Patient Specific 4D Coronary Models from ECG-gated CTA Data for Intra-operative Dynamic Alignment of CTA with X-ray Images*

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Abstract. We present an approach to derive patient specific coronary models from ECG-gated CTA data and their application for the alignment of CTA with mono-plane X-ray imaging during interventional cardiology. A 4D (3D+t) deformation model of the coronary arteries is derived by (i) extraction of a 3D coronary model at an appropriate cardiac phase and (ii) non-rigid registration of the CTA images at different ECG phases to obtain a deformation model. The resulting 4D coronary model is aligned with the X-ray data using a novel 2D+t/3D+t registration approach. Model consistency and accuracy is evaluated using manually annotated coronary centerlines at systole and diastole as reference. Improvement of registration robustness by using the 2D+t/3D+t registration is successfully demonstrated by comparison of the actual X-ray cardiac phase with the automatically determined best matching phase in the 4D coronary model.

1 Introduction

Coronary artery disease is one of the main causes of death in the world [1]. Atherosclerotic plaque build-up in the coronary arteries leads to vessel narrowing and occlusion, which may eventually cause heart failure. An often applied therapy to reopen occluded vessels is coronary angioplasty. During these procedures X-ray imaging is applied to visualize the arteries and guide wires. This modality unfortunately lacks depth information due to its projective nature, and only visualizes the vessel lumen, which makes the visualization of total occlusions impossible. Coronary CTA, on the contrary, also allows the visualization of coronary plaque and total occlusions. Integration of this information into the

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interventional scene may thus improve the treatment of these disorders. This is, for example, especially important when an ablating catheter is needed to open occlusions, making correct positioning of the catheter essential to prevent perforation of the vessel wall.

The goal of our work is therefore to integrate pre-operative CTA data into the interventional scene. Due to cardiac motion, the coronary arteries are under continuous deformation during therapeutic procedures. A rigid registration approach is therefore not sufficient to align the CTA data with the intra-operative X-ray images. Moreover, diagnostic CTA scans are generally reconstructed at those phases of the cardiac cycle where the deformation of the coronary arteries is minimal. In other phases, image quality is not only degraded by more excessive motion of the coronary arteries, but also due to lowering the tube current by ECG-derived pulsing windows which aim to minimize effective patient dose.

In this work, we employ the phase with minimal coronary motion for 3D coronary reconstruction, and use the lower quality phases for defining a deformation model. Together, this yields a 4D (3D+t) coronary model, which can be applied to make high quality information available over the complete cardiac cycle. This information can be used to improve the robustness of CTA/X-ray alignment, which is useful for improved navigation in interventional cardiology. To this end, we propose a novel 2D+t/3D+t registration approach.

Related work with respect to the 4D model building has, for example, been presented by Wierzbicki et al., who present an approach to derive heart motion from CTA and MRA data by means of a non-rigid registration procedure [2]. To the best of our knowledge, the application of this approach to derive patient specific 4D coronary models has not been reported previously. Moreover, we show the application of these models for the registration of CTA data to intra-operative X-ray data; this 2D+t/3D+t registration approach is also novel.

Static registration of simulated X-ray images and CTA data has been performed by Turgeon et al., who presented results on both mono- and biplane registration at end-diastole [3]. Deformable 2D/3D registration of vasculature was presented by Zikic et al., who constrained the deformation of the vessels based on a priori information about plausible deformations [4]. Especially for mono-plane X-ray imaging, these free-form deformations can in theory introduce ambiguity, *i.e.* multiple 3D deformations can result in similar projection images. The approach presented in this work is different in two aspects: (i) the movement of the 3D vasculature is restricted to patient specific deformations derived from ECG-gated CTA data and (ii) a window of multiple sequential X-ray images is simultaneously aligned to a window of multiple sequential 4D coronary model positions.

2 Method

The method consists of a number of steps. First, A 3D centerline or lumen model of the coronary arteries is derived manually or semi-automatically from a phase in the cardiac cycle with minimal motion. Deformation of the coronary arteries is

subsequently derived from the 4D CTA data by means of a non-rigid registration procedure. We assume that the coronary arteries move with the larger structures in the image to which they are attached, such as the heart chambers, which is especially advantageous in those phases of the cardiac cycle where the arteries are not well visible due to motion artifacts. Finally, the resulting 4D coronary model is applied in a new 2D+t/3D+t registration procedure for the dynamic alignment of CTA with X-ray data. The overall method is depicted in Fig. 1; details of the different steps are presented below.

