Clinical Data Evaluation of C-arm-based Motion Compensated Coronary Artery Reconstruction

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Abstract—**Angiographic C-arm systems are capable of performing computed tomography (CT) imaging for assisting in therapy planning, performance and assessment. Due to the long acquisition time, C-arm CT of dynamic structures is challenging. Cardiac motion has to be estimated and compensated in the reconstruction step. The quality of the motion estimation algorithm mainly dictates the resulting image quality. A common strategy to reduce the requirement of motion estimation is to exclude problematic heart phases by ECG-gating. A small ECG window improves the temporal resolution, but the usage of fewer data leads to undersampling artifacts. In contrast, larger ECG windows yield better image quality at the account of stronger cardiac motion artifacts. The bootstrapping approach presented here allows increasing the size of the ECG window in an iterative manner. The technique was evaluated on a clinical data set of 58 cases. Image quality was assessed by a human observer. Vessel sharpness and diameter were determined by a semi-automatic evaluation tool. The vessel diameter in 3-D was compared to a gold standard measurement in the 2-D projection images. Good image quality was achieved. The diameter of the arteries was determined reliably. The evaluation study clearly shows the benefit of using more projection data for dynamic image reconstruction. Besides avoiding undersampling artifacts a sharper reconstruction filter kernel can be applied. There is no clear choice in using either an 80% or 100% width of the ECG gating window. While using (almost) all acquired projection data, the technique appears efficient in dose and contrast agent.**

Keywords—C-arm computed tomography, cardiac imaging, motion compensation, image reconstruction, clinical evaluation

I. INTRODUCTION

Angiographic C-arm systems are capable of performing computed tomography (CT) imaging. 3-D imaging in the catheter laboratory assists in therapy planning, performance and assessment. However, due to the long acquisition time of several seconds, CT imaging of dynamic structures like coronary arteries is a challenging task. In recent years various approaches were developed that account for cardiac motion in the reconstruction step [1], [2], [3], [4] by first estimating the coronary motion from the acquired data and then compensating it in the image reconstruction algorithm.

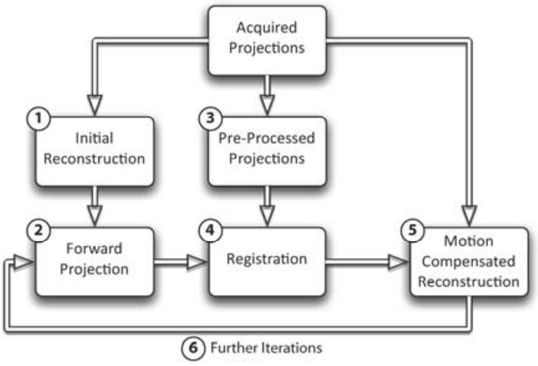

Fig. 1. Overview of the motion estimation and compensation reconstruction framework.

The quality of the motion estimation algorithm is a key factor for the resulting image quality. Any type of error is strongly propagated into the quality of the motion compensated reconstructed image. Especially data from heart phases with strong motion, e.g. systole might degrade reconstruction results significantly. Therefore a common technique is to use that prior knowledge and to exclude the strong motion phases by ECG-gating of the input data. However, there is a trade-off in ECG-gating. A small ECG window improves temporal resolution but the utilization of few data leads to undersampling artifacts. A large ECG window yields better image quality but strong cardiac motion yields errors in estimation and compensation.

The approach [4] presented here allows for flexibility in ECG gating. In particular, it allows increasing the size of the ECG window by an iterative bootstrapping [5]. Finally, all acquired data might be used for the final image reconstruction step. So far, no investigations about the optimal size of the ECG window have been performed. This paper reports on an empirical study on 58 human, clinical data sets. Different algorithmic parameters are investigated on that ensemble.

II. MOTION COMPENSATED IMAGE RECONSTRUCTION

A. *Brief description of the algorithm*

A detailed description can be found in [3][4]. A short summary is given here. Fig. 1 shows an overview of the components. (Step 1): An initial ECG-gated reconstruction is performed. (Step 2): Non-vascular tissue is removed by a thresholding operation. The vascular structure is forward projected using a maximum intensity forward projection. (Step 3): The original projection images are pre-processed using a morphological top-hat operation and a thresholding,

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so that non-vascular tissue is removed. (Step 4): The pre-processed original projections and the forward projections are registered using affine and deformable 2-D–2-D registration in a multi-resolution scheme. (Step 5): A motion-compensated, ECG-gated reconstruction is performed using the deformation field from the registration step. (Step 6): The procedure is repeated either for further refinement or for increasing the number of acquisition data used for image reconstruction.

