INNOVATIVE TECHNIQUES

REVIEW ARTICLE

Catheter Contact Force: A Review of Emerging Techniques and Technologies in AF Ablation

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ABSTRACT. *Catheter ablation for atrial fibrillation (AF) has gained significant attention during the last decade. Owing to the increase in patients undergoing AF ablation with only moderate long-term outcomes, there is considerable interest in developing new tools to assist the electrophysiologist during the procedure. Catheter contact force (CF) has been known to be an important determinant of radiofrequency (RF) lesion quality during pulmonary vein isolation (PVI) for over 20 years, yet it is only recently that the technology to allow the real-time measurement of catheter tip-to-tissue CF during the ablation procedure has been possible. Direct assessment of lesions during ablation has so far been elusive, with indirect measures being used as a surrogate of transmurality. Novel technologies such as microwave radiometry, magnetic resonance thermometry, and near-field ultrasound are attempting to address this problem. This review will discuss the role of emerging techniques and technologies to achieve permanent lesions during a single ablation procedure.*

Introduction

Circumferential pulmonary vein isolation (PVI) at the PV antrum is an established method to treat patients with atrial fibrillation (AF) refractory to antiarrhythmic drug therapy.[1] Despite achieving pulmonary vein isolation at the time of the initial procedure in nearly all procedures, recurrence of AF is common after catheter ablation, with single procedure success rates ranging from 15–60% at 1 year. Recovery of left atrial (LA) PV conduction is ubiquitous in patients with and without documented AF during follow-up.[2–4] Although there is currently debate surrounding the importance of the pulmonary veins in the perpetuation of AF, until we can reliably isolate pulmonary veins permanently,[5] it will be difficult to resolve this fundamental question.

Lesion formation during catheter ablation depends on biophysical parameters including power delivery, duration of energy application, tissue temperature, contact force (CF), and ablation catheter tip size and orientation.[6–8] However, to achieve lesion transmurality the tissue depth has to be taken into account, which none of the aforementioned parameters can determine. Even when transmural lesions are formed, such as with the cut and sew technique for the surgical maze, or with heart–lung transplantation, there are numerous reports of reconduction[9] and donor–recipient[10] tachycardias due to conduction across the surgical lesion.

As the myocardium heats up, the impedance of the tissue decreases, and this has long been used as a marker of

effective lesion formation. Similarly, a rise in temperature of the catheter tip has also been used as a marker of lesion formation. The drawbacks of these markers are that there are multiple other influencing factors such as electrode orientation and current catheter designs and thermocouple placement makes measurement of electrode temperature almost meaningless. A better quantification of the local tissue effect during energy delivery remains an unmet need in clinical cardiac electrophysiology.

Lesion formation using contact force ablation catheters

Current catheter ablation for AF typically requires continuous circular lesions to be delivered in the thin-walled left atrium and is associated with uncommon but serious complications. Better knowledge of the biophysics of ablation has helped to improve the quality, safety, and outcome of AF ablation. With normal catheter tip-to-tissue contact, only a fraction of all power is effectively delivered to the tissue.[6] Therefore catheter tip-to-tissue CF has been until now assessed subjectively by the operator using surrogate methods such as fluoroscopic visualization of the catheter tip, tactile feedback from catheter manipulation, and changes in intracardiac electrograms as well as impedance.[11] However, all of these indirect measurements have been shown to be of limited value as a reliable predictor of actual catheter contact.[11,12] To address this need, two new CF sensor catheters have been brought to market that allow real-time measurement of the catheter tip-to-tissue CF during catheter ablation.[7,8,13,14] There is clear evidence from previous studies that atrial ridges and muscular folds between the ipsilateral PVs (carina area) may decrease catheter stability and consequently CF,[15,16] and that PV reconnections are more frequently located in these areas.[17] In this context, recent data demonstrates that there is an important clinical impact of the average CF as low catheter tip-to-tissue CF is associated with higher rates of AF recurrence in the follow up period after PVI.[7,8,18] One of the potential advantages of continuous CF monitoring is an optimal initial placement of the ablation lesion, but also the ability to determine catheter stability in real-time based on a shift in CF and therefore to halt ineffective radiofrequency (RF) energy delivery. To avoid temporary PV electrical isolation, it appears to be of particular importance to ensure that first time ablation lesions are optimal and result in permanent, titrated myocardial tissue damage.[17] Optimal catheter tip-to-tissue CF during RF application is key to delivery of effective transmural ablation lesions.[8,19–22]

Real-time measurement of contact force: the technology and parameters

Currently, there are two different mature technologies available to measure the tip-to-tissue CF – TactiCath (St. Jude Medical, St. Paul, MN, USA) and SmartTouch

Thermocool (Biosense Webster, Diamond Bar, CA, USA). The TactiCath catheter system (**Figure 1**) consists of an RF ablation catheter (TactiCath), a base station, and a splitter interfacing between the catheter, the base station, and the RF ablation generator available in the electrophysiology laboratory. The TactiCath catheter is a steerable 3.5-mm-tip open-irrigation RF ablation catheter. The CF measurement is obtained using a triaxial fiberoptic cable inside the catheter. The CF sensor at the distal tip measures the force with amplitude and direction of the contact between the catheter tip electrode and the tissue. CF is measured every 100 ms and is displayed continuously in grams. During RF delivery, measurement of the area under the force–time curve gives a novel parameter to guide catheter ablation, the force–time integral (FTI), which is measured in grams per second.[23] The system can be used as a stand-alone force-sensing ablation catheter or can be visualized within the EnSite Velocity Platform (St. Jude Medical). The SmartTouch Thermocool catheter (**Figure 2**) is a steerable 3.5-mm six-hole open-irrigated tip ablation catheter. The CF measurement is performed via recordings of microdeformation of a precision spring connecting the tip and the shaft of the catheter. The CF is measured every 50 ms and displayed continuously in real time in grams.[13]

Several studies characterized the CF at different anatomical areas during PVI for AF and the monitoring of catheter tip-to-tissue CF during RF ablation demonstrated that there was significant variability in CF both within and between different PV anatomical sites as well as between what different operators recognized as an appropriate CF.[7,8,12,15] In this context, the TOCCATA study[19,24] and recent data from Haldar et al.[18] have demonstrated that there is an important clinical impact of the average CF as low catheter tip-to-tissue CF was associated with a higher rate of AF recurrence in the follow-up period after PVI.

The TOCCATA[7,8] and EFFICAS studies[19] firstly described a strong relationship between CF and clinical outcome following PVI for paroxysmal AF.[8] However, information about lesion formation is currently not available in routine clinical settings, but preclinical work suggests that these parameters may correlate with impedance drop and electrogram attenuation.[24] Characterization of the relationships between catheter CF, ablation time, and these surrogate markers of lesion formation may allow us to define numerical targets for effective, transmural ablation lesions. Recent work has described a new method for quantitative magnetic resonance imaging (MRI) analysis following catheter ablation and may offer a methodology to assess *in vivo* the relationship between CF and LA scar formation.[15]

Impact of contact force guidance on procedural parameters

Beyond the biophysical effects of increased contact force, there is evidence that an optimal catheter tip-to-tissue CF during radiofrequency catheter ablation (RFCA) application for PVI affects procedural parameters by significantly reducing procedure duration and fluoroscopy

Figure 1: TactiCath catheter system consisting of a radiofrequency ablation catheter (TactiCath), a base station, and a splitter interfacing between the catheter and the base station. (Reproduced with permission from St. Jude Medical, St. Paul, MN, USA).

time, without increasing the acute and mid-term complication rates.[25,26] Recent data on PVI using CF sensing demonstrated a strong linear relationship between the number of ablation lesions with low average CF or FTI and the time to achieve acute PVI, confirming that catheter tip-to-tissue CF is an important determinant of
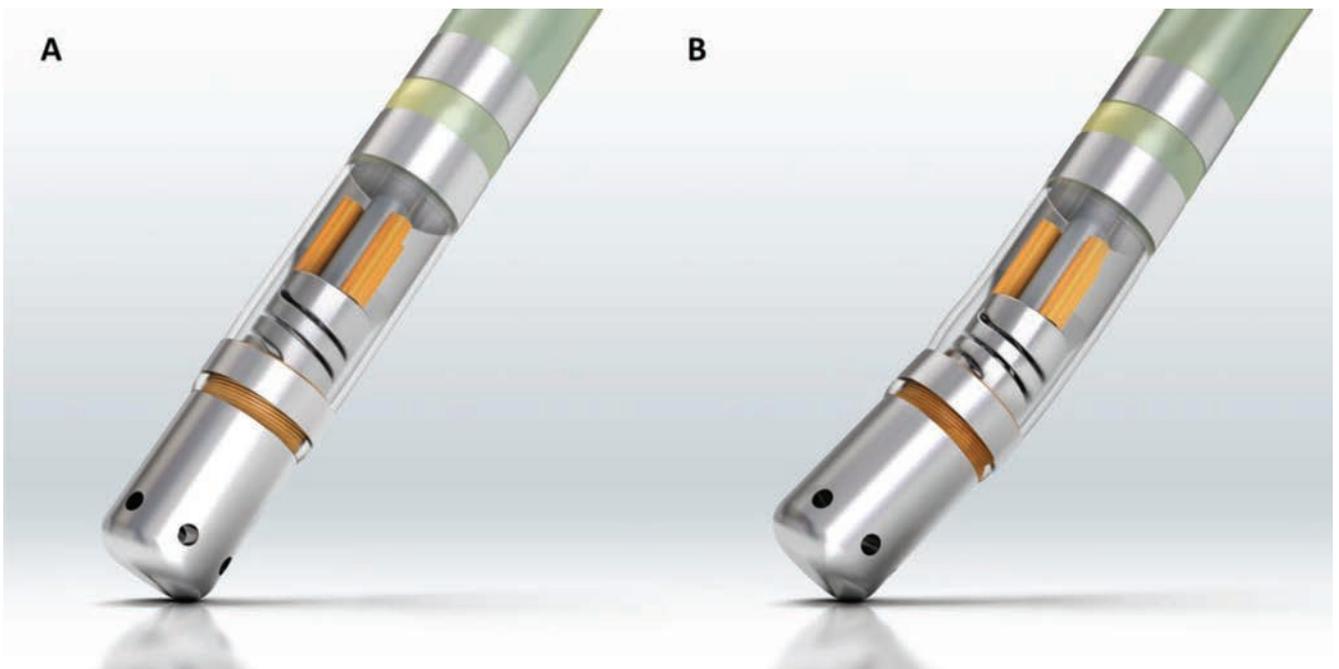

Figure 2: The Thermocool Smarttouch ablation catheter senses the amount of force the physician is using during an ablation. (a) Non-deflected and (b) deflected catheter tip. (Reproduced with permission from Biosense Webster, Diamond Bar, CA, USA).

ablation efficacy as well as procedural duration.[23,27] In addition, acute PV reconnection was strongly associated with low values of CF and FTI.[28] This is in line with a publication from Neuzil et al.[19] indicating that minimum CF and minimum FTI values are strong predictors of gap formation following PVI for AF. Furthermore, Martinek et al.[13] found that the CF sensing technology using the Thermocool SmartTouch™ catheter was able to significantly reduce ablation and procedural times during PVI (**Figure 3**). Energy delivery was substantially reduced by avoiding RF delivery in areas with insufficient catheter tip-to-tissue CF.[13] In this context, the recent data from Marijon et al.[26] confirmed an acute procedural benefit of the use of CF technology over standard open-irrigated-tip RF catheter in ablation of paroxysmal AF in their prospective, nonrandomized, single-center trial (**Figure 4**). Based on these data one can reasonably speculate that a CF-guided PVI therapy allows for fewer energy applications by creating more effective lesions at the first delivery attempt, with a resulting reduction of procedure duration as well as X-ray dose.

Real time measurement of contact force: Effect on clinical outcome

In the TOCCATA[7,8] and EFFICAS I[19] studies, an average CF of nearly 20 g was associated with higher long-term freedom from AF recurrence. Also, ablations with CF<10 g and FTI<400 gs were associated with unstable catheter contact and reduced patient outcome at 12 months. From the TOCCATA study it is reported that the success rate of PVI increases significantly with increasing contact force–time integral FTI.[7,8]

In this context, we recently described the ability of late gadolinium enhancement (LGE) cardiovascular magnetic resonance imaging (CMR) to examine the relationship between CF, FTI, and LA scar formation following PVI. Our data demonstrated that there is a good correlation between FTI and CMR LGE signal intensity (SI) following catheter ablation for AF,[15] which provides a tissue effect confirmation of the clinical outcome observation from TOCCATA and EFFICAS I. Although we have shown a strong correlation between FTI and LGE SI when the FTI is >1,200 gs, only small increments in LGE SI are observed up to a FTI of 1,200 gs, suggesting that the relationship is not as direct as might be expected intuitively (**Figure 5**).[15] In EFFICAS I, the authors concluded that to achieve durable successful PVI, a target CF of 20 g is recommended, with a minimum CF of 10 g and an absolute minimum FTI of 400 gs per individual ablation lesion.[19] This is in line with data from Kumar et al.,[29] who demonstrated that an FTI >404 gs or average CF>16 g had the best sensitivity and specificity for predicting an effective RF lesion using electrogram (EGM) characteristics for their analysis.

