2D-3D Registration of Cardiac Images Using Catheter Constraints

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Abstract

Cardiac catheterization procedures are routinely guided by X-ray fluoroscopy but suffer from poor soft-tissue contrast and a lack of depth information. These procedures often employ pre-operative magnetic resonance or computed tomography imaging for treatment planning due to their excellent soft-tissue contrast and 3D imaging capabilities. We developed a 2D-3D image registration method to consolidate the advantages of both modalities by overlaying the 3D images onto the fluoroscopy by using catheters that are placed in vessels of the heart where they remain throughout the procedure. To achieve registration, an automatic global-fit algorithm was developed which minimized the root-mean-square distance error of the catheter to the medial line of its respective vessel. Data were processed for three clinical cases and an accurate registration was validated by visual inspection.

1. Introduction

Cardiac catheterization procedures are routinely guided using X-ray fluoroscopy. This modality is suitable due to its high spatial and temporal resolutions, relative low-cost, ubiquitous availability and excellent catheter visibility. However, fluoroscopy has poor soft-tissue contrast and the cardiologists need to rely on their expertise to accurately position the catheters. Cardiac electrophysiology (EP) procedures are commonly carried out to treat electrical pathologies, such as arrhythmias, usually using radio-frequency (RF) ablation of endocardial tissue. These procedures are often prolonged due to the requirement of accurate positioning of catheters and therefore there is significant radiation exposure to the patient and staff, and often a suboptimal success rate. Recently, there has been much research to register pre-procedural three-dimensional (3D) anatomical information from computerized tomography (CT) or magnetic resonance (MR) imaging to help guide EP procedures by overlaying the 3D anatomical information onto the live two-dimensional (2D) X-ray fluoroscopy [1]. Rhode *et al.* previously reported a technique that uses a pre-calibrated hybrid X-ray/MR (XMR) imaging system [2]. However, these systems are not widely available outside the research environment. 2D-3D registration for these procedures can be carried out using surrogate structures such as fiducial skin markers. However, the relative motion between the heart and the surrogates due to cardiac and respiratory motion may compromise their accuracy, and surrogates must be in the same field of view as the heart in order to perform registration; these would not be an issue if the target organ is used itself. Approaches that do so include manual registration with biplane contrast-filled angiograms [3, 4] and using the catheter that is placed within the coronary sinus (CS) during EP procedures (EPNavigator, Philips Healthcare).

Using the CS catheter for registration is attractive since no additional data acquisition is required and therefore there is no disturbance to the routine clinical workflow. Sra *et al.* first proposed using the CS catheter for 2D-3D registration [5]. However, in this approach, the author reported that manual adjustment of registration was required in nine out of 20 of the reported clinical cases. Additionally, registration would have to be performed every time there was motion of the X-ray c-arm, patient table or patient relative to the table.

We aim to develop a clinically robust method to perform 2D-3D registration of 3D cardiac data (CT or MR) to X-ray fluoroscopy using catheters that are reconstructed in 3D from sequential biplane X-ray images, and structures segmented from 3D data. We focus on the use of the CS and the aortic catheters. Our approach differs from that of Sra *et al.* because we perform the registration in 3D and then project to the X-ray image using a pre-calibration of the X-ray system. Furthermore, the registration only needs to be performed at the beginning of the procedure and is then updated automatically by tracking the motion of the X-ray c-arm and table. Repeat registration is only required if the patient has moved on the X-ray table. We demonstrate the use of the approach on three clinical EP procedures.

2. Methods

The clinical procedures were performed in the XMR interventional suite at St. Thomas' Hospital, London, which is equipped with a 1.5T cylindrical bore MR scanner (Achieva, Philips Healthcare) and a single plane X-ray system (BV Pulsera, Philips Healthcare). The X-ray system projection geometry was pre-calibrated and the c-arm and patient table were tracked [2]. Three patients with heart failure were imaged using MR and underwent a pacing study prior to pacemaker implantation. The imaging used a whole heart MR sequence carried out after the administration of a blood pool contrast agent (Vasovist, Bayer Schering Pharma). The sequence was a 3D steady-state free precession scan with an inversion recovery preparation RF-pulse, respiratory navigator gated at end-expiration and ECG triggered at late diastole. During the EP procedure, the CS was catheterized followed by the acquisition of sequential biplane fluoroscopy images at ten frames per second during free-breathing.

