High Intensity Focused Ultrasound (HIFU) Therapy Guidance System by Image-based Registration for Patients with Cardiac Fibrillation

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Univ Rennes, INSERM, LTSI – UMR 1099, F-35000 Rennes, France

Abstract

Transesophageal high-intensity focused ultrasound (HIFU) energy can be used to treat cardiac arrhythmia efficiently non-invasively. Since the esophagus is located just behind the heart, it offers a perfect acoustic window. Hence, HIFU can be directed toward the heart to perform ablation. In a previous study a HIFU probe with one 2D US image perpendicular to the esophagus axis for guidance purpose has been proposed. A new dual-mode HIFU probe with two perpendicular 2D US imaging plane is now under development. In this paper we propose a therapy guidance system, based on an intensity-based registration of the two perpendicular 2D US to preoperative 3D CT. As a proof of concept we developed the following evaluation framework on a numerical phantom: 1) because the probe is under development we define a ground truth (GT) initial pose inside a CT volume and simulated two perpendicular US images from the CT data; 2) we run the registration framework from 55 randomly defined pose initializations around the initial GT pose; and 3) we estimated the accuracy of the registration by (a) the transformation parameter estimation errors (translation error and quaternion distance for rotation) and (b) Target Registration Error (TRE) on 8 features. The accuracy of the registration using two 2D US plane has been compared to the previous work performed on only one US plane. An improvement was observed when using two 2D US planes with regards to the previous one US plane

1. Introduction

Catheter ablation procedure is an important therapeutic option for patient with arrhythmia (e.g this procedure aims to eliminate the sites of early activations of ventricular fibrillation [1]). Depending on the arrhythmia, the success rate varies from 30% to more than 95% [2]. The more challenging the arrhythmia is to ablate, the more complications can occur. The complication rate is about 1% to 3% [2]. Strokes represent the most serious one, and vascular injuries are the most frequent. Ultrasound-guided HIFU is an alternative to other ablation techniques [3]. HIFU energy can be used to create thermal propagation path [4] without damaging the intervening tissues.

Transesophageal HIFU cardiac fibrillation therapy is a mini-invasive treatment that places the HIFU transducer close to the ablation zone by navigating inside the esophagus, the probe navigation and transducer positioning is carry out using an embedded ultrasound (US) imaging system [4, 5]. As any mini-invasive procedure, first a therapy planning (the ablation path) is defined on a high-resolution anatomical preoperative 3D imaging (CT/MRI). The goal of this work is to propose a therapy guidance system by the registration of the intraoperative 2D US images to the preoperative 3D CT volume, in order to guide and ablate a specific zone of the heart chosen by the experts in the 3D CT volume.

An intensity-based cardiac 2D US to cardiac CT image rigid registration method has been described in [5]. In [6] an intensity-based similarity measure is used to register interventional 2D CT-fluoroscopy to high-resolution contrast-enhanced preoperative CT image data for a radiofrequency liver ablation procedure, and in [7] an intensity-based similarity metric is employed within a small region to register intra-operative 2D CT-fluoroscopy images to a preoperative CT volume to track the motion of pulmonary lesions for a robotically assisted lung biopsy. Similarly in [8], intensity-based similarity measures is employed to register intraprocedural 2D MR images with preprocedural 3D MR images during an MRI-guided intervention. Finally, in [9] a rigid registration is performed to align 3D reformatted preoperative 3D CT volume with 2D US image, they reduce the number of DOF to two DOF (the depth of slices and the rotation in that slice) by assuming that US probe is perpendicular to the esophagus axis. The idea was to extract all the CT slices perpendicular to the esophagus and to perform a 2D US/CT registration on these reformatted slices. The main drawbacks of their method were that they weren't sure that the US slice was really perpendicular to the esophagus axis, and that one plane seemed not to be enough to reach the needed accuracy.

In this paper, we propose to perform a two 2D/3D (slice-volume) registration of the intraoperative 2D US and the preoperative CT without any external tracking system. More precisely the 2D /3D registration consists of finding the 3D pose (location and orientation) of the US image slice inside the preoperative 3D volume using only image-based information.

