CLINICAL APPLICATIONS OF IMAGE FUSION FOR ELECTROPHYSIOLOGY PROCEDURES

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ABSTRACT

Cardiac electrophysiology procedures are routinely used to treat patients with rhythm disorders. The success rates of ablation procedures and cardiac resynchronization therapy are still sub-optimal. Recent advances in medical imaging, image processing and cardiac biophysical modeling have the potential to improve patient outcome. This manuscript provides an overview of how these advances have been translated into the clinical environment.

Index Terms— cardiac imaging, cardiac image registration, electrophysiology, image-guided intervention, biophysical modelling

1. INTRODUCTION

Patients with rhythm disorders of the heart are increasingly treated using interventional cardiac electrophysiology (EP) procedures, such as ablation therapy and pacemaker implantation. Interventional procedures offer the distinct advantage over long-term pharmacotherapy that they can provide a cure. However, the success rate for these procedures is still sub-optimal and many patients require redos. Examples include ablation treatments [1] for atrial fibrillation (AF) and ventricular tachycardia (VT). These treatments aim to disrupt the arrhythmogenic electrical circuits by appropriate destruction of the myocardial substrate. For AF, the success rates improve after multiple procedures and are lower for those patients with persistent or permanent AF versus those with paroxysmal AF (PAF). In a recent worldwide survey consisting of 16309 AF patients [2] it was found that ablation therapy for AF was approximately 80% successful after an average of 1.3 procedures. For VT, the figures are lower, varying from 50% upwards [3, 4], since locating the correct ablation substrate can be very difficult. Cardiac resynchronisation therapy (CRT) [5] has been a popular treatment for patients with heart failure. This treatment involves implantation of a pacemaker device that targets both the right and left sides of the heart. This expensive treatment has the ability to improve cardiac function and reduce morbidity and mortality for these patients. However, the success rate is again sub-optimal with one-third of patients failing to respond as shown by the MIRACLE and FREEDOM trials [5].

There may be a variety of reasons for sub-optimal success rates that include (1) inappropriate patient selection; and (2) incomplete or incorrect delivery of treatment during the intervention. Recent advances in medical imaging coupled to recent advances in image processing and cardiac biophysical modelling may improve patient outcome [6].

2. TYPES OF IMAGING FOR EP

All mainstream forms of imaging (computerised tomography (CT), magnetic resonance imaging (MRI), ultrasound (US) and rotational x-ray imaging (RXA or C-arm CT)) can be used to image EP patients prior to intervention (figure 1). In the case of US and RXA/C-arm CT, these modalities can also be used peri- or intra-procedurally. Pre-procedural imaging offers the ability to determine the cardiac geometry, the distribution of myocardial scarring, the myocardial motion and the flow inside the cardiac chambers and the great vessels. Computational image processing is used to extract these types of data from the imaging modalities. Examples of such processing include segmentation of the heart [7], segmentation of fibrosis [8], and extract of ventricular deformation [9].

During the intervention, procedures are guided using X-ray fluoroscopy and electroanatomical mapping systems (EAMS) such as CARTO (Biosense Webster) or Ensite (St. Jude Medical) (figure 2). Catheters are used to collect cardiac electrical data, deliver ablation therapy and to pace the heart.

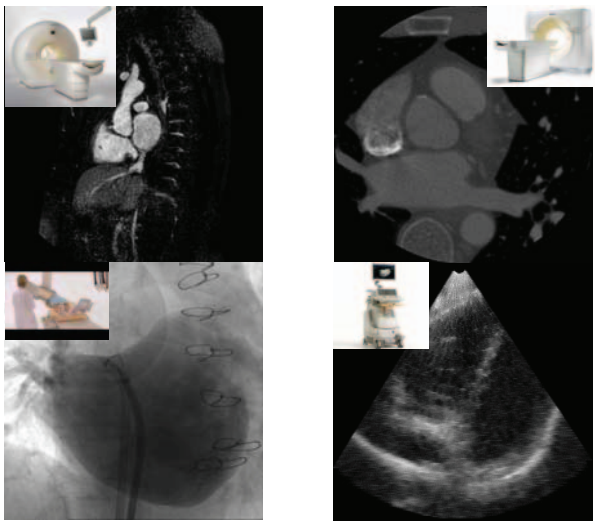


Fig. 1. Examples of pre-/peri-procedural imaging: *top left*: contrast-enhanced 3D steady-state-free-precession MR image; *top right*: prospectively-gated, contrast-enhanced CT image; *bottom left*: rotational X-ray angiography of left atrium; *bottom right*: live 3D ultrasound.



Fig. 2. Intra-procedural imaging: *left*: X-ray fluoroscopy; *centre*: Ensite left atrium reconstruction; *right*: CARTO reconstruction.