2.1. Registration workflow

The workflow of our registration is divided into three parts. First, the CS' medial line is extracted from MR Next, the CS catheter is reconstructed in 3D from a sequential biplane X-ray pair. Lastly we find a transformation that minimizes the root-mean-square (RMS) distance error between the medial line of the CS and the catheter reconstruction. This transformation, combined with a calibrated and tracked X-ray system, enables us to perform the overall 2D-3D registration.

2.2. Coronary sinus extraction from MRI

The interactive segmentation of the CS from the MR scan was carried out using a specially modified version of ViewForum (Philips Healthcare) (Fig. 1a). Since the CS is a thin structure, we approximate it to its medial line. The initial medial line was found using a 3D 6-subiteration curve thinning algorithm [6] but it was sensitive to imaging and segmentation artifacts resulting in extraneous branches, internally-closed circuits (ICC) and large nodes (LN) (Fig. 1b). Therefore we employed a combination of image processing techniques [7], first applying an erosion and subsequent dilation to the pre-skeletonized segmented CS. We then convolved the skeleton with a 3×3×3 Gaussian kernel and reapplied the skeletonization to eliminate the ICCs and LNs. Finally, short end-branches were removed. This two-pass thinning process produced a cleaner and simpler skeleton while maintaining the topology of the CS (Fig.1b, 1c).

Geometrically the catheter is homeomorphic to a line and thus may only be contained by one skeleton pathway. To avoid manual selection of the containing pathway, our algorithm employs a global-search strategy by considering all possible pathways of the skeleton and their reverse directions.

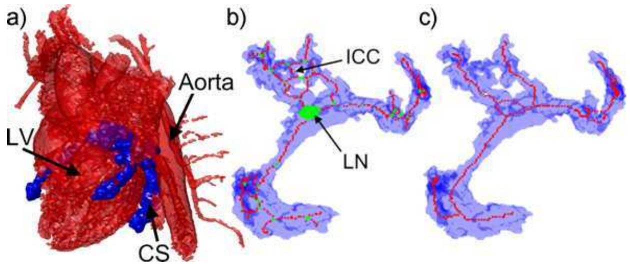

Figure 1. a) The CS (*blue*) segmented from the rest of the heart (*red*) with the left ventricle (*LV*) and aorta labeled. b) The CS (*blue, translucent*) and its skeleton divided into branches (*red, opaque*) and nodes (*green, opaque*). The skeleton produces 1202 distinct pathways. c) Two-pass skeleton with only 80 distinct pathways.

2.3. Coronary sinus catheter from X-ray

The CS catheter is reconstructed in 3D using epipolar geometry [8] from cardiac and respiratory gated X-ray images. We calibrate our X-ray c-arm using the methods described in [2]. With this calibration and a tracked c-arm system, we manually select catheter points in one view and their corresponding points in the other with the aid of the epipolar constraint (Fig 2a). Back projection of the corresponding X-ray point pairs is used to determine their 3D positions (Fig 2b).

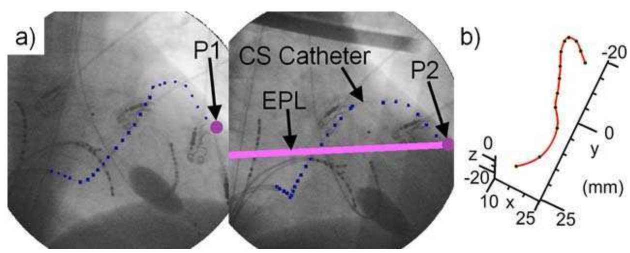

Figure 2. a) AP (*left*) and LAO 30° (*right*) X-ray views of the heart gated at end-diastole and end-expiration. Points along the CS catheter are selected in both images (*blue dots*). A point from the left image (*P1*) generates an epipolar line in the right image (*EPL*); its corresponding point lies at an intersection of EPL and the catheter (*P2*). b) 3D Spline reconstruction of the catheter.