B. *Iterative bootstrapping approach for ECG windowing*

The iterative loop of step 6 is used for enlarging the width of the ECG window and therefore improving image quality. ECG gating is defined by the center at heart phase h_r and the width ω of the gating window. h_r and ω are expressed as a fraction of the heart cycle in the range of 0 and 1.

Three iteration cycles are performed. Cycle 1 is started with an initial image using an ECG gating window of width $\omega=0.4$. This cycle determines a first approximation of the motion field since the motion artifacts of the initial image degrade motion estimation. Cycle 2 refines motion estimation using the motion-compensated image of cycle 1. Cycle 3 allows increasing the ECG gating window width. Two variants are investigated using $\omega=0.8$ and $\omega=1.0$.

III. CLINICAL EVALUATION

A. *Patient population*

This study investigates 58 human cases. The coronaries were contrasted selectively. Rotational angiograms were acquired of 39 left coronary arteries (LCA) and 19 right coronary arteries (RCA). Heart rate and variability are critical parameters: The length of the heart's rest-phase with minimal motion is reduced by increasing heart rate. ECG-gating relies on a periodic motion during different cardiac cycles. A variability of the heart rate is likely to degrade the temporal resolution. The median heart rate during acquisition was 71bpm. 18, 18, and 22 cases showed low (<60bpm), medium (between 60bpm and 75bpm), and high (>75bpm) heart rate. The median heart rate variability was 1.3bpm with 50 cases smaller 5bpm and 8 cases above.

B. *Image acquisition and reconstruction parameters*

Images were acquired on an Artis zeego system (Siemens AG, Healthcare Sector, Forchheim, Germany) using a large flat panel detector of size 40cm×30cm. An acquisition rotation lasts 5s at a frame rate of 30fps achieving 133 projection images in total. Detector resolution is 308µm pixel length in each direction. Acquisitions were performed under strict breath-hold. Normal sinus heart rhythm occurred without any regulation drugs. Contrast agent was injected directly into the coronaries at a flow rate of 1-2ml/s, achieving a total contrast burden below 10ml.

All reconstructed volume images show an isotropic voxel length of 500µm. The ECG gating window center was set to end systolic and end diastolic heart phases in 7 and 51 cases. The median of h_r was 75%. Four reconstructed volume images will be compared. (Initial): Initial image with ECG window width $\omega=0.4$ reconstructed from 45-56 projection images using a smooth filter kernel. (RMC 40%): Motion-compensated reconstruction after iteration 2 with $\omega=0.4$ and using a smooth filter kernel. (RMC 80%): Motion-compensated reconstruction after iteration 3 with $\omega=0.8$ and using a normal filter kernel. (RMC 100%): Motion-compensated reconstruction after iteration 3 with $\omega=1.0$ and using a normal filter kernel.

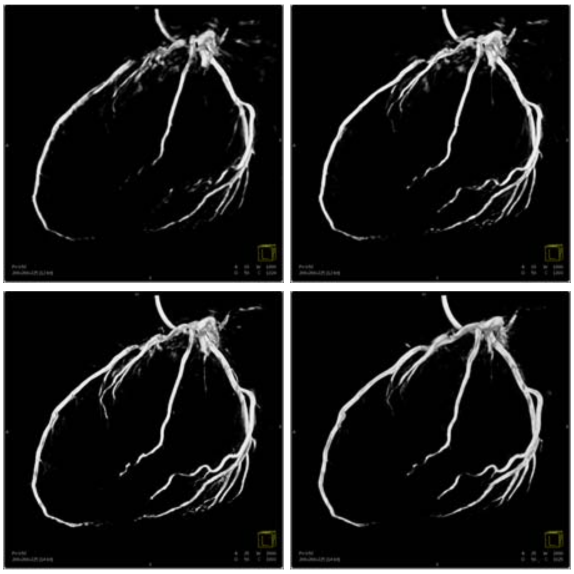

Fig. 2. Volume rendered image of a left coronary artery. Top left: Initial image. Top right: RMC 40%. Bottom left: RMC 80%. Bottom right: RMC 100%.

C. *Visual image inspection*

Image quality was assessed visually by a human observer. The coronary tree was divided into segments according to Ref. [6]. Each segment was scored using grades from 0 (not visible), 1 (substantial artifact), 2 (moderate), to 3 (perfect).

