INTRACARDIAC ULTRASOUND-GUIDED APPROACHES FOR MANAGING HEART RHYTHM DISORDERS

Dirar S. Khoury
From Methodist DeBakey Heart Center and Baylor College of Medicine, Houston, Texas

INTRODUCTION

Heart rhythm disorders (atrial and ventricular arrhythmias) result in significant morbidity and mortality. Atrial fibrillation is the most common cardiac arrhythmia, affecting more than two million Americans, responsible for one-third of all strokes in patients over 65 years of age, and costing $9 billion annually to manage.[1] Another 300,000 Americans die of sudden cardiac death each year, mainly due to ventricular tachyarrhythmias that cause intractable, extremely rapid heartbeats.[2]

Since current pharmacological therapy for managing cardiac arrhythmias is often ineffective and can even be proarrhythmic, treatment has emphasized non-pharmacological therapies such as ablation, pacing and defibrillation. Effectively managing complex cardiac arrhythmias during electrophysiology studies hinges on several factors including: 1) developing catheter mapping techniques to identify causes and details of arrhythmias; 2) integrating anatomical imaging methods to connect the arrhythmias with underlying cardiac structure; 3) targeting non-pharmacological therapies to abolish arrhythmias; and 4) advancing diagnostic methods to elucidate the effects of therapy. This report is a brief review of recent translational research conducted in collaboration with scientists at Methodist DeBakey Heart Center and Baylor College of Medicine to address some of these issues.

INTRACARDIAC ULTRASOUND IN ARRHYTHMIA MAPPING

In the past, conventional endocardial mapping has been performed in the electrophysiology laboratory using fluoroscopy to guide electrode-catheters to a limited number of recording sites, and the accurate three-dimensional positioning of these electrode-catheters has been important for successful diagnosis and therapy. The process is time-consuming and carried our over several heartbeats without accounting for possible beat-ro-beat variability in activation.

Currently, however, new mapping systems are reducing the fluoroscopy time and achieving better three-dimensional positioning by: 1) applying an external magnetic field and determining the location of a specialized magnetic sensor at the tip of the catheter;[3] 2) delivering low-strength external currents and measuring the electrical field strength at the catheter tip-electrode;[4] or 3) calculating the distances between multiple ultrasonic transducers mounted on both a roving electrode-catheter and a reference stationary catheter.[5] While these new approaches have provided significant advantages over traditional methods, present mapping systems are still laboriously performed over several heartbeats and continue to lack an online anatomical imaging capability that could visualize detailed cardiac structures, verify contact of electrode-catheters with the endocardium and direct therapeutic interventions.

To advance cardiac mapping, we have been researching an alternative mapping approach that uses a non-contact probe with multiple electrical surface sensors to measure cavitary electrograms from several directions simultaneously during a single heartbeat.[6] In conjunction, we have developed numeric methods and algorithms to compute endocardial surface electrical activities and reconstruct their corresponding activation sequences based on the cavitary electrograms. After repeatedly testing and validating this approach on animals,[7] and successfully implementing it in humans,[8] we have found non-contact mapping advantageous for three-dimensional mapping on a beat-by-beat basis.

To relate the sequence of heartbeat activation with underlying anatomy, recent investigations have imported into the catheterization procedure high-quality images of cardiac anatomy that are constructed prior to cacheterization using computed tomography or magnetic resonance imaging.[9] While chis detailed cardiac description could provide a road map for managing complex arrhythmias, the idea of navigating electrode-catheters and fusing electrical information with anatomical images has several drawbacks including: 1) difficulty in aligning the independenrly acquired electrical maps and anatomical images; 2) absence of imaging means during catheterization to verify eleccrode-cacheter contact with specific endocardial structures; 3) lack of online assessment of anatomical or hemodynamic variations before, during or after therapy; and 4) time and financial constraints associated with performing cwo separate procedures.

Incracardiac echocardiography (ICE), which uses catheters carrying ultrasonic transducers, has proved advantageous in guiding clinical, interventional electrophysiology procedures in that it images anatomical structures, confirms electrode-tissue contact and monitors ablation lesions. Accordingly, we have integrated a non-contact multi-electrode catheter-probe for endocardial electrical mapping and an ICE catheter for endocardial anatomical imaging into a single system.[10] Our recent studies have demonstrated chat this technique accurately reconstructs single-beat endocardial surface electrograms from measured probe electrograms; provides detailed images of cardiac anatomy based on ICE; and digitally fuses both modalities to produce realistic, three-dimensional electrical-anatomical images of the endocardium (Figure 1). Furthermore, online ICE imaging has allowed us co navigate standard electrode-catheters to specific endocardial locations and verify their contact with respect to important anatomical structures. Therefore, this non-fluoroscopic imaging approach can facilitate diagnosis of arrhythmias and advance their therapy.