Fig. 1. Overview of 4D model creation and 2D+t/3D+t registration approach

2.1 Deriving the 4D Coronary Model

The registration approach applied to derive the coronary deformation from the 4D CTA data is similar to the one proposed by Wierzbicki et al. [2]. The 4D datasets are divided into n different 3D images, denoted I_i , where $i \in \{0 \dots n-1\}$ indicates the phase in the cardiac cycle, further referred to as time-point. A 3D model of the coronary arteries is derived manually or semi-automatically from one of these images, *e.g.* at end-systole or end-diastole where image quality is in general higher than in other parts of the cardiac cycle. This 3D coronary centerline/lumen model is subsequently mapped to the other time-points by applying deformations that are derived by a non-rigid registration procedure. The image at the time-point in which the 3D model is defined is chosen as reference image (I_f) as we want to minimize the error of the registration to this time-point in order to find the model deformation as accurate as possible. All other time-point images $I_{i \neq f}$ are subsequently registered to this fixed image. Registration starts using I_{f+1} as moving image and the resulting transformation T_{f+1} is used as the initial transformation for registration of the next time-point image I_{f+2} .

Registration is performed using a multi-resolution approach in which Gaussian filtering is applied to reduce the scale of the image in the resolution steps. The optimal B-spline deformation is searched using a stochastic gradient descent optimization approach in which mutual information is used as similarity measure [5,6].

Using the transformations $T_{i \neq f \rightarrow f}$ resulting from the registration approach, the 3D coronary model is deformed to all time-points of the 4D CTA data. As these time-points do not necessarily match the frame rate of the X-ray data

acquired during the intervention, spline interpolation is applied to derive intermediate coronary model positions.

2.2 2D+t/3D+t Registration Procedure

For the alignment of the CTA with the X-ray data, a rigid intensity-based registration framework is applied [7]. Instead of matching one time-point of the 4D coronary model with one X-ray image, we propose to match multiple sequential time-points of the 4D coronary model in a window w to multiple sequential X-ray images simultaneously. This window includes the time-point we want to match and the $w - 1$ previous time-point positions, mimicking the clinical situation. This approach is expected to improve the robustness of the registration procedure as there is additional information in the time-dimension of the data, which is especially useful in the case of mono-plane X-ray imaging.

On the X-ray series, static structures are removed by subtracting from each pixel the average pixel intensity of this pixel over time. Before registration, the 4D model of the coronary arteries is automatically positioned with its center of mass on the isocentre of the X-ray coordinate system. Manual initialization is subsequently performed by applying one 2D translation in the plane orthogonal to the projection line for the complete cardiac cycle. Optimization is performed using a multi-resolution gradient ascent procedure. For every pose estimation, digitally reconstructed radiographs (DRRs) of the coronary lumen model are rendered on the graphical processing unit and compared with the real X-ray images using normalized cross correlation (NCC). The resulting NCC values are averaged over the time window w to derive the quality of the current pose.

3 Experiments

3.1 CTA and X-ray Data

CT coronary angiography for thirty-one patients with known or suspected coronary artery disease was acquired using a dual-source CT system (Somatom Definition; Siemens Medical Solutions, Forchheim, Germany). No beta-blockers were administered in preparation for the scan. The entire volume of the heart was scanned in one breath-hold, while simultaneously recording the ECG trace. An optimized heart-rate-dependent ECG pulsing protocol was applied. Outside the ECG pulsing window a tube current of 4% was used in order to reduce the effective dose of the CT examination. Multi-phase 4D datasets were reconstructed at 5% steps from 0% to 95% of the RR-interval, with a slice thickness of 3 mm and slice increment of 1.5 mm. Voxelsizes of the reconstructed volume are approximately $0.7 \times 0.7 \times 1.5 \text{ mm}^3$.

X-ray data was acquired with an AXIOM-Artis C-arm system (Siemens Medical Solutions, Forchheim, Germany). The pixel size of these images is $0.22 \times 0.22 \text{ mm}^2$.

