the irregular breathing on the other hand, was substantially reduced by our proposed MVF upsampling method for all numbers of respiratory phases. Each row of Figure 1 shows the impact of the upsampling method regarding to the sharpness of the diaphragm. E.g. for the first row one can see that the large bin size of 40% (R = 5) leads to strong motion blurring next to the edge of the diaphragm. Due to the bin size this blurring is already in PCF images present and cannot be correct by the MoCo algorithm without upsampling. By increasing the upsampling factor the motion blurring is reduced. In the bottom part of Figure 1 we evaluate several edge profiles at different positions of the diaphragm, each with a length of about 12 mm. This illustrates the advantage of our upsampling method in terms of motion blurring.

Acknowledgements

This study was supported by Varian Medical Systems. Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.

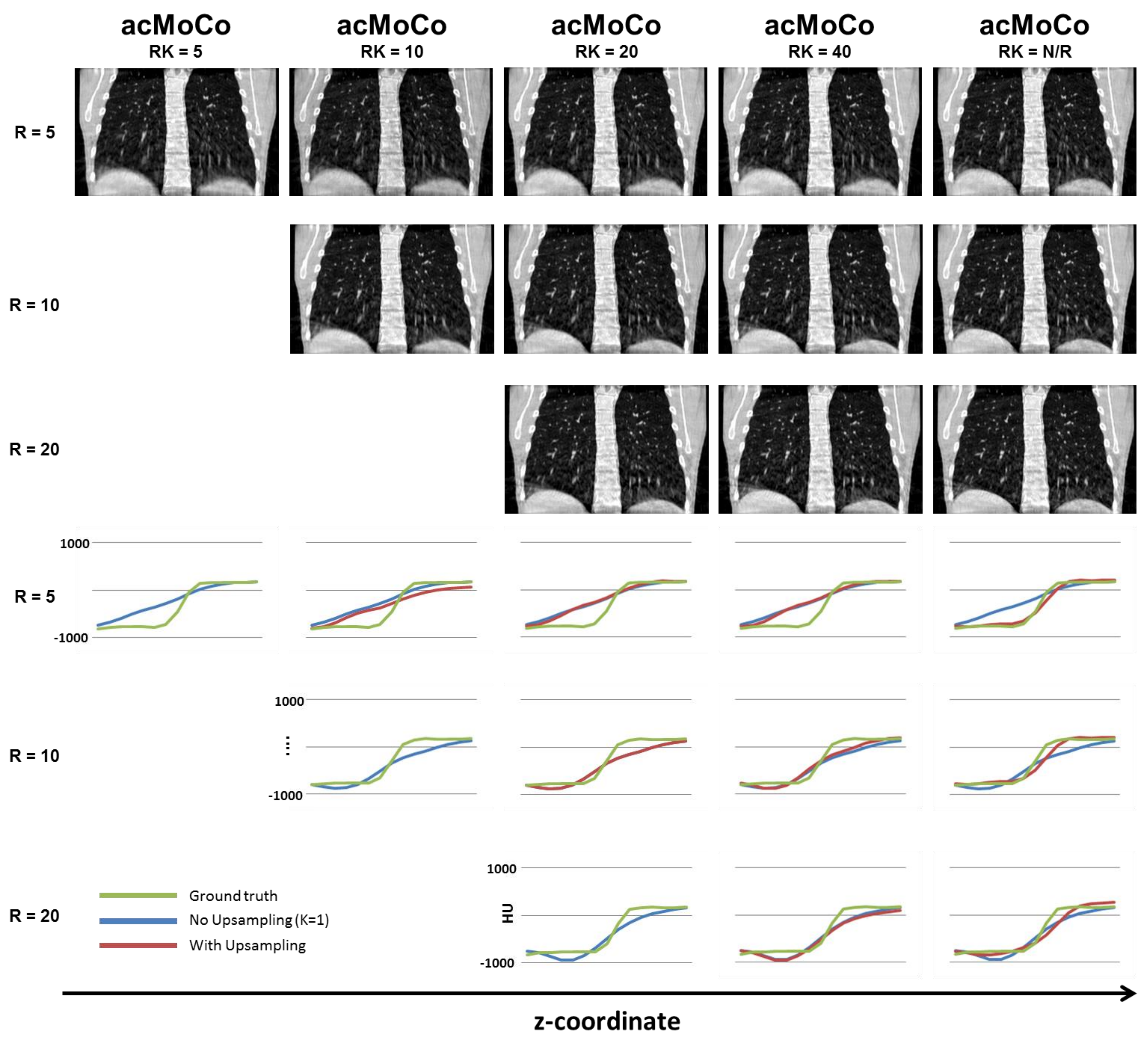

Figure 1 – Upsampling matrix to compare different upsampling factors *K* by a different number of respiratory bins *R* with the appropriate diaphragm edge profile for evaluation of motion blurring.

For all images a window level of -250 HU and a window width of 1400 HU was applied.

[1] M. Brehm, P. Paysan, M. Oelhafen, P. Kunz, and M. Kachelrieß, "Self–adapting cyclic registration for motion–compensated cone–beam CT in image–guided radiation therapy," Med. Phys. 39, pp. 7603–7618, Dec. 2012