Real-time monitoring of cardiac radio-frequency ablation lesion formation using an optical coherence tomography forward-imaging catheter

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Abstract. Radio-frequency ablation (rfa) is the standard of care for the treatment of cardiac arrhythmias; however, there are no direct measures of the successful delivery of ablation lesions. Optical coherence tomography (OCT) imaging has the potential to provide real-time monitoring of cardiac rfa therapy, visualizing lesion formation and assessing tissue contact in the presence of blood. A rfa-compatible forward-imaging conical scanning probe is prototyped to meet this need. The forward-imaging probe provides circular scanning, with a 2-mm scan diameter and 30-μm spot size. During the application of rf energy, dynamics are recorded at 20 frames per second with a 40-kHz A-line rate. Real-time monitoring of cardiac rfa lesion formation and imaging in the presence of blood is demonstrated ex vivo in a swine left ventricle with a forward, flexible, circular scanning OCT catheter. © 2010 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3459134]

Keywords: radio-frequency ablation; optical coherence tomography; cardiac imaging; catheter.

1 Introduction

Cardiac arrhythmias are a major source of morbidity and mortality in the United States. Radio-frequency ablation (rfa) directed at interrupting critical components of arrhythmia circuits is the standard of care for the treatment of tachyarrhythmias. Current techniques for anatomical guidance of ablation therapy utilize low-resolution 2-D fluoroscopic images or static images from computed tomography merged onto fluoroscopy. Monitoring of rfa is by indirect means, such as assessment of tissue temperature, power delivery, and impedance at the tip of the ablation catheter. This indirect method of monitoring can often result in delivering more rfa lesions than necessary to achieve a therapeutic effect, prolonging procedure times and thereby increasing the risk of these procedures. Intracardiac echocardiography monitors rfa therapy in real time to assess catheter-tissue contact and contact angle, visualize stenosis of pulmonary vessels, and embolic events. However, intracardiac echocardiography does not have sufficient contrast to visualize the formation of rfa lesions. Additional technology for directly monitoring ablation lesion formation during procedures in real time can further decrease procedural time and improve patient and operator safety.

Optical coherence tomography (OCT) is an emerging modality that provides high-resolution, depth-resolved imaging of tissue microstructures. OCT has demonstrated the ability to distinguish ablated from untreated tissue, and image the atrioventricular node, and abnormal fiber organization within ex vivo cardiac animal models. To translate OCT technology, optical catheters have been developed for imaging internal structures, and have been used for gastrointestinal endoscopy and intravenous imaging. A variety of designs have been employed including forward-imaging and side-viewing catheter. Designing a forward-imaging catheter that is both small in diameter and flexible presents many challenges. Others have designed probes with distal actuation to provide a wide range of scanning patterns. However, these catheters are not easily miniaturized, as the scanning mechanism limits the outer diameter of the catheter tip. Proximal actuation has been shown, but the probe was rigid.

In this work, we present real-time imaging of rfa lesion formation and imaging in the presence of blood with a flexible, forward-imaging OCT catheter.

2 Methods and Results

Cardiac rfa lesions are formed most effectively if the ablation catheter is perpendicular and has adequate contact with the tissue. Therefore, a flexible forward-scanning OCT catheter was designed and prototyped that allows for in-contact, circular-scan imaging (Fig. 1). Light is delivered via a SMF28e optical fiber, the beam is focused by a GRIN lens, deflected 1-mm off-axis by a Risley prism, and a fused-silica optical window isolates the probe interior from the tissue environment [Fig. 1(a)]. The mechanical support was designed from glass, ceramic, and polymer materials (no metal) to avoid thermal effects and interference in close proximity to the rfa catheter [Fig. 1(b)]. Rotary motion imparted by torque applied to the fiber proximally, at the fiber rotary joint, allowed for circular scanning. The rigid portion of the catheter was 18 mm in length and the outer diameter was 2.5 mm. Polytetrafluoroethylene moisture seal heat shrink tubing was placed on the probe end cap, increasing the outer diameter at the probe tip to 3.2 mm. The spot diameter of the design is 28-μm full-width at half-maximum (FWHM), with minimal aberrations over 1 mm of axial scan range from the optical glass [Fig. 1(c)]. Spot profiles measured using a beam analyzer [Fig. 1(d)] were circular, clean, and under 30 μm.