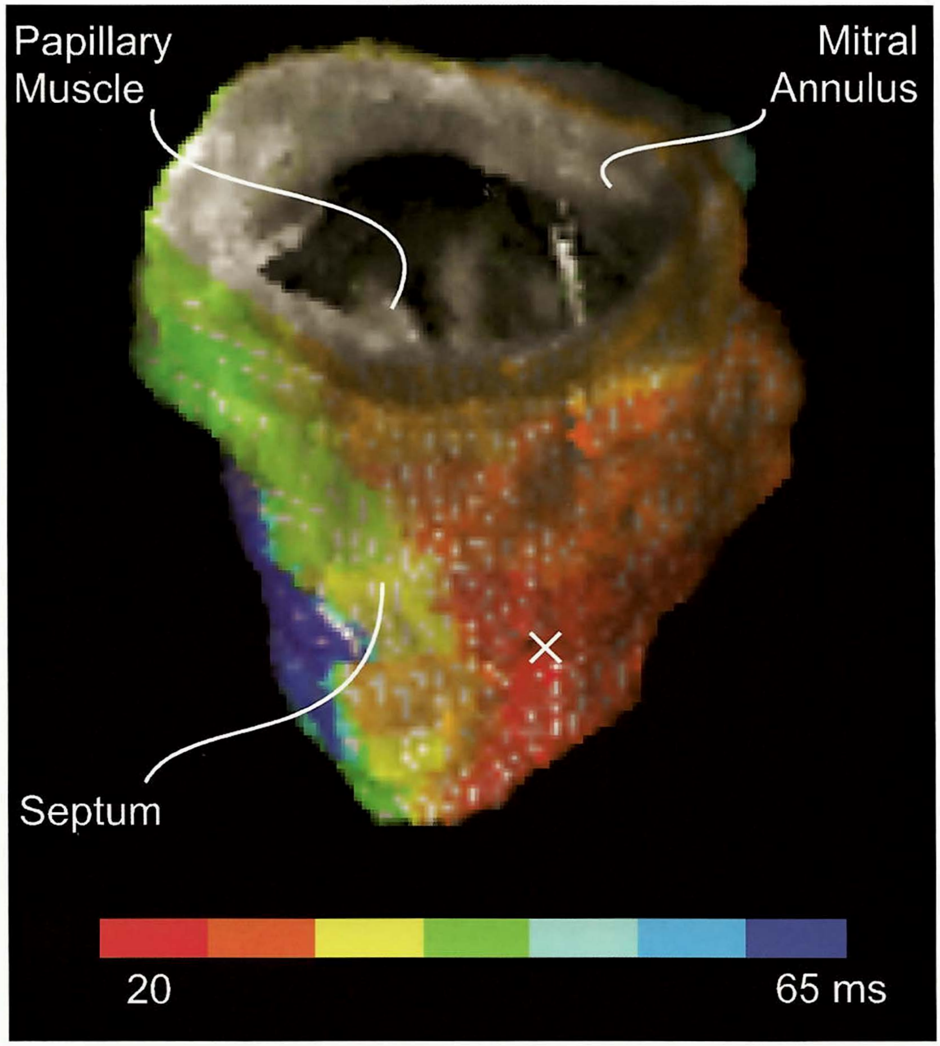

Figure 1
Example of digital fusion of left ventricular activation sequence by non-contact mapping and geometry by intracardiac echocardiography. Earliest region of activation (red) depicts the site of pacing (X), which simulates an abnormal premature heartbeat.

INTRACARDIAC ULTRASOUND N ARRHYTHMIA THERAPY

Radio frequency catheter ablation has been routinely used as a safe and effective first-line therapy for managing many supraventricular arrhythmias. Recent clinical evidence has confirmed char more than 80% of atrial fibrillation triggers are caused by premature electrical impulses originating from che pulmonary veins. While clinical data have shown chat pulmonary isolation by catheter ablation can successfully suppress atrial fibrillation in some patients, present pulmonary vein mapping and ablation techniques are laborious and time consuming, do not adequately map or ablate atrial fibrillation, and result in adverse effects. Researchers are investigating alternative catheter systems for pulmonary vein isolation that incorporate various energy sources including radiofrequency, ultrasound, laser, microwave and cryothermy. Each system has inherent advantages and limitations relating to catheter alignment wich the pulmonary vein ostium, efficacy of lesion formation and the ability co verify successful isolation by recording electrograms at the junction of the atrium with the vein.

