Augmented Reality for Improving Catheterization in Magnetic Resonance Imaging-Guided Cardiac Electrophysiology Therapy 1

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Augmented Reality for Improving Catheterization in Magnetic Resonance Imaging-Guided Cardiac Electrophysiology Therapy[1]

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1 Background

Magnetic resonance imaging (MRI)-guided cardiac electrophysiological (EP) radio-frequency (RF) catheter ablation is a rapidly growing field for treatment of heart rhythm disorders, such as atrial fibrillation and premature ventricular contractions [1]. Compared with fluoroscopy and ultrasound techniques for image-guided cardiac catheter therapies, cardiac MRI is a superior imaging modality for its high resolution and high contrast visualization of soft tissue. Despite its capability to provide excellent roadmaps for EP RF ablation, the risk of cardiac tissue perforation and steam pops, which occur primarily in the anterosuperior atrial walls and/or adjacent aorta [2,3], adversely affects the safety of the EP procedure. Perforation arises from (1) lack of tactile and force feedback and (2) the inability to adequately determine the catheter-tissue contact force (CF). Steam pops are mainly caused by an overheated catheter tip boiling the cardiac tissue. We hypothesized that a device which simulates haptic (force and tactile) feeling and provides simultaneous CF and temperature monitoring of the interaction between the cardiovascular structure and catheter tip could enhance the RF ablation procedure's safety and reliability.

2 Methods

2.1 Catheter Haptic Feedback Interface Design. A haptic platform, integrated with a vibrational shaker unit and a catheter brake unit, was developed to produce intermittent vibration and resistance forces during the EP catheter control. Figure 1(*a*) demonstrates the working principle of the brake unit. The resistance force against the catheter advancement is generated by the displacement of the pneumatic piston. This prevents the catheter tip from perforating cardiovascular tissue during RF ablation (RFA) procedures. The actuation of brake unit will be trigged when the catheter tip is beyond the boundary of the virtual cardiac model. The brake unit allowed an 8-French EP ablation catheter (St Jude Medical, Inc.) to insert smoothly through the predesigned hole in the brake unit. The shaker consists of an unbalanced-weighted rotor (Fig. 1(*b*)), with the angular speed pneumatically controlled based on the real-time distance between the catheter tip and the target lesion or the image margin [4,5], thus yielding vibration at various levels of frequency. The vibration signals to the operator while the catheter tip is moved closer to, until reaching the RFA targets predefined on the image model. MR-conditional piezoelectric valves (Hoerbiger, Inc.) regulate the pressure supplied to both the brake and vibration units (Fig. 1(*c*)). The control command is transmitted from the control room to the MRI room through optical fibers with a set of bidirectional optical-to-electrical converters. Figure 1(*d*) shows the setup for a simulated RFA procedure using the proposed haptic platform.

2.2 Fiber Bragg Grating (FBG)-Based Real-Time CF and Temperature Monitoring Interface. The optical FBG sensor was installed at the tip of the EP catheter with the aim to monitor CF and temperature during the RF ablation. The optical spectrum analyzer was located outside the MRI room (Fig. 2(*a*)) to provide real-time analysis of the measured wavelength (WL) which is shifted due to variation in temperature or CF exerted on the catheter tip [6]

$$\frac{\Delta\lambda_B}{\lambda_B} = C_S\epsilon + C_T\Delta T \quad (1)$$

where $\Delta\lambda_B$ is the Bragg length shift, C_S is the coefficient of strain, and C_T is the coefficient of temperature. Figure 2(*b*) shows the

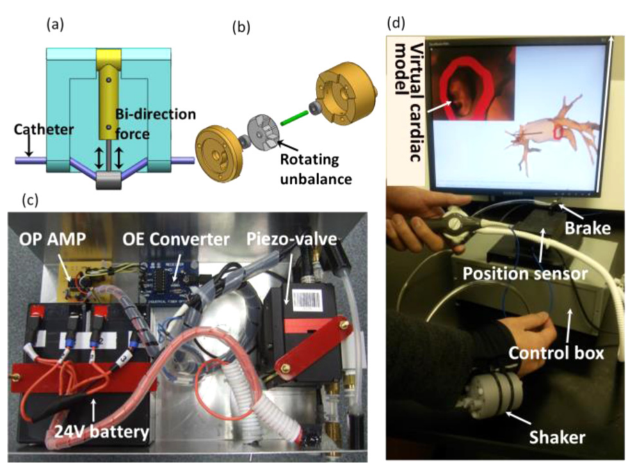

Fig. 1 (*a*) Key components of the brake unit; (*b*) unbalanced-weighted rotor in the shaker unit; (*c*) MR-compatible mechatronic devices for regulation of pneumatic pressure; and (*d*) setup for the simulated RFA procedure

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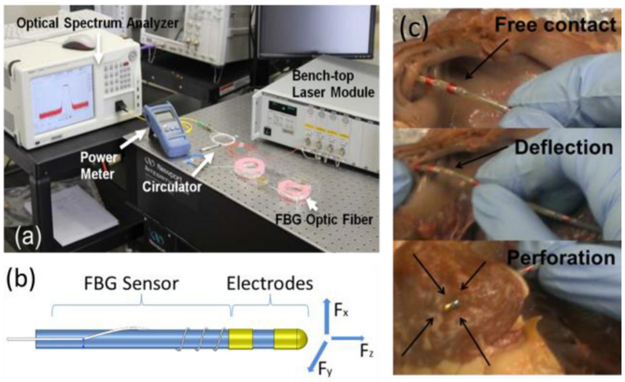