2.4. Registration

Registration of our MR to X-ray images requires that we find the relationship between the patient's positions while in the MR scanner and when on the X-ray table. Since the images acquired are cardiac and respiratory gated in both modalities, we assume that the heart returns to the same shape at the same phase and therefore describe this relationship as a *rigid-body transformation* which can be represented as $T = (R, \vec{r}_0)$, with

$$\vec{r}_{t,i} = R\vec{r}_{s,i} + \vec{r}_0 + e_i; \forall i \in [1,n] \quad (1)$$

Where $\{\vec{r}_{t.i}\}$ and $\{\vec{r}_{s.i}\}$ are the set of points in the X-ray table coordinate system and in the MR scanner coordinate system respectively, R is the 3×3 rotation matrix, and $\vec{r}_0$ is the translation vector. The residual error of this transformation e is calculated by Eq. 2. By representing the transformation in this form, it readily identifies itself as the Orthogonal Procrustes problem [9].

$$e = \tfrac{1}{n}\sum_{i=1}^{n}\|e_i\|^2 = \tfrac{1}{n}\sum_{i=1}^{n}\left\|\left(R\vec{r}_{s,i} + \vec{r}_0\right) - \vec{r}_{t,i}\right\|^2 \quad (2)$$

Since the 3D reconstructed points of the CS catheter obtained from X-ray are non-uniformly sampled in space, we fit a natural cubic spline through it and sample the spline at 0.2 mm intervals (catheter curve), and do the same for each CS pathway obtained from its skeletonization (CS curves). These evenly sampled points are used with the Procrustes solution. The following global-fit pseudo-code algorithm determines which CS curve, when compared against the catheter curve, would yield the lowest error.

```
Let rt[i] be the ith point of the catheter curve
Let rs[k][i] be the ith point of the kth CS curve
Let r[a:b] be the subcurve of r between a and b.
for k = 1 to # of CS curves
  n = # points in rt; m = # points in rs[k]
  L = max(m, n) - min(m, n) + 1
  if n>m:I=argmin{i}(e(rs[k][1:n],rt[i:i+L-1])),
         E[k]=e(rs[k][1:n],rt[I:I+L-1]);
  else:I=argmin{i}(e(rs[k][i:i+L-1],rt[1:m])),
         E[k]=e(rs[k][I:I+L-1],rt[1:m]);
return argmin{k}(E[k])
```

Registration can be performed once we find the minimum error-yielding transformation by applying it to the MR image and projecting it onto the X-ray images.

2.5. Registration with multiple catheters

A potential problem of a single catheter/vessel-pair approach occurs if their curvatures are insufficient. For example, if both the catheter and its containing vessel were straight, then the catheter may slide along, and rotate around, the vessel axis while yielding the same residual error. Additionally, in our global-fit algorithm, it is possible that two or more vessel paths may have a very similar shape to the catheter, yielding competitively low residual errors. Both these degenerate scenarios may be improved by introducing an additional catheter that is constrained to lie in a vessel throughout the procedure, such as the one lying in the aorta. A drawback to using the aorta or other large-diameter vascular structures is that the catheter has more room to move around, thus the assumption that catheter lies close to its medial line is less likely to be correct. However, the gain in accuracy of introducing a second catheter/vessel pair should outweigh any potential reductions in accuracy caused by the catheter lying a distance from the vessel's medial line.

3. Results

We applied our algorithm on three clinical cardiac catheterization cases and show example results from one of them. Following the method outlined above, the CS was extracted from the heart and skeletonised (Fig. 1). Extraction by an expert could be performed in under 30 minutes and its skeleton requires one hour to compute. (Intel Core 2 Extreme @ 2×3 GHz, 4 GB RAM). The catheter was also reconstructed in 3D by selected points from sequential biplane images (Fig. 2) and could be performed by an expert in under 20 minutes. Approaches to automate and speed up the extraction of the catheter and vessels are addressed in the discussion section.

An example residual error curve is shown in Fig. 3a where the Procrustes solution in applied for a particular CS and catheter curve. We choose the transformation that yields the lowest residual error for our registration. The dual-catheter equivalent graph is a residual surface (Fig. 3b) where all combinations of the CS curves with the CS catheter, and the aorta curves with the aortic catheter, must be explored.