2. Two 2D-US/3D-CT image-based Registration

This registration method is using a 3D CT volume and two perpendicular US images acquired on the HIFU probe (Figure 1). Because the US imaging tool is ECG-gated, we consider only the US images at the same cardiac phase as the CT (diastolic phase when the heart muscle relaxes and the blood fills the heart) so only a 3D rigid transform with six DOF has to be estimated. We have also an initial rough estimation of the pose of the probe inside the 3D CT. From this initial pose, we performed the following two 2D/3D (two perpendicular slices/volume) image-based registration approach to refine the estimation of the transesophageal probe pose

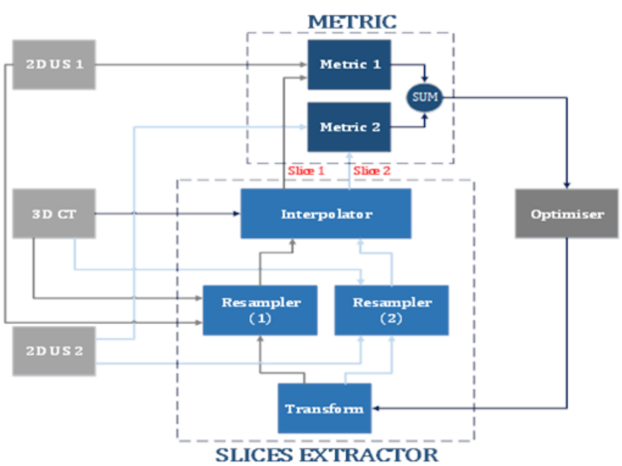

Figure 1. General framework of our proposal approach

This approach is characterized by:

1. slice extraction

For a specific probe pose, the 3D transform allows us to define the US imaging referential system $\left(\vec{O}_i, \vec{x}_i, \vec{y}_i, \vec{z}_i\right)$, in which the 2 perpendicular planes $(x_i–y_i)$ and $(y_i–z_i)$ represent the US perpendicular slices. The CT volume is then sampled along these two fixed planes to provide the information in the same spatial context (same size, spatial location and orientation) as the US images, by using the transformation parameter.

The space coordinates of the 3D image are mapped through the transform in order to generate new images. The interpolator is required since the mapping from one space to the other will often require an evaluation of the intensity of the image at non-grid positions.

2. similarity metric

The metric component is one of the most critical component of our framework. We used Mutual Information, winch is the most suitable to our data [10], to compare the information of the US images and the corresponding information extracted from the CT data. The global similarity will be the sum of the similarity measures between the two sets of slices.

3. Optimizer

At each iteration, the previous metric component provides a measure of how well the fixed images is matched by the transformed moving images. This measure forms a quantitative criterion to be optimized over the search space defined by the parameters of the transform.

We used stochastic gradient descent to estimate the pose which maximize the global similarity.

3. Results

3.1. Data

This study has been conducted on a patient with fibrillation CT dataset, obtained from Louis Pradel University Hospital in Lyon, France. The dimensions of the reconstructed image is $512 \times 512 \times 323$ voxels with an image spacing of $0.546875 \times 0.546875 \times 0.55031\ \mathrm{mm}^3$. Because the HIFU probe with the two perpendicular US imaging planes is still under development, we validate our method on simulated US data. Hence, we defined an initial pose (the ground truth-GT) inside the CT volume. From this pose we extracted two perpendicular slices from the CT and simulated the corresponding US slices with the method described in [11].

3.2. Experimental protocol

We want to look about the robustness of the method, for that we arbitrary produced 55 initial poses in a range of $\pm 5\ \mathrm{mm}$ on translation and $\pm 5°$ in rotation around the GT pose, then we performed the registration from these poses and compare it to our GT.

3.3. Evaluation

We evaluate the influence of using two planes compared to use only one. The accuracy of the registration has been estimated using two metrics.

1. Transformation estimation error

For each parameters (translation/rotation along x, y, z), the distance between the estimated pose of each trial and GT is computed. We estimated the translation errors by equation

(1), where $T_{GT,i}$ and $T_{EST,i}$ are the positions of the pose of respectively the GT and the estimated one.

$$|T_{GT,i} - T_{EST,i}| \tag{1}$$

The rotation error has been estimated by the quaternion distance by equation (2), where $q_{GT,i}$ and $q_{EST,i}$ are the quaternion that encode the orientation the pose of respectively the GT and the estimated one.

$$2\cos^{-1}\left(real(q_{GT,i} * q_{EST,i})\right) \tag{2}$$

If we compared the results obtained by using two perpendicular planes vs one plane only we can notice that the median translation error is reduced from 1.5 to 0.7 mm. (Figure 2) and that rotation transformation errors were reduced from $3°$ to $2.1°$ when using two perpendicular slices (Figure 3).