Fig. 2 (*a*) Experimental setup for the WL determination of FBG; (*b*) implementation of FBG on the catheter; and (*c*) the catheter deflected until causing perforation on atrium wall of ex vivo pig heart

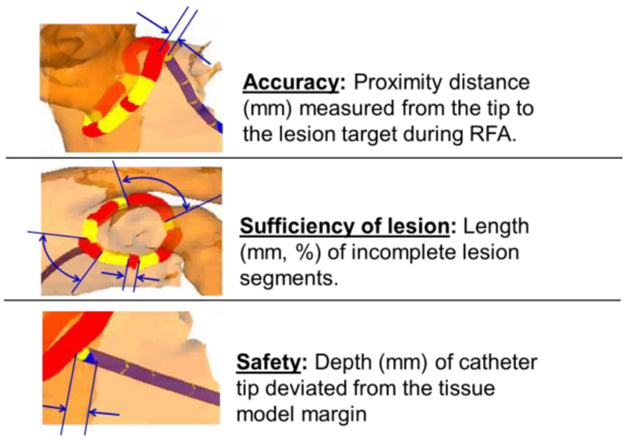

Fig. 3 Three types of clinically relevant indices for evaluating the simulated RFA performance

FBG implemented on the catheter near the tip. To find the correlation between the CF and the measured WL, the catheter was driven to perforate the pig heart tissue by increasing the force from zero to the point at which perforation occurred (Fig. 2(*c*)). To calibrate the WL with respect to temperature, the catheter with the FBG sensor was submerged into a water bath, where the temperature could be adjusted accurately by a water heater.

3 Results

An EP RFA task was simulated virtually to investigate the clinical potential of using the proposed platform. Subjects ($N=12$) were invited to complete the RFA task twice: once with and once without haptic feedback provided. Given a 5-min time, he/she was required to manipulate the catheter tip in contact with the RFA targets predefined along the connection between the pulmonary vein and left atrium. The simulated RFA task was evaluated in three aspects relevant to its clinical practice: (1) accuracy, (2) sufficiency of lesions, and (3) safety during the RFA task (Fig. 3). Six performance indices are shown in Fig. 4, each of which demonstrates a significant improvement (at least >30%). The results testify to the clear benefits of using the proposed haptic platform.

The CF, indicating the interaction between the catheter tip and the cardiac tissue, is shown in Fig. 5. The WL increased from about 1549.68 nm to 1550.38 nm, where the maximum force was reached just before the tissue was perforated by the catheter. The WL dropped rapidly after the perforation. The strain was no longer applied on the catheter at that point. For the temperature calibration, linear regression was applied to describe the correlation of the WL and the temperature. Seven temperature levels ranging from 20 °C to 80 °C were sampled. The linear regression resulted in an R-square value of 0.9967 with a root mean square error of 1.31 °C. This linear correlation enables accurate temperature measurements during RFA procedures.

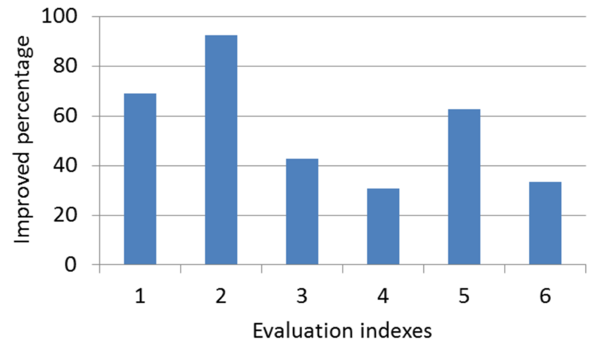

Fig. 4 Improvement over the task without haptic guidance, in terms of six performance indices: 1, number of tip deviations; 2, average tip deviation depth; 3, average accuracy; 4, average tip deviation time; 5, average RFA time; and 6, incomplete RFA length

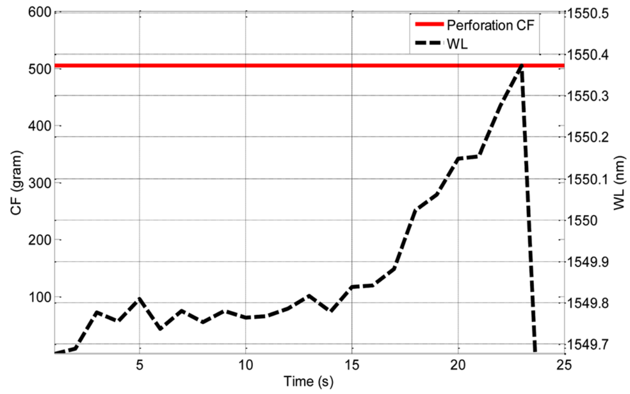

Fig. 5 FBG-measured CF with respect to WL

4 Interpretation

The proposed haptic feedback platform integrated with simultaneous force and temperature sensing has been demonstrated to improve EP catheter manipulation. In future work, not only will the platform design be miniaturized so as to integrate with the clinically used catheter sheath but we will also propose an intraoperative MR imaging scheme so that the 3D cardiovascular image model can be updated frequently for delicate RFA guidance.

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