3.2 4D Coronary Model Consistency and Accuracy

The 4D coronary models were evaluated using manually annotated coronary centerlines at both systole and diastole of the cardiac cycle. In every dataset one of the following vessels was randomly selected for annotation: right coronary artery (RCA), left anterior descending artery (LAD) or left circumflex artery (LCX). In total 11 LADs, 11 LCXs and 9 RCAs were annotated. Two experiments were conducted: one to assess model consistency and one to assess model accuracy.

Consistency was measured as follows. First, coronary deformation was derived using the approach described in section 2.1. This deformation was also derived by applying the registration procedure in reverse order, *viz.* by registering image I_{f-1} to I_f , followed by a registration of I_{f-2} to I_f using $T_{f-1 \rightarrow f}$ as initial deformation, etc. The two 4D coronary centerline models are compared by measuring the average distance between the resulting centerlines at every time-point, which is defined as the area between the centerlines divided by the length of the annotated centerline. This experiment is performed using both the image at systole and diastole as reference image in the registration procedure.

The accuracy of the 4D coronary models was determined using the same centerlines as used for the consistency experiment. By applying the deformations resulting from the registration procedure to the centerlines annotated at systole, a deformed version of these centerlines at diastole is derived and compared to the actually annotated centerline at this time-point. Centerlines are clipped at their distal parts, as it is not always possible to annotate them equally distal in both images, due to low resolution of the data and motion artifacts. Clipping is performed by determining the Euclidian closest points on both centerlines and disregarding all points distal from these points in the evaluation. Accuracy is measured by computation of the average distance between the clipped centerlines. The same procedure is applied for the centerlines annotated at diastole.

3.3 2D+t/3D+t Registration

To demonstrate an improvement in registration robustness using the proposed 2D+t/3D+t registration approach, a 4D coronary lumen model was constructed for one dataset for which X-ray data was available. This was performed by manual extraction of the centerlines of the vessels at diastole, followed by automatic segmentation of the lumen [8], and subsequent manual correction of the segmentation results.

One RR-interval of the X-ray data was selected and the 4D coronary lumen model was matched using a 2D/3D+t approach ($w = 1$) and the proposed 2D+t/3D+t approach ($w = 4$). For both approaches and for each X-ray image in the RR-interval, we search exhaustively for the best matching time-point position in the 4D coronary lumen model, by consecutively registering the 3D coronary lumen model at each time-point position to the 2D X-ray image. Subsequently, the best matching time-point is selected as the one yielding the maximum NCC value. In the ideal situation, resulting coronary lumen model time-point positions should exactly match the actual X-ray time-point positions.

Fig. 2. Model consistency: the average distance between the centerlines is plotted against the time-point index number. Each line represents a dataset (blue=LAD, red=LCX and green=RCA). The median over all centerlines is plotted in black.

4 Results and Discussion

4.1 4D Coronary Model Consistency and Accuracy

Graphs showing the results for the model consistency experiment can be found in Fig. 2. Results for both using the image at systole and diastole as reference image in the registration procedure are presented. The average distance between the centerlines is plotted against the time-point index number. Each line in the plot represents a dataset. The thick black line represents the median distance over all datasets, which is below 1 mm for both the systolic and diastolic experiment. Model accuracy is presented in Fig. 3, which displays a boxplot of the distance between the centerlines at systole and diastole before (I) and after (R) registration, and the difference between these two (D). Distances are averaged over systolic and diastolic measurements. Results are presented for all vessels combined and for the LAD, LCX and RCA separately. It can be noticed that the LAD shows the least deformation during the cardiac cycle and the RCA the most. The median accuracy is approximately 1 mm.

4.2 2D+t/3D+t Registration

Results of the 2D+t/3D+t experiment are shown in Fig. 4. X-ray time-point positions are plotted against the best matching CT time-point. The dashed line shows the results for $w = 1$ and the solid line for $w = 4$. It can be noticed that using a larger window in the registration procedure results in a much better time-point position derivation than the 2D/3D+t procedure. For some time-phases at the end of the RR-interval, registration ended up in a local optimum, caused by using the same manual initialization for the complete cardiac cycle, which is for some phases outside the capture range of the registration procedure. This may be solved in the future by using the resulting optimal pose for the previous

Fig. 3. Accuracy of 4D coronary models. (I)Initial distance between systole and diastole centerlines, after (R)registration, and (D)ifference (I-R).

