Registration of Atrium Models to C-arm X-ray Images Based on Devices Inside the Coronary Sinus and the Esophagus

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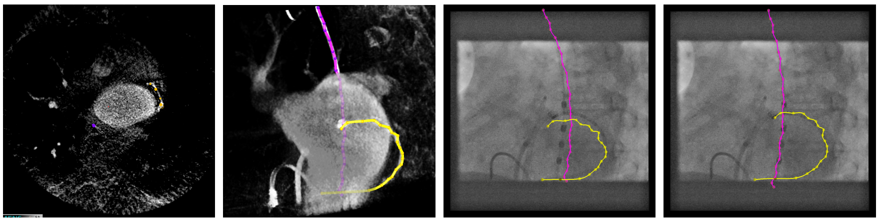
Abstract. For augmented fluoroscopy in the context of minimally invasive EP procedures, a patient-specific model of the atrium segmented from a 3-D volume can be overlaid on fluoroscopic images. This requires a registration between the 3-D model coordinate system and the coordinate system of the C-arm X-ray device. We propose an indirect registration that makes use of surrounding anatomical structures that can be segmented both in the 3-D volume obtained by CT or MRI and also in fluoroscopic images. More precisely, the coronary sinus and the esophagus segmented from the 3-D volume is registered to reconstructed 3-D devices which are located in the respective structures during the intervention. An evaluation on 6 images of 6 different patients yielded a mean registration error of 3.2 mm. Results became significantly worse if only one of the anatomical structures was used.

1 Introduction

Cardiac ablation is a minimally invasive procedure in the field of electrophysiology (EP) which is used to treat several types of heart arrhythmia, e.g., atrial fibrillation (AFib) [1]. During the procedure, transmural lesions are to be set at certain parts of the heart tissue using, e.g., a radio-frequency (RF) catheter. In many cases, a diagnostic catheter is placed in the coronary sinus (CS). The CS is a coronary vein that runs from the great cardiac vein along the heart wall between left atrium (LA) and the left ventricle (LV) until it drains into the right atrium (RA). As it is attached to both the LV and the LA, its position is subject both to ventricular and atrial contraction. For RF ablation, there is a risk of injuring the esophagus which can lead to an esophageal fistula [1]. To address this risk, the esophagus can be monitored using a temperature probe. Unlike the CS, the esophagus is not subject to cardiac motion, but it can also move slowly throughout a procedure.

Guidance during AFib procedures can be obtained by using fluoroscopic images, e.g. acquired with a biplane C-arm X-ray system. Navigation can be further



(a) (b) (c) (d)

Fig. 1. (a) The coronary sinus (yellow) and the esophagus (purple) are annotated in a slice-view of the volume. (b) Annotated devices rendered together with the volume. (c) Devices segmented from volume overlaid to fluoroscopic images before registration and (d) after registration.

improved by means of augmented fluoroscopy [2]. In this case, extra data is overlaid on fluoroscopic images to provide the physician with additional information. For example, a patient-specific 3-D model of the LA which was acquired before the procedure using, e.g., MRI or CT could be superimposed to simplify the orientation during the intervention. In this case, the coordinate systems of the previously acquired 3-D model and the C-arm have to be registered such that the position, size and orientation of the patient model as displayed in the fluoroscopic image, is correct.

This registration could be performed manually [3] or using contrast agent which highlights the shape of the left atrium [4]. Sra et al. [5] proposed an indirect approach using a segmentation of the CS in the 3-D data and to register it to the 2-D CS catheter in a single fluoroscopic image. Brost et al. [6] suggested not to register to a 2-D CS catheter but to a 3-D model of the CS catheter. This model was created from two fluoroscopic images from different views using manual point-by-point triangulation. The registration was then performed using the iterative closest point (ICP) algorithm [7].

We propose to use not only the segmented CS in the 3-D voxel data and a 3-D CS-catheter model computed from two fluoroscopic images, but to expand this approach to the esophagus and an associated temperature probe. To keep manual interaction low, the 3-D centerline models of the temperature probe and the CS catheter are computed semi-automatically using a manually marked tip of each catheter in two fluoroscopic images of a biplane C-arm system.