D. *Quantitative evaluation tool CoroEval*

The semi-automatic evaluation tool CoroEval computes vessel sharpness and diameter from volume images of magnetic resonance or C-arm CT [7]. CoroEval requires a centerline segmentation which can be performed either manually using CoroEval or by an external tool. The centerline is smoothed and sampled regularly at an interval of 1.0mm. At each sample point ten radial profile lines are extracted, smoothed and examined. Nine points of interest are detected at each profile line: The maxima at the vessel center, the left and the right minima beyond the border of the vessel, and for each side the point of 20%, 50%, 80% of the difference between maximum and minimum.

1) Vessel sharpness. Let d_l and d_r be the distances of the 20% and 80% points on the left and right side of the maximum, respectively. The vessel sharpness s on a profile line is defined as $s = 2/(d_l + d_r)$. The vessel sharpness at a centerline sample point is just the average of the sharpness measures of all profile lines.

2) Vessel diameter. The elliptical shape of a vessel cross-section is taken into consideration. An ellipse is fit to the 50% points of each profile line after outlier detection.

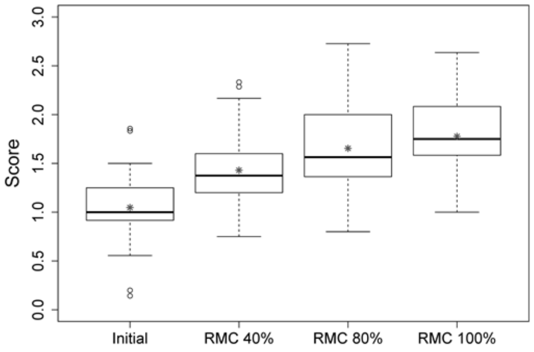

Fig. 3. Image quality score for all vessel sections examined by a human observer. The average over all vessel segments is computed.

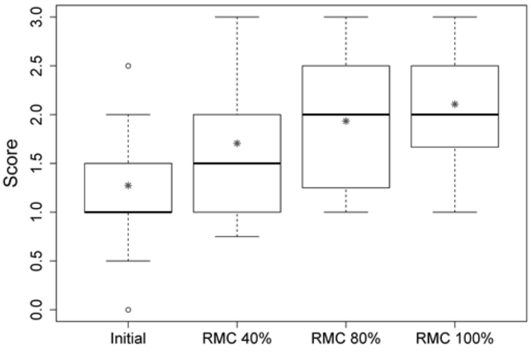

Fig. 4. Image quality score of large vessel sections examined by a human observer. The average over all vessel segments is computed.

The diameter of the cross-section is just the radius of a circle which has the same area as the constructed ellipse.

E. Ground truth of vessel size

As a ground truth the vessel diameter was measured in the 2-D projection data by the validated Quantitative Coronary Analysis (QCA) tool of the *syngo* Workplace – Angio/Quant package (Siemens AG, Healthcare Sector, Forchheim, Germany). The QCA tool segments the coronary artery automatically after manual detection of the start and end point of the section. Length measurements are calibrated by the known diameter of the contrasting catheter.

F. Statistical analysis

The statistical distribution of the evaluation results is shown in boxplots. The box contains the middle 50% of all values (interquartile range IQR). Within the box, the median is shown by a thick line, the mean by a star. The whiskers extend to the last data value within $1.5 \cdot \mathrm{IQR}$ of the box. More extreme values are shown as circles.

Statistical significance of the difference of the means of two distributions was tested with t-tests. Since all four reconstructions for a specific dataset were generated from the same projection data, paired t-tests with Bonferroni correction [8] for multiple testing were used. The significance of all results shown in the following is $p<0.001$.

IV. RESULTS

A. Visual image inspection

As an example Fig. 2 shows volume rendered images of a left coronary artery using all four methods to be compared. Increasing the ECG gating window width from $\omega=0.4$ (RMC 40%) to $\omega=0.8$ (RMC 80%) clearly improves image quality. The comparison of $\omega=0.8$ (RMC 80%) and $\omega=1.0$ (RMC 100%) is ambivalent. Using all projection data at RMC 100% removes background noise, but some final parts of distal vessels vanish at the same time.

Fig. 3 displays the image quality score of a human observer. The shown score is computed as the average of the scores given for each vessel segment. Reconstructing from all projection data ($\omega=1.0$) achieved the best image impression. Fig. 4 shows the same score evaluated for vessel sections of large diameter only. The quality scores improve for all images reconstructed using motion compensation.

B. Quantitative evaluation

1) Success rate. Quantitative analysis is performed only for cases with a successful vessel segmentation for all reconstructed volumes. 31 of 39 LCA and 15 of 19 RCA cases are assessed, 12 are rejected. In six of them the segmentation failed for the initial image only. In the other six cases no reconstructed image could be segmented. In five cases this is due to acquisition errors such that not sufficient contrast agent is admitted into the coronary arteries. In one case the failing reason is not known.

