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

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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 [1]. A new dual-mode HIFU probe with two perpendicular 2D US imagining 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 initialization 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 previous work with 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 aim to establish a line of lesions around the pulmonary veins in order to block trigger points of atrial fibrillation). 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], [5], 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 oesophagus, the probe navigation and transducer positioning is carry out using an embedded ultrasound (US) imaging system [6]. 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 [1], [3], [6]–[11].

An intensity-based cardiac 2D US to cardiac CT image rigid registration method has been described in [8]. The 2D slice is one slice imaged from a 3D object with a randomly pose and is equivalent to a slice extracted from a 3D volume of the object. In [12] an intensity-based similarity measure is used to register interventional 2D CT-fluoroscopy to high-resolution contrast-enhanced preoperative CT image data for a radio-frequency liver ablation procedure, and in [13] 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 [14], intensity-based similarity measures is employed to register intraprocedural 2D MR images with pre-procedural 3D MR images during an MRI-guided intervention. Finally, in [1] 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 is perpendicular to the oesophagus axis, then all the CT planes perpendicular to the oesophagus is extracted and reformatted the CT volume. The main drawbacks they weren't sure that the US slice is really perpendicular to the oesophagus axis, and one plane it seems to be not enough.

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. Materials and methods

2.1. 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 × 512 × 323 voxels with an image spacing of 0.546875 × 0.546875 × 0.55031 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 [9].

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

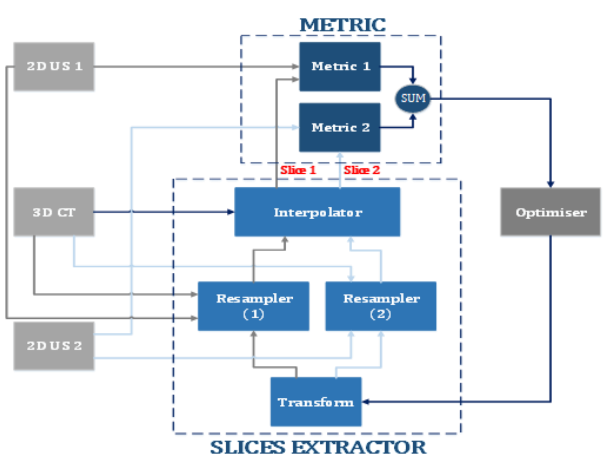

Figure 1 General framework of our proposal approach.

This registration method is using a 3D CT volume and two perpendicular US images acquired on the HIFU probe Fig 1. Because the US imaging tool is ECG-gated, we consider only the US images at the same cardiac phase as the CT and 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 (e.g. estimated roughly by the method described in [7]). 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.

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 $(\vec{O_\iota}, \vec{x_\iota}, \vec{y_\iota}, \vec{z_\iota})$, 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 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 metric component S (f, m ∘ T) 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. Experimental protocol

We arbitrary produced 55 initial poses in a range of ± 5 mm on translation and ± 5° in rotation around the GT pose and performed the registration.

3.2. Evaluation

The accuracy of the registration using two 2D US plane has been estimated and compared to a previous work with only one US plane.

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. The median translation error is reduced from 1.5 to 0.7 mm. Figure 1 and Figure 2 shows the rotation transformation errors which are reduced from 3° to 2.1° when we used two perpendicular slices.

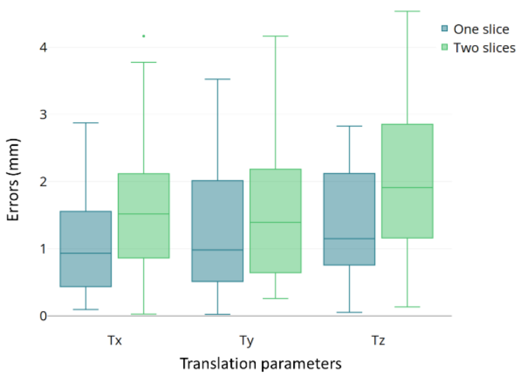

Figure 2 distance between estimated translations and GT along each axis.

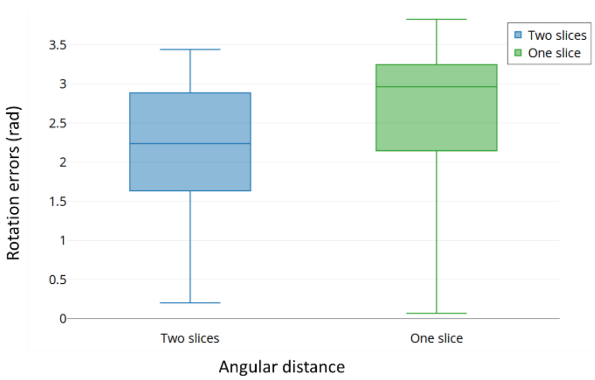

Figure 3 angular distance between estimated rotations and GT.

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 two transformations matrices Test and TGT to project these points in the 3D-CT volume. The estimated error called the Target Registration Error (TRE) will be the distance between these two projected points [15].

$$TER(Pj) = TGTPj - TEstPj$$

From Figure 4, we can observe that the global mean error of all the fiducial markers was decreases from 2.54 to 1.7 mm while using two perpendicular slices.

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 [16] and 1.5 − 4.2 mm for [17] and 5.6 mm for [1].

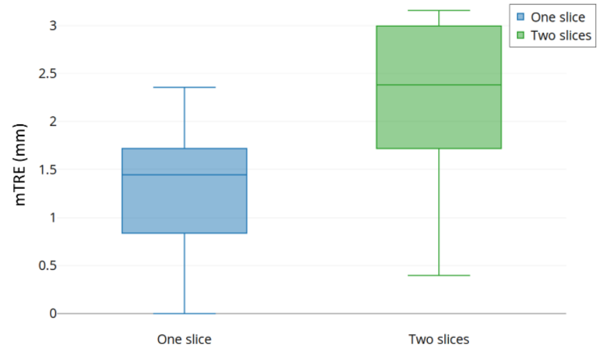

Figure 4 Box plots of the mean Target Registration Error (mTRE).

3) Visual validation

Figure 5 shows the simulated US images (a and c) and their superimposition to the estimated corresponding reformatted CT slice (b and d). 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.

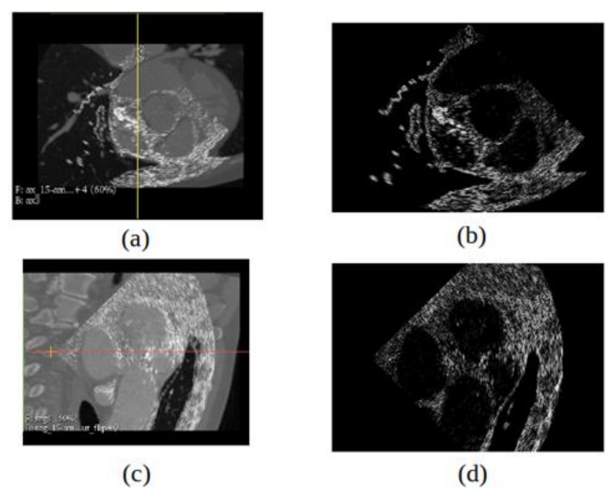

Figure 5 Visualization result (a) resulted CT_slice 1, (b) image_US1, (c) resulted CT_slice 2, (d) image_US2.

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 transesophageal HIFU therapy. We performed rigid registration of two 2D planar echocardiography images with a cardiac 3D CT volume.

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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