2 Materials and Methods

Section 2.1 describes the extraction of the 3-D esophagus $\mathcal{E}_{\mathrm{V}}^{\text{3-D}}$ and the 3-D CS $\mathcal{C}_{\mathrm{V}}^{\text{3-D}}$ in the acquired volume. Section 2.2 explains how the 3-D shape $\mathcal{E}_{\mathrm{F}}^{\text{3-D}}$ of the esophageal temperature probe and the 3-D shape $\mathcal{C}_{\mathrm{F}}^{\text{3-D}}$ of the catheter is reconstructed from two fluoroscopic images from different views. We describe the actual registration procedure using ICP in Section 2.3 and our experimental setup in Section 2.4. Finally, we discuss our results and present conclusions.

2.1 Extraction of the 3-D Anatomy in the Volume Data Set

At first, the esophagus and the CS need to be segmented in a volume data set of the heart, either obtained with CT, MRI, or C-arm CT. In our case, the extraction can be performed by manually clicking on the points which belonged to the esophagus and the CS, respectively, see Figure 1. For the esophagus, also an automatic approach exists [8]. If the 3D image data was acquired intra-operatively using C-arm CT, with devices positioned both in the CS and the esophagus, then segmentation is rather straightforward. These devices are well visible, e.g., in the axial slices and can easily be located. If CT is used, the esophagus may not be as clearly visible since there is no temperature probe, but it still can be found as the neighboring spine and aorta descendens provide means of orientation. Once the LA has been segmented from the volume, also the CS, which runs next to it, can be annotated. If MRI is used as acquisition technique, the visibility of the CS is often poor in commonly used acquisition protocols and it may only be possible to find the first part of the CS.

2.2 Reconstruction of 3-D Anatomy from Fluoroscopic Images

As a second step, the 3-D shape of the esophagus and the CS has to be computed within the C-arm coordinate system, respectively. To this end, two fluoroscopic images of the patient from two views, Plane A and Plane B, are acquired. To keep the user interaction during intervention low, an automatic detection and reconstruction method [9] was used to obtain the 3-D centerline of temperature probe and CS catheter.

This method requires the user to mark in the image of each plane the tip of the esophageal temperature probe and the CS catheter, respectively. Then this method imposes a graph structure on the image and, based on features like curvature or length, the 2-D centerline is extracted. For the esophagus, the algorithm needed to be adapted slightly as the method assumes that EP catheters leave the image at the bottom, whereas the temperature probe leaves the image at the top. The resulting 2-D centerline can, if necessary, be corrected manually before automatic 3-D reconstruction. For 3-D reconstruction, points of the curve in Plane A are sampled and, using epipolar geometry, corresponding points on the respective curve in Plane B are found. If more than one intersection is possible, a monotony criterion is used to select the correct intersection.

2.3 Registration using Iterative Closest Point Algorithm (ICP)

The 3-D curves of the volume, $\mathcal{E}_{\mathrm{V}}^{\text{3-D}}$ and $\mathcal{C}_{\mathrm{V}}^{\text{3-D}}$, are registered to the 3-D curves $\mathcal{E}_{\mathrm{F}}^{\text{3-D}}$ and $\mathcal{C}_{\mathrm{F}}^{\text{3-D}}$ computed from the fluoroscopic images using the ICP method [7]. As the ICP is point-based, 10 to 60 3-D points were sampled from each curve, depending on their length.

For each point of the curves $\mathcal{E}_{\mathrm{V}}^{\text{3-D}}$ and $\mathcal{C}_{\mathrm{V}}^{\text{3-D}}$, a matching needs to be performed, i.e. the closest point sampled from the curves $\mathcal{E}_{\mathrm{F}}^{\text{3-D}}$ and $\mathcal{C}_{\mathrm{F}}^{\text{3-D}}$ is found. As each curve is labeled, either as esophagus or as CS, points from $\mathcal{E}_{\mathrm{V}}^{\text{3-D}}$ were matched only to points $\mathcal{E}_{\mathrm{F}}^{\text{3-D}}$ and points from $\mathcal{C}_{\mathrm{V}}^{\text{3-D}}$ only to points from $\mathcal{C}_{\mathrm{F}}^{\text{3-D}}$. As the number of points was small exhaustive search could be applied.