2) Vessel sharpness. According to Fig. 5 motion-compensated reconstruction using an ECG-gating window width of $\omega=0.8$ yields the sharpest vessel edges. Regarding this property $\omega=0.8$ seems to be optimal in the trade-off between temporal resolution and sufficient input data.

3) Vessel diameter. For ground truth values, a QCA measurement has to be performed in 2-D projection images. In 24 and 15 of LCA and RCA cases appropriate data sets were found displaying the desired vessel in good quality and contrast. The main branch of the vessel is selected and the average of the diameter deviation on that selection is plotted in Fig. 6. Intra-observer variations in using QCA on projection images at different angulations are indicated as dashed green lines. The standard deviation of repeated QCA measurements was 0.14mm. All volume images reconstructed using motion-compensation slightly underestimate the diameter value, while the initial image overestimates it. Most values of the RMC diameters are located inside the variance region of the ground truth. However, the median of RMC 80% is slightly below the variance region.

V. DISCUSSION

The gain of using more projection data for motion-compensated image reconstruction is clearly seen. On the other side there is no clear answer which width of the ECG gating window might be optimal. The investigated quality properties either prefer $\omega=0.8$ or $\omega=1.0$.

The image quality score of the human observer in Fig. 3 seems to be disappointing since the largest median value is still below 2 (moderate image quality). However, we have

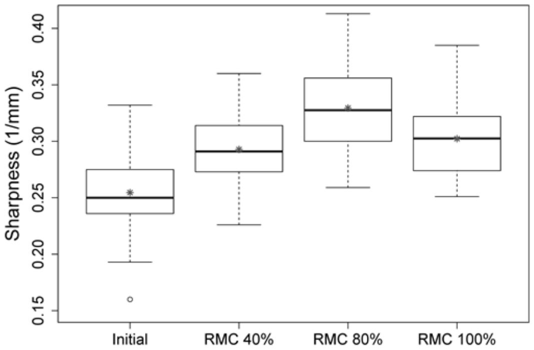

Fig. 5. Vessel sharpness as an average over all sampling points of the centerline.

to keep in mind that all cases are considered in that study even those deficient acquisitions having not sufficient contrast agent into the vessels. Further, distal vessels are included in the quality score as well. Motion estimation of distal vessels is quite complex since larger structures dominate the cost function. Distal vessels are not relevant for most clinical applications since e.g. percutaneous coronary interventions (PCI) solely focus on dilating stenosis of proximal to mid vessel sections, which feed a large portion of the myocardial mass. The image quality scores from vessels having larger diameter values significantly improve.

The diameter of the vessels is measured reliably. The observed deviations might be explained by measurement errors. There is also a variance in the ground truth values. The diameter of elliptical vessels alters with the viewing angle in 2-D.

VI. CONCLUSION

The proposed reconstruction technique using motion estimation and compensation was evaluated on a clinical data set of 58 cases. Good image quality was achieved. The diameter of the coronary arteries was determined reliably in consideration of the variance in the ground truth.

The evaluation study clearly shows the benefit of using more projection data for image reconstruction. Undersampling artifacts can be reduced and a sharper reconstruction filter kernel can be applied improving spatial resolution. On the other hand temporal resolution is reduced when increasing the width of the ECG-gating window. Most of the object motion can be estimated and compensated. However, some remains. There is no clear choice in using either an 80% or 100% width of the ECG-gating window, yet.

The presented method allows dynamic imaging of coronary arteries in the catheter laboratory using an angiographic C-arm system. While using (almost) all acquired projection data the technique appears efficient in dose and contrast agent.

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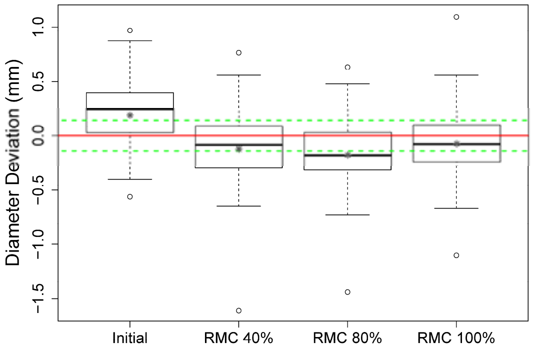

Fig. 6. Deviation of the vessel diameter measured in 3-D by CoroEval and in 2-D by QCA as an average over the selected vessel section. The full red line indicates zero value, the dashed green line the intra-observer variations in using QCA on projection images at different angulations.

Disclaimer: The concepts and information presented in this paper are based on research and are not commercially available.

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