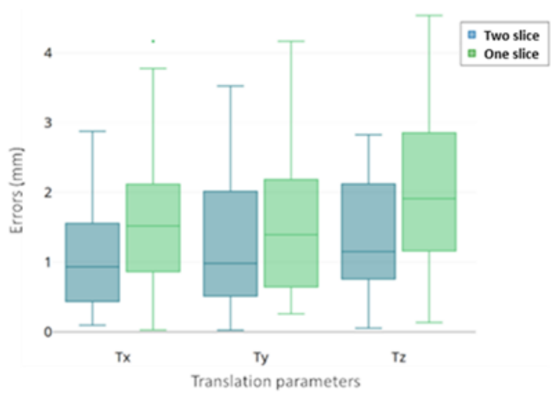

Figure 2. Distance between the estimated translations and the GT along each axis

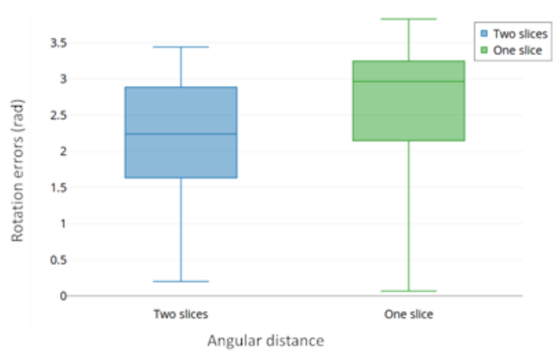

Figure 3. Angular distance between the estimated rotations and the GT

2. Target Registration Error (TRE)
The validation can be done by estimating registration errors on some specific feature points. To quantify the error, we defined eight specific feature points (or landmarks) P_j in the two 2D-US fixed images, and we used the estimated transformations matrix $\mathbf{T_{est}}$ and the ground truth $\mathbf{T_{GT,i}}$ to project these points in the 3D-CT volume (equation 3). The estimated error, called the Target Registration Error (TRE), will be the distance between these two reprojected points in the 3D volume [12].

$$TRE(P_j) = \|T_{real,i} - T_{EST,i}\| \tag{3}$$

From Figure 4, we can observe that the global mean error of TREs on all the fiducial markers was decreased from 2.54 to 1.7 mm when using two perpendicular slices. This accuracy increase is statistically significant (p-value = 0.035).

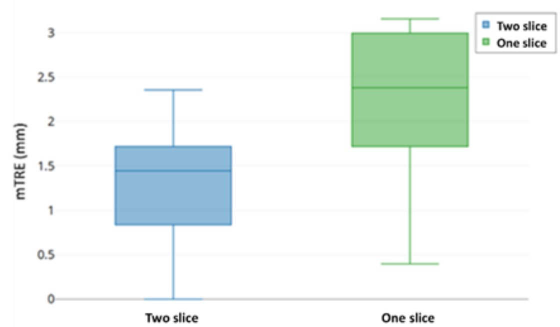

Figure 4. Box plots of the mean Target Registration Error (mTRE)

Regarding the registration accuracy, The global mean target registration error (mTRE) of 1.7 mm is on the same range of magnitude as those reported in the literature: less than 5 mm for [13] and $1.5-4.2$ mm for [14] and 5.6 mm for [9].
3. Visual validation
Figure 5 shows the simulated US images (b and d) and their superimposition to the estimated corresponding reformatted CT slice (a and b). The visual examination of these two figures shows a good alignment with an initial point around the ground truth (GT). Some more accuracy could probably be gained by considering the estimated pose as a starting point closer to the ground truth.

4. Conclusion

In this study, a minimally-invasive HIFU procedure was proposed for the treatment of atrial fibrillation. In this context, image processing methods were proposed to improve the planning and the guidance of the therapy. We have proposed a novel two perpendicular 2D-CT/3D-CT registration approach adapted to the guidance of the trans-esophageal HIFU therapy. We performed rigid registration of two 2D planar echocardiography images with a cardiac 3D CT volume.

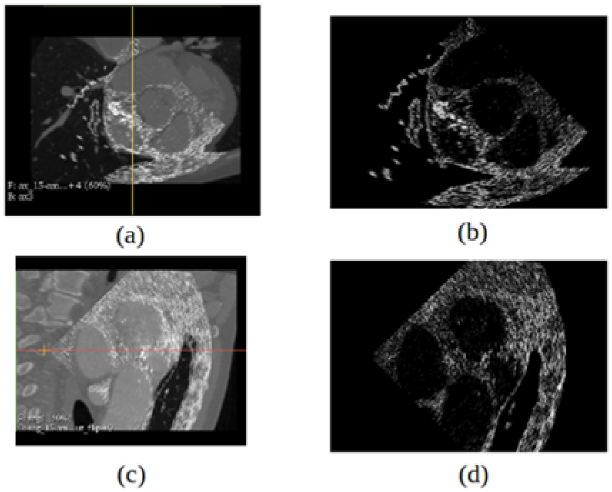

Figure 5. Visualization result (a) resulted CT slice 1, (b) image US1, (c) resulted CT slice 2, (d) image US2

The results indicate a promising accuracy of the proposed technique. Our future work aims to include a phantom and real-patients data to evaluate the contribution registration scheme for the therapy guidance

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Address for correspondence:

Batoul Dahman
LTSI / Université Rennes 1
Campus de Beaulieu / F-35042 Rennes / France
Tel: +33 2 23 23 56 05 - Fax : +33 2 23 23 69 17
batoul.dahman@univ-rennes1.fr