Successful ablation results in terminating the arrhythmia and halting its recurrence. Meanwhile, incracardiac electrogram characteristics (amplitude, morphology and activation) are applied to locate and estimate the extent of ablation lesions. Catheter ablation has had limited success in managing ventricular tachyarrhythmias because of its inadequacy in consistently achieving these conditions, due mainly to limitations in endocardial electrical criteria, difficulty in determining lesion incramural depth and possible involvement of deep myocardial regions in arrhythmias. To address these limitations, part of our research has focused on finding an efficient and applicable means to describe the effects of ablation immediately after therapy.

We recently tested a theory based on microbubble enhancement during myocardial contrast echocardiography, in which contrast microbubbles are used during ultrasound imaging to enhance the backscattered ultrasound signal, improve the detection of endocardial borders and assess tissue microvascular perfusion. Our research tested the hypothesis that, during ICE imaging, microbubble-rich blood flow in the coronary microcirculation enhances the backscatter of ultrasound signals reflected by the normal myocardium, and that blood-deficient ablation lesions could subsequently be distinguished from the neighboring normal myocardium.[11] In this regard, we have described the first successful application of contrast-enhanced ICE in localizing radiofrequency ablation lesions and more importantly, accurately and reproducibly quantifying their extent and depth within the myocardium in the intact beating heart (Figure 2). This new application of myocardial contrast echocardiography may advance the use of ablation in managing ventricular arrhythmias by providing instantaneous anatomical feedback on its effects during cathererization.

Another research goal has been to address the use ofICE in assessing hemodynamics. Evaluating cardiac function and hemodynamics is an integral component in managing patients with heart disease. While ICE has been used to guide electrophysiology procedures, ic has not been effectively used to assess hemodynamics. Our research demonstrated the feasibility of using ICE to accurately reconstruct LV volume throughout the cardiac cycle[12] - an approach chat may positively impact studies suggesting that ventricular pacing can be beneficial in heart failure patients and that different pacing sites in the left ventricle have varying effects on ventricular function and hemodynamics. Electrical and hemodynamic assessments are critical in determining the optimal pacing site and correlating electrical activation with interventricular septa! wall motion, diastolic filling times and micral valve function. Our studies with ICE have highlighted the possibility of using