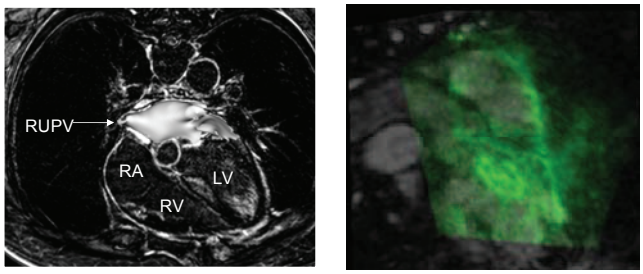


Fig. 3. Examples of image fusion: *left*: intra-modality registration of SSFP to DE MRI [10]; *right*: inter-modality registration of SSFP MRI to 3D US [11].

3. IMAGE FUSION

Fusing the pre-procedural and intra-procedural information can be useful in all stages of patient management, i.e. diagnosis, treatment planning, treatment guidance and patient follow-up. Furthermore image fusion provides information for validation and testing of cardiac biophysical modelling that also have the potential to be used throughout the patient care pathway.

It is possible to carry out image registration on pre-procedural images. This can be either intra-modality, such are registering 3D steady-state-free-precession (SSFP) MRI to delayed enhancement MRI (DE-MRI) [10]; or inter-modality, such as registering 3D SSFP to 3D US [11] (figure 3). Intra-modality registration is often more accurate and robust than inter-modality registration since images from the same modality tend to have similar intensities and features.

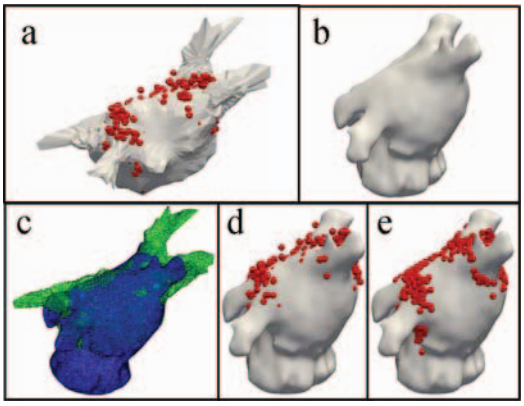


Fig. 4. Image integration using MRI and Ensite: (a) Ensite left atrial surface with ablation points; (b) MRI surface; (c) fused surfaces (blue-MRI, green-Ensite); (d) ablation points mapped to MRI; (e) ablation points projected onto MRI surface. Image taken from [10].

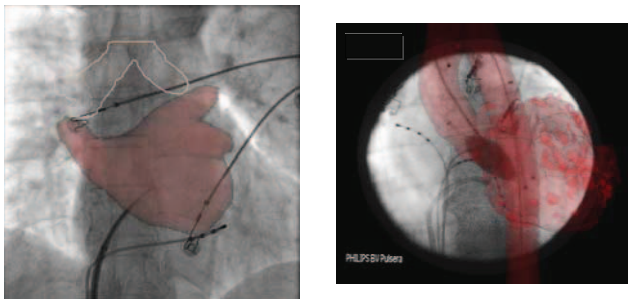


Fig. 5. Registration of pre-procedural images to X-ray fluoroscopy: *left*: using the tracheal bifurcation; *right*: using an XMR system [21].

Registering pre-procedural images to intra-procedural images, often known as *image integration*, can be a challenge since the pre-procedural modalities are very different to X-ray fluoroscopy and EAMS used intra-procedurally. This is almost always the case except for RXA/C-arm CT images that are acquired with the same X-ray system used intra-procedurally. Surface models of the cardiac chambers derived from CT/MRI/RXA/C-arm CT can be registered to reconstructed chamber anatomy from EAMS using a combination of point- and surface-based registrations [12] (figure 4). This integrated approach, called CARTO-Merge or Ensite-Fusion, has been shown to reduce

procedures times, reduce radiation dose and improve patient outcome in several studies on cardiac ablation therapies [13].

An alternative approach is to register the pre-procedural images with the X-ray fluoroscopy (figure 5). This can be carried out using manual registration from multiple X-ray views (EP Navigator, Philips Healthcare) and by automated techniques, such as using the tracheal bifurcation or catheters in known vessels [14]. This can also be done automatically using hybrid imaging systems such as X-ray combined with MRI (XMR) [15].



Fig. 6. Ablation point tagging: green dots show where ablations have already been made on this left atrial surface model.

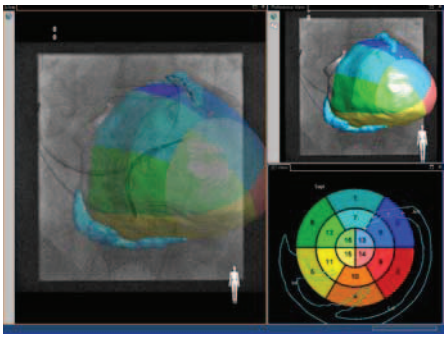


Fig. 7. Image integration for guiding CRT: 17 segment AHA model of left ventricle with different colours for different segments; the coronary sinus is shown in blue; a bull's-eye representation shows the position of the pacing lead electrodes (crosses) relative to the anatomy.