The CS segmentation in the volume and the CS reconstructed from the fluoroscopic images may describe different but overlapping parts of the CS. To compensate for this, matchings having a large distance between their points are rejected. The number of matchings rejected is defined by the rejection rate r. The value of r should correspond to the fraction of the reconstructed 3-D model that has no counterpart in the 3-D device segmented from voxel data.

Finally, the transform that minimizes the distance between both 3-D point sets is computed and a next iteration is performed. The iteration number was set to 10, a higher number of iterations provided similar results.

2.4 Experimental Setup

For evaluation, we used data from six different patients. Each patient data set comprised a C-arm CT volume ($256\times 256\times 256$ voxels, 0.92 mm/voxel) and a biplane image sequence (512×512 pixels, 0.43 mm/pixel) acquired directly after the C-arm CT. All data (3-D and 2-D) was recorded on a AXIOM Artis biplane C-arm System (Siemens Healthcare GmbH, Forchheim, Germany) under breath hold and rapid pacing. The left atrium was acquired in five data sets, and the sixth data set included a right atrium.

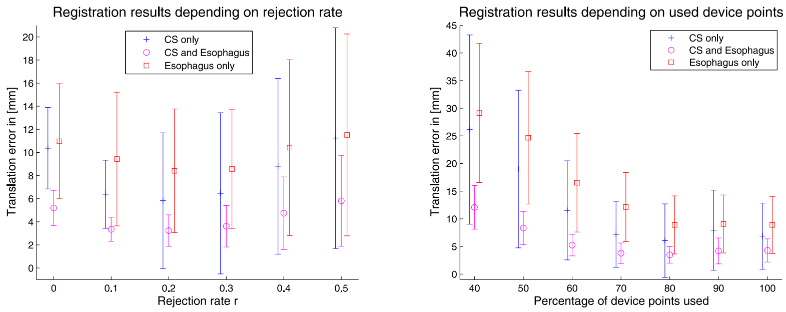
A reference registration was performed for the first frame of the biplane sequence with respect to the contrast agent that was injected into the atrium. The 3-D shape of the anatomy in the volume was extracted by manually segmenting the catheters visible in the C-arm CT volume.

In clinical practice, the relative rotation between 2-D projection data and forward projected 3-D data of atria is very small and not perceivable in the fluoroscopic images and therefore typically ignored. In the experiments, we considered therefore only the translation error as in [6]. Nevertheless, we tested robustness against rotation by using 30 different random initializations involving a normally distributed translation and rotation with zero mean and standard deviation of 10 mm and 5 degree, respectively.

Depending on the anatomy and the physician's preference, the CS catheter may or may not be introduced far into the CS. As a result, it may happen that only a shorter piece of the catheter is visible in the 2-D images. To evaluate the registration performance for devices introduced less far, we removed points from the device tip to reduce their lengths by a certain percentage c. Additionally, we investigated the impact of the parameter r on the registration performance.

3 Results

The evaluation results for different values of the rejection rate r and $c = 20\,\%$ are shown in Figure 2(a). Registration using both the CS and the esophagus outperformed registration using only one anatomical structure considerably. The best results were obtained for $r = 20\,\%$. In this case, the translation registration error



(a) (b)

Fig. 2. Registration translation error. (a) Regardless of the choice of r, the combination of CS and esophagus outperforms a registration based on only a single anatomical structure. For this figure, $c = 20\,\%$ of the reconstruction of the 2-D devices was cut away. Note that results are best for $r = 20\,\%$ which corresponds to the value of c. (b) Results when using only a certain percentage of the catheter reconstructed from two 2-D images.

was 3.2 ± 1.4 mm when relying on both CS and esophagus and 5.8 ± 5.9 mm when only the CS was used. The difference is significant according to Student's t-test. Evaluation results of the registration performance when using only parts of the catheters reconstructed from 2-D are shown in Figure 2(b). While the registration using the esophagus depends heavily on this percentage, the registration using the CS is affected less. Still, a combination of CS and esophagus is superior.