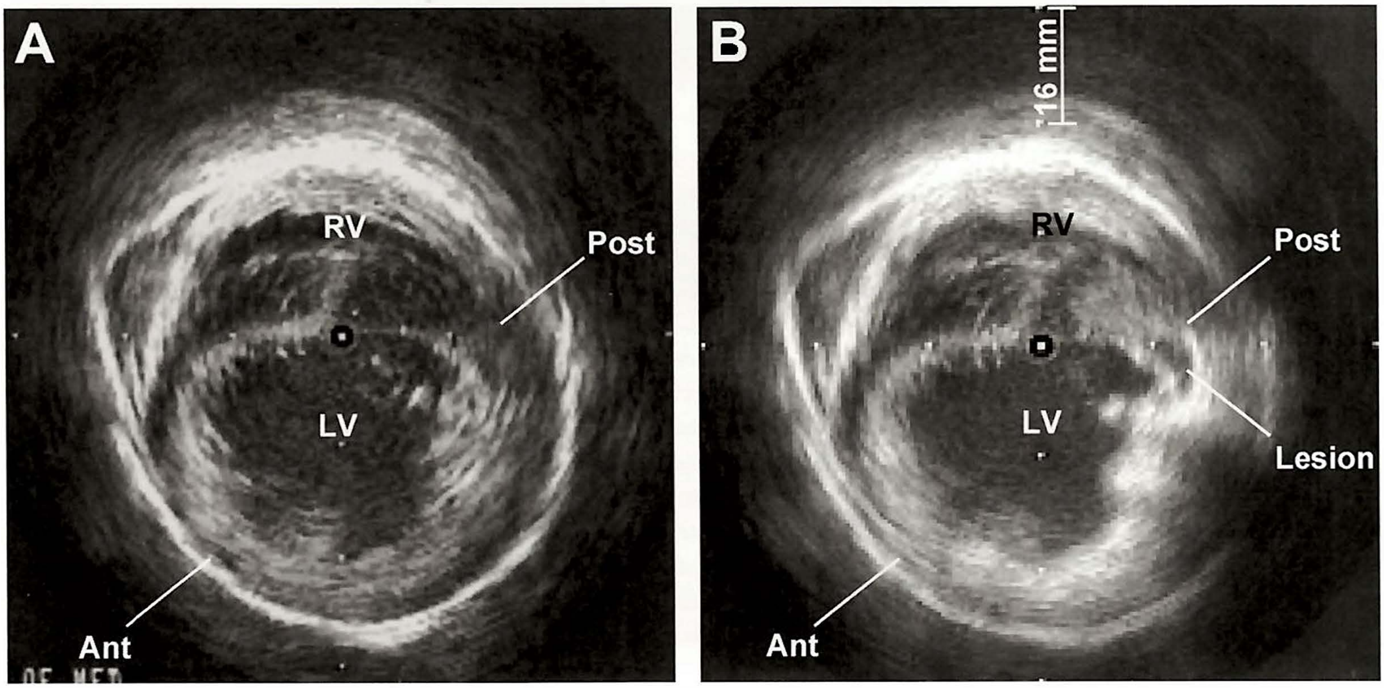

Figure 2. Illustration of standard intracardiac echocardiographic image (A) and myocardial contrast enhanced intracardiac echocardiographic image (B), both in the presence of a radio frequency ablation lesion in posterior left ventricle.

hemodynamic imaging during catheterization ro efficiently evaluate the effects of ventricular pacing and variability in the pacing site.

CONCLUSIQ NS

Introducing real-time anatomical imaging into the electrophysiology laboratory, as we have by combining ICE with non-contact electrical mapping, could directly impact clinical catheterization procedures in several aspects. Anatomical imaging is conducted with little use of fluoroscopy, and non-contact elecrrical mapping is performed on a beat-by-beat basis, which allows the study of brief, rare or even chaotic rhythm disorders chat are difficult ro evaluate with existing techniques. The combined catheter imaging system could improve our understanding of the mechanisms of initiation, maintenance, and termination of arrhythmias, leading to the selection or development of better pharmacological or nonpharmacological therapies. In addition, electrical-anatomical imaging could be preeminent in providing immediate feedback on the effects of therapy.

REFERENCES

1. *Benjamin EJ, WolfPA, Agostino RB et al Impact of atrialfibnllation on the risk of death: The Framingham Heart Study. Circulation 1998;98:946-952.*
2. *American Heart Association. Heart Disease and S t'oke Statistics-2005 Update. Dallas, Texas. American Heart Association; 2005.*
3. *Gepstein L, Rayam G, Ben-Haim SA. A nol'el method for nonjluoroscopic catheter-based electroanatomica/ mapping of the heart. In vitro and in t•fro accuracy results. Circulation 1997;95:1611-1622.*
4. *Wittkampf FHM, Wez,er EFD, Derklen R et al. New technique for real-rime 3-dimensional localization of regular intracardiac electrodes. Circulation 1999; 99: 1312-1317.*
5. *De Groot NMS, Bootrma M, Van Der Velde ET, Schaiij Mj. Three-dimensional catheter positioning during radiofrequency ablation in patients: First application of a real-time position management system. J Cardiovasc Elet:trophy1iol 2000;11:1183-1192.*
6. *Khoury DS, Taccardi B, Lux RL et al. Recomtruction of endocardial potentials and excitation sequences from intracavitary probe measureme1JtJ. Localization of pacing 1ites and effects of myocardial structure. Circulation 1995:91:845-863.*
7. *Khoury DS, Berrier KL, Badruddin SM, Zoghbi WA. Three-dimemional electrophysiologica/ imaging of the intact canine left i•entricle using a non-contact multielectrode cavitary probe. Study of sinus, paced, and 1pontaneo11s premattlre beats. Circulation 1998:97:399-409.*
8. *Schilling Rf, Peters NS, Davies DW Simultaneous endocardial mapping in the human left ventricle using a non-contact catheter: Comparison of contact and recomtructed electrograms during sinus rhythm. Circulation 1998;98:887-898.*
9. *Morady F. Catheter ablation of supraventricular arrhythmias: State of the art. j Cardioz•asc Electrophysio/ 2004;15:124-139.*
JO. *Rao L, He R. Ding C, Khoury DS. Novel non-contact catheter system for endocardial electrical and anatomical imaging. Ann Biomed Eng 2004:32:573-584.*
11. *Khoury DS, Rao L, Sun L, Youker KA et al. Localizing and quantifying ablation lesions in the left ventricle by myocardial contrast echocardiography. J Cardiovasc E/ectrophysio/ 2004:15:1078-1087.*
12. *Ding C. Rao L, Nagueh SF, Khoury DS. Dynamic three-dimensional visualization of the left ventricle by intracardiac echocardiography. Ultrasound Med Biol 2005;31:15-21.*