4. CLINICAL APPLICATIONS OF IMAGE FUSION

Clinical applications of image fusion include guiding ablation therapies and CRT. For ablation therapy, it is possible to use anatomical images to provide a roadmap for delivery of ablation lesions. Furthermore, the location of delivered lesions can be recorded [16] (figure 6). Patients that are having redo ablations can be guided using information integrated from anatomical imaging and scar imaging to provide a *scar roadmap* to enable targeting of lesion gaps from the previous ablation/s [17]. Scar roadmaps can also be useful in identifying the correct sites for targeting VT ablation [18]. Another application is contact force mapping using force-sensing ablation catheters, such as that from Endosense. Force mapping directly onto anatomical models may help in predicting recurrence [19].

In the case of CRT, it is possible to integrate anatomy (chamber geometry and coronary vein morphology), scar distribution and dyssynchrony information from pre-procedural images in order to guide the placement of left ventricular pacing leads [20] (figure 7).

5. IMAGE FUSION FOR BIOPHYSICAL MODELLING

The fusion of imaging information into a common coordinate system can provide rich data for the validation and testing of cardiac biophysical models. These image data can be augmented with other types of physiological data such as body surface potentials, endo- and epicardial electrograms and intracardiac pressure measurements . Once the data fusion process has been carried out, cardiac electromechanical models can be personalised to data to enable patient-specific simulations. The most-developed example of this process is application to CRT. In [21], data fusion model personalisation coupling was used to predict acute haemodynamic response to CRT in 2 patients. Results were compared to intracardiac pressure measurements using a pressure wire. The predicted temporal pressure derivative curves compared favourably with the ground truth (figure 8).

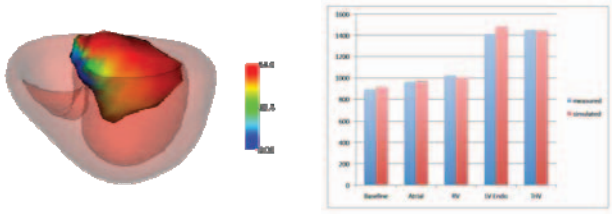


Fig. 8. Patient-specific modelling for CRT: *left*: integration of personalised biventricular model with invasive electrical measurement from an Ensite balloon (scale is activation time in ms); *right*: simulated and measured maximum pressure derivative for one of the patients in [21].

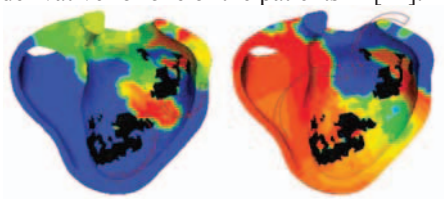


Fig. 9. Patient-specific modelling for VT: Activation maps from a simulated VT stimulation protocol; *left*: early activation in the isthmus region (between areas of scar - black) shown in red; *right*: late activation – blue – leads to re-entry [22].

Clinical application of data fusion model personalisation coupling to ablation therapy is very challenging. This is

better developed for the ventricles. In [22] the approach was used to predict targets for VT by simulating the standard VT stimulation procedure (figure 9).

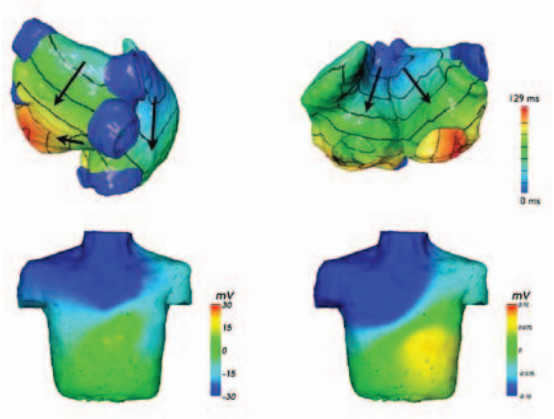


Fig. 10. Patient-specific modeling of atrial electrophysiology: *top*: simulated activation maps of bi-atrial model; *bottom*: validation by comparing computed body surface potential map (right) with measured map (left).

However, due to the limitations in imaging the atria, limited knowledge on the pathophysiology of atrial rhythm disorders and the complexities of simulating multiple re-entrant atrial circuits, clinical examples of atrial electromechanical personalisation and simulation are in very early stages of validation. In [23] electrical personalisation using data fusion was demonstrated in 2 healthy volunteers. Validation was carried out by comparing body surface potential maps (BSPM) to simulated BSPMs (figure 10).

5. CONCLUSION

In summary, image fusion is a powerful tool that combined with cardiac biophysical modelling may have a high clinical impact in improving outcomes for patients undergoing EP procedures. Early examples of data fusion model personalisation coupling for patient-specific simulations have shown promising results.

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