4 Discussion

Our experiments showed that a registration using the CS is possible for our C-arm CT data. For EP applications, an error of below 5 mm is required [10]. In this case, the esophagus need to be integrated into the registration as well. Although the esophagus alone is not well suited for finding a unique registration solution in head-foot-direction due to its line-like shape, see Fig. 2(b), it helps constraining the result in the transverse plane. This could be also achieved by including the spine into the registration procedure. Note, however, that the spine may only be partially visible depending on the detector size and C-arm angulation.

In our data, only linear temperature probes were used. For spiral-shaped temperature probes, a spatial averaging with respect to the transverse plane might be required after 3-D reconstruction to obtain the esophagus center line.

The way the data was acquired was well suited for device-based registration: The patients were fully anaesthetized and intubated and both, the C-arm CT and the following X-ray biplane images, were acquired under breath-hold and rapid pacing. So, there was almost no cardiac and respiratory motion between the volume and the X-ray images. A registration using image acquisition without rapid pacing would be more difficult as the position of the CS depends highly on the cardiac phase, i.e. the contraction of both the ventricle and the atrium. For patients suffering from AFib, this motion might be irregular. Also the esophagus moves slowly, even within a procedure. As the fluoroscopic images were acquired directly after the volume, this motion could be neglected. If the volume would have been acquired, e.g., a day before, the error might have been larger.

As a conclusion, integrating the esophagus into device based registration improves results for data acquired using a C-arm CT setup as encountered here. Having an esophagus model available, could also be helpful, e.g., for re-registration which may be required during intervention. The improvement holds also for a less ideal fit which we generated by cutting parts of the catheter away, see Fig. 2(b). In a future work, a study should be conducted to assess the accuracy of a registration based on multiple devices with respect to a different clinical workflow including unpaced heart rhythm and free breathing.

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References

1. Calkins H, Brugada J, Packer DL, Cappato R, Chen SA, Crijns HJG, et al. HRS/EHRA/ECAS Expert Consensus Statement on Catheter and Surgical Ablation of Atrial Fibrillation: Recommendations for Personnel, Policy, Procedures and Follow-Up. Europace. 2007 June;9(6):335 – 379.
2. Ector J, Buck SD, Huybrechts W, Nuyens D, Dymarkowski S, et al. Biplane three-dimensional augmented fluoroscopy as single navigation tool for ablation of atrial fibrillation: Accuracy and clinical value. Heart Rhythm. 2008 July;5(7):957 – 964.
3. Hoffmann M, Bourier F, Strobel N, Hornegger J. Structure-Enhancing Visualization for Manual Registration in Fluoroscopy. In: Proc. BVM; 2013. p. 241–246.
4. Zhao X, Miao S, Du L, Liao R. Robust 2-D/3-D Registration of CT Volumes with Contrast-Enhanced X-ray Sequences in Electro-physiology Based on a Weighted Similarity Measure and Sequential Subspace Optimization. In: Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE Int. Conf. on; 2013. p. 934–938.
5. Sra J, Krum D, Malloy A, Vass M, Belanger B, Soubelet E, et al. Registration of Three-Dimensional Left Atrial Computed Tomographic Images With Projection Images Obtained Using Fluoroscopy. Circulation. 2005;112(24):3763–3768.
6. Brost A, Bourier F, Yatziv L, Koch M, et al. First steps towards initial registration for electrophysiology procedures. In: Medical Imaging 2011: Visualization, Image-Guided Procedures, and Modeling. vol. 7964. SPIE; 2011. p. 79641P.
7. Besl PJ, McKay ND. A Method for registration of 3-D shapes. IEEE Trans Pattern Anal Mach Intell. 1992;14(2):239–256.
8. Fieselmann A, Lautenschläger S, Deinzer F, John M, Poppe B. Esophagus Segmentation by Spatially-Constrained Shape Interpolation. In: Proc. BVM. Springer Berlin Heidelberg; 2008. p. 247–251.
9. Hoffmann M, Brost A, Koch M, Bourier F, Maier A, Kurzidim K, et al. Electrophysiology Catheter Detection and Reconstruction from Two Views in Fluoroscopic Images. Transactions on Medical Imaging. 2015;ahead of print.
10. King AP, Boubertakh R, Rhode KS, Ma YL, Chinchapatnam P, Gao G, et al. A subject-specific technique for respiratory motion correction in image-guided cardiac catheterisation procedures. Medical Image Analysis. 2009;13(3):419 – 431.