Fig. 4. X-ray time-point positions plotted against best 4D model time-point position resulting from the 2D+t/3D+t registration procedure

Fig. 5. Examples of 2D+t/3D+t registration results at 20% and 40% of the RR interval. Projected coronary model boundaries are overlaid on the background-subtracted X-ray images

time-point as initial pose for the time-point under consideration. Illustrations with registration results at two phases in the cardiac cycle are shown in Fig. 5. Although this experiment was limited to one dataset, it demonstrates the feasibility of this approach. Moreover, it indicates that registration of CTA and mono-plane X-ray images, which is an ill-posed problem, can benefit from the information in the time dimension of the imaging data. Some misalignment is still visible in Fig. 5, which may be caused by irregular heart deformation, inaccurate reporting of the projection geometry of the X-ray system in the DICOM headers, errors in the 4D coronary model, or non-rigid deformation caused by the breathing cycle. The registration procedure for derivation of the 4D coronary model still needs some improvements, especially to be better able to handle the more excessive motion of the RCA. It can, for example, be advantageous to take the cyclic behavior of the heart motion into account or to imply a smoothness constraint on the registration in the time-dimension of the image. Furthermore,

as we discretized the 4D coronary model in the time dimension, there may still exist a small time mismatch between the X-ray time-point and coronary model time-point.

5 Conclusions

We presented a method to derive patient specific 4D coronary models from ECG-gated CTA data and demonstrated the usefulness of these models for better relating pre-operative CTA to intra-operative X-ray images, which can improve guidance during interventional cardiology procedures. Hereto, a novel 2D+t/3D+t registration procedure was developed and we demonstrated that this procedure was better able to determine the correct CTA time-point position for the X-ray phase of interest, which is an indication that registration robustness can be improved compared to a 2D/3D+t approach. We conclude that the combination of the 4D coronary models and the 2D+t/3D+t registration method is a promising approach for improved image guidance in interventional cardiology.

References

1. Rosamond, W., Flegal, K., Furie, K., et al.: Heart disease and stroke statistics – 2008 update: Report from the american heart association statistics committee and stroke statistics subcommittee. *Circulation* 117, 25–146 (2008)
2. Wierzbicki, M., Drangova, M., Guiraudon, G., Peters, T.: Validation of dynamic heart models obtained using non-linear registration for virtual reality training, planning, and guidance of minimally invasive cardiac surgeries. *Med. Image Anal.* 8(3), 387–401 (2004)
3. Turgeon, G.-A., Lehmann, G., Guiraudon, G., Drangova, M., Holdsworth, D., Peters, T.: 2D-3D registration of coronary angiograms for cardiac procedure planning and guidance. *Med. Phys.* 32(12), 3737–3749 (2005)
4. Zikic, D., Groher, M., Khamene, A., Navab, N.: Deformable registration of 3D vessel structures to a single projection image. In: *Proc. SPIE (Medical Imaging: Image Processing)* (2008)
5. Klein, S., Staring, M., Pluim, J.P.W.: Evaluation of optimization methods for non-rigid medical image registration using mutual information and b-splines. *IEEE Transactions on Image Processing* 16(12), 2879–2890 (2007)
6. Mattes, D., Haynor, D.R., Vesselle, H., Lewellen, T.K., Eubank, W.: PET-CT image registration in the chest using free-form deformations. *IEEE Trans. Med. Imag.* 22(1), 120–128 (2003)
7. Penney, G.P., Batchelor, P.G., Hill, D.L., Hawkes, D.J., Weese, J.: Validation of a two- to three-dimensional registration algorithm for aligning preoperative CT images and intraoperative fluoroscopy images. *Med. Phys.* 28(6), 1024–1032 (2001)
8. Schaap, M., Neefjes, L., Metz, C., et al.: Coronary lumen segmentation using graph cuts and robust kernel regression. In: *Information Processing in Medical Imaging* (2009)