The forward-imaging catheter was integrated into a Fourier domain OCT system. A superluminescent diode centered at 1310 nm with a 75-nm (FWHM) bandwidth was used for the light source (Inphenix, Livermore, California). A linear in-wavelength (λ=2π/λ) spectrometer was used to project spectral interference fringes onto a 1024-pixel InGaAs line.
scan camera (Goodrich, Princeton, New Jersey). The system had a 4.3-mm imaging range, 2-mm −6-dB fall off, 115-dB signal-to-noise ratio, and 11-μm axial resolution (in tissue). An image of in vivo human thick skin taken at 10 frames per second (fps) with 4000 lines per frame (lpf) is shown in Fig. 1(e).

Visualizing real-time ablative lesion formation using the forward-imaging catheter was demonstrated using ventricular wedges from a freshly excised swine heart. Following the onset of general anesthesia, a lateral thoracotomy was performed, and the heart was rapidly excised and placed in ice-cold phosphate buffered saline (PBS). Individual sections of left ventricular muscle were placed in a custom chamber with PBS maintained at 37 °C. The OCT forward-imaging probe was bound side by side to the rfa catheter [Fig. 2(a)] and imaging was conducted at 20 fps with 2000 lpf. Imaging was conducted for 90 sec, 15 sec prior to the start of rf energy delivery, 60 sec during energy delivery, and 15 sec after the conclusion of energy delivery [Fig. 2(b)]. RFA lesions were created with a temperature-controlled (80 °C) protocol with a maximum delivered power of 50 W using the Maestro 3000 generator and 8-Fr, 5-mm tip catheter Blazer II (Boston Scientific, Natick, Massachusetts). Staining with 1.0% triphenyltetrazolium chloride in PBS for 30 min at 37 °C was used to validate lesion formation [Fig. 2(g)]. Baseline images show a birefringence-dependent dark band characteristic of healthy, untreated myocardium [Fig. 2(c)]. With the application of rf energy, the band broadens and appears deeper in the tissue [Figs. 2(d)–2(f)]. It is important to note that the rf energy, and the temperature rise during energy delivery, did not affect the image quality nor the mechanical stability of the catheter.

The effect of the presence of blood was evaluated by imaging the ventricular wedge submerged in heparinized swine blood. An image of the myocardium was obtained when the catheter was in direct contact with the tissue, displacing the blood (Fig. 3). Blood strongly attenuates light at 1310 nm. When the catheter probe was not in direct contact with the tissue, the imaging depth was significantly reduced [Fig. 3(b)]. An important factor that affects lesion size is the maintenance of tissue-rfa electrode contact. This visual feedback could allow assessment of contact.

3 Discussion and Conclusion

We demonstrate a flexible forward-imaging OCT catheter made without metal that provides circular scanning by proxi-
We show that OCT can provide real-time direct visualization of rf energy delivery. Using a forward-imaging catheter, OCT can be integrated into a rfa catheter for future use, and adapted to other applications where a miniature, flexible forward-imaging OCT probe is needed. A direct image by OCT also has the potential to guide the precise application of rf energy, and to identify normal cardiac structures where ablation could be harmful. Importantly, this advance in catheter technology can decrease the procedural time and radiation exposure to the patient and physician.

Acknowledgments

The authors thank Steve Schomish for his technical assistance and Avo Photonics for prototyping the catheter. The project was supported by the Wallace H. Coulter Foundation and by the NIH (F31HL085939, R01HL083048, and RR1246). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Heart Lung and Blood Institute or the NIH.

References