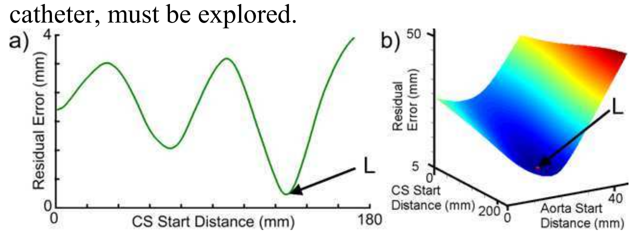

Figure 3. a) For a CS curve, the Procrustes solution is applied between its subcurves and the catheter curve. The lowest point (*labeled L)* indicates where the catheter starts along the particular CS curve. b) The two-catheter equivalent of a); the minimum is at the valley of the surface (*L*).

In Fig. 4a we apply our transformation on the segmented CS image and draw the catheter onto the image in 3D. Once we find the transformation to get the image into the table coordinate system, we may apply it to the 3D image of the heart using Eq. 1, then use the intrinsic parameters to project it onto one of the intraoperative X-ray images as in Fig. 4a and b.

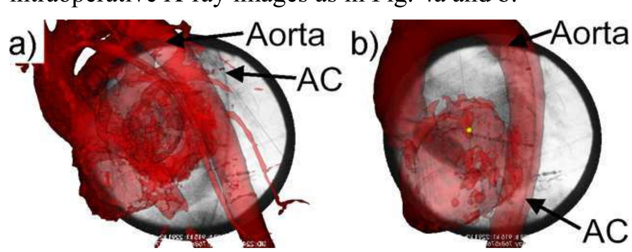

Figure 4. a) Model of the heart (*red*) overlaid on the X-ray using only the CS to constrain the registration, but is misaligned. b) Both the CS and aortic catheter/vessel pairs are used, resulting in a more accurate registration.

While our algorithm was able to find an accurate registration for two cases, it was unsuccessful when applied to the third. We found that the geometric relationship between the CS and aorta from MR did not match the relationship between the reconstructed CS and aortic catheters from X-ray, resulting in a misaligned registration. This is discussed further in the next section. The global-fit registration algorithm for a single-catheter could be performed in 25 minutes and a significant 30.8 hours for the dual-catheter registration.

4. Discussion and conclusions

We have shown that we can accurately perform a 2D-3D registration algorithm to overlay pre-operative MR image onto intra-operative X-ray using data from routine clinical cases. The algorithm relies on catheters placed within vessels that remain there throughout the procedure. In cardiac catheterisation procedures, this is a valid assumption as it is typical to employ several such catheters to collect essential EP data from the patient.

Our method also uses the rigid-body assumption; that the heart is the same shape for all images taken at end-diastole and end-respiration. However, the heart is a non-rigid structure that undergoes significant motion and deformation over the respiratory and cardiac cycles. Since our MR and X-ray images used for registration are acquired with many of these cycles between them, this assumption may be compromised. A small improvement can be made by using simultaneous biplane, as show in [10], however a biplane X-ray system is required and this is not widely used for EP procedures. Additionally, the relative rigidity of the catheter may deform the vessel that it rests in during the procedure compared to the when the 3D images are acquired. Therefore, we believe that the deformability of the heart is a primary contributing factor to the error of our registration and is likely the cause of failure in our second case. On the other hand, hereto this paper, we have only considered using two catheters for registration and we have yet to determine if the inclusion of a third may increase accuracy, precision, or provide redundancy and hence robustness.

The computational cost of our algorithm is a concern since it is intended to be employed intra-operatively; once for the initial registration of the heart and for each time there is bulk patient motion. A future improvement to reduce computing time would be to adaptively sample the catheter and vessel splines, initially at a courser resolution to reduce the number of potential vessel pathway candidates, then at the finer resolution of 0.2 mm as per the current algorithm on the remaining candidates. Additionally, our algorithm would benefit greatly from using parallel and GPU processing since most of the computations may be performed independently of each other due to the global-fit nature of our approach. Lastly, our method requires the manual extraction of the catheters in X-ray and of the corresponding vessel in MR, which adds to the overall processing time. In the future, we envision our algorithm to be completely automated, potentially by employing the techniques presented in [8] for automatic catheter extraction from biplane X-ray, in [11] for automatic segmentation in MR and in [12] for CT.

While our results are preliminary, we believe that our 2D-3D registration algorithm, combined with a tracked c-arm for real-time capabilities, may improve visualization of fluoroscopy guided catheter interventions.

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