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Integration of electro-anatomical and imaging data of the left ventricle: An evaluation framework

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ABSTRACT

Integration of electrical and structural information for scar characterization in the left ventricle (LV) is a crucial step to better guide radio-frequency ablation therapies, which are usually performed in complex ventricular tachycardia (VT) cases. This integration requires finding a common representation where to map the electrical information from the electro-anatomical map (EAM) surfaces and tissue viability information from delay-enhancement magnetic resonance images (DE-MRI). However, the development of a consistent integration method is still an open problem due to the lack of a proper evaluation framework to assess its accuracy. In this paper we present both: (i) an evaluation framework to assess the accuracy of EAM and imaging integration strategies with simulated EAM data and a set of global and local measures; and (ii) a new integration methodology based on a planar disk representation where the LV surface meshes are quasi-conformally mapped (QCM) by flattening, allowing for simultaneous visualization and joint analysis of the multi-modal data. The developed evaluation framework was applied to estimate the accuracy of the QCM-based integration strategy on a benchmark dataset of 128 synthetically generated ground-truth cases presenting different scar configurations and EAM characteristics. The obtained results demonstrate a significant reduction in global overlap errors (50–100%) with respect to state-of-the-art integration techniques, also better preserving the local topology of small structures such as conduction channels in scars. Data from seventeen VT patients were also used to study the feasibility of the QCM technique in a clinical setting, consistently outperforming the alternative integration techniques in the presence of sparse and noisy clinical data. The proposed evaluation framework has allowed a rigorous comparison of different EAM and imaging data integration strategies, providing useful information to better guide clinical practice in complex cardiac interventions.

1. Introduction

Ventricular tachycardia (VT) caused by re-entry circuits is one of the most critical forms of arrhythmia, which is usually treated with anti-arrhythmic drugs and, in more severe cases, with radio-frequency ablation (RFA) (Zipes et al., 2006). The aim of RFA is to eliminate the myocardial substrate responsible for the VT. It is generally performed using a special navigation system such as CARTO (Biosense, Cordis Webster, Marlton, NJ), which provides an electro-anatomical voltage map (EAM) that characterizes the electrical behavior of the heart. In these contact-mapping systems a EAM is reconstructed from the processing of unipolar or bipolar electrograms acquired through the contact of a catheter with the endocardial (or epicardial) wall in a discrete set of points. Peak-to-peak amplitudes of 1D electrograms are estimated to generate both Local Activation Time (LAT) and voltage maps. Such maps are used to identify both the myocardial substrate and potential ablation targets by finding electrogram abnormalities such as low voltage regions, delayed activation times or double potential events. However, the success rate of RFA is still low (recurrence rates up to 91% (Berruezo et al., 2012) in some patients) and the ablated area is usually larger than optimal, partially due to some limitations of the EAM acquisition system: availability of a reduced number of measurements, lack of transmural information, the effect of far-field signals, uncertainties in the EAM point localization or imperfect catheter contact among other reasons.

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In order to improve the localization of the ablation targets and to reduce the ablated areas in scar-related VTs, advanced ablation strategies have been developed (Fernández-Armenta et al., 2013). Such VTs are commonly observed in post-myocardial infarction patients, which present heterogeneous scars composed by a non-conducting zone, known as core zone (CZ), and a slow-conducting one, often referred to as border zone (BZ) or peri-infarct zone. Border zone regions are extremely important since they can be located within a non-conducting zone linking two healthy tissue (HT) regions, thus creating a conduction channel (CC) that forms a circuit of action potential re-entry. One of the most successful ablation strategies, the so-called dechannelling technique (Berruezo et al., 2012), precisely aims at only ablating the entrances of the CCs, eliminating thus the re-entry circuit responsible for the VT with a minimal damage of the BZ and HT regions. Nevertheless, identifying CCs exclusively from EAMs requires considerable operator experience, suffers from substantial inter- and intra-observer variability and is highly time consuming (Codreanu et al., 2008).

Some studies have shown how delay-enhancement magnetic resonance images (DE-MRI) can assist on characterizing the scar (BZ and CZ) prior to the intervention, identifying possible locations of the CCs and incorporating the extracted information into clinical VT therapy planning (Andreu et al., 2011). The BZ channels are defined as continuous corridors of BZ surrounded by scar core/mitral annulus (Fernández-Armenta et al., 2013). A corridor of BZ is then considered a channel when connecting two areas of normal myocardium. Relating CC information obtained from EAM and DE-MRI is challenging due to the intrinsic limitations of the modalities (e.g. limited number of slices and anisotropic resolution in DE-MRI) and their different acquisition nature (e.g. coordinate systems, different and/or incomplete fields of view). A robust approach is then needed for establishing correspondences between these complementary sources of information. In clinical routine correspondences are usually obtained in two stages[1]: first applying a rigid registration technique guided by a set of landmarks manually selected in both modalities; then mapping information available at each point of the EAM surface onto the closest point of the LV geometry segmented from DE-MRI. During the registration stage, point-to-surface distance and landmark alignment are both optimized to determine the best transformation (Li-Fern, 2008). Nevertheless, a registration technique only based on landmarks might not be sufficient to compensate for spatial differences between EAM and DE-MRI data, as demonstrated by a recent study (Andreu et al., 2015), where 79.2% of all the EAM CC's could be visually identified in the corresponding DE-MRI data. Some researchers (Tao et al., 2012; Roujol et al., 2012) have incorporated scar information in the registration process to further constrain rigid transformations between EAM and DE-MRI data. This strategy strongly depends on the scar definition in both modalities, which in turn is highly influenced by the thresholds employed to classify scar tissue types (Andreu et al., 2011). Furthermore, all these advanced registration techniques are hampered by subsequently using a simple closest point mapping method once EAM and DE-MRI surface meshes are registered.

A thorough comparison among these different integration techniques cannot be easily performed due to the lack of ground-truth data in this application since EAM and DE-MRI data represent different, even if related, physical phenomena. For instance, scar regions are identified from voltage amplitude of the EAM signals, while DE-MRI gives information about how much time the injected Gadolinium contrasts has been infiltrated in myocardial tissue (necrotic tissue taking more time to release the Gadolinium out). It is quite obvious that both modalities will provide different scar definitions, independently of the integration strategy. In this paper, we propose a rigorous evaluation framework, with appropriate global and local measures, to assess the accuracy of the integrated multimodal information, allowing a detailed and quantitative analysis of the process as a whole, but also to identify which steps (e.g. registration, mapping) and parameters are the most critical for the final result. Some of the developed evaluation measures are particularly tailored for EAM and DE-MRI data of the left ventricle (LV) since they relate EAM critical sites (CC entries, double potential points) with scar tissue information (CZ, BZ, HT) extracted from DE-MRI.

We also propose a new mapping technique for integrating EAM and DE-MRI information that relies on a conformal mapping between LV endocardial surfaces and a 2D disk, followed by a correction of anatomical landmarks based on Thin-Plate Splines (TPS) that relaxes the established conformal mapping to quasi-conformal (QCM). Several researchers have recently proposed mapping techniques to construct 2D reference systems for different organs such as the left ventricle (De Craene et al., 2012), the atria (Karim et al., 2014; Tobon-Gomez et al., 2015), the brain (Auzias et al., 2013; Yushkevich et al., 2006), the liver (Vera et al., 2014), vertebral bones (Lam et al., 2014), the cochlea (Vera et al., 2015) or even faces (Gu et al., 2010). Information derived from both EAM and DE-MRI of a single patient at different time points or from different patients can easily be represented on the disk and then jointly be analyzed in the constructed common reference space. As an example, this approach was initially applied to compare and perform statistical analysis on different EAMs of porcine data (Soto-Iglesias et al., 2013).

The developed evaluation framework was used to estimate the accuracy of the proposed QCM-based mapping technique and compare its performance to alternative state-of-the-art EAM and DE-MRI integration strategies. A simple rigid transformation guided by landmarks, the Iterative Closest Point (ICP) (Besl and McKay, 1992) and a non-rigid registration technique based on *currents* (Vaillant and Glaunes, 2005) were analyzed for the registration stage. For the mapping stage, the commonly used closest point strategy was compared with the new quasi-conformal mapping (QCM) technique. All integration approaches were tested on a benchmark dataset of 128 synthetically generated ground-truth cases presenting different scar configurations and EAM characteristics, as well as in seventeen clinical datasets.

The paper is structured as follows. In Section 2 the acquisition protocols to obtain EAM and DE-MRI data are detailed. Section 3 is devoted to the proposed evaluation framework, including the extraction of relevant information from multimodal data, the generation of the ground-truth data and the global and local measures used to estimate integration accuracy. The QCM-based mapping technique is described in Section 4, whereas the alternative state-of-the-art integration strategies are listed in Section 5. Results obtained from applying the developed evaluation framework to the different integration strategies are presented in Section 6 and finally discussion and conclusions are given in Section 7.

2. Data acquisition

In this work, we applied different integration techniques to the data of 17 patients that underwent VT ablation at Hospital Clínic de Barcelona. All subjects had a DE-MRI examination prior to the VT ablation procedure using a 3T clinical scanner (Magnetom Trio, Siemens Healthcare). The 3D slab of images was acquired in the transaxial direction. Slice thickness was 1.4 mm, with no gap between slices. The field of view was set at 360 mm and matrix size was kept to 256 $\times$ 256 pixels in order to yield an isotropic spatial resolution of 1.4 $\times$ 1.4 $\times$ 1.4 mm, giving a set of images (typically

[1] Within the CARTO system (CARTO, Biosense, Cordis Webster, Marlton, NJ), correspondences are obtained with the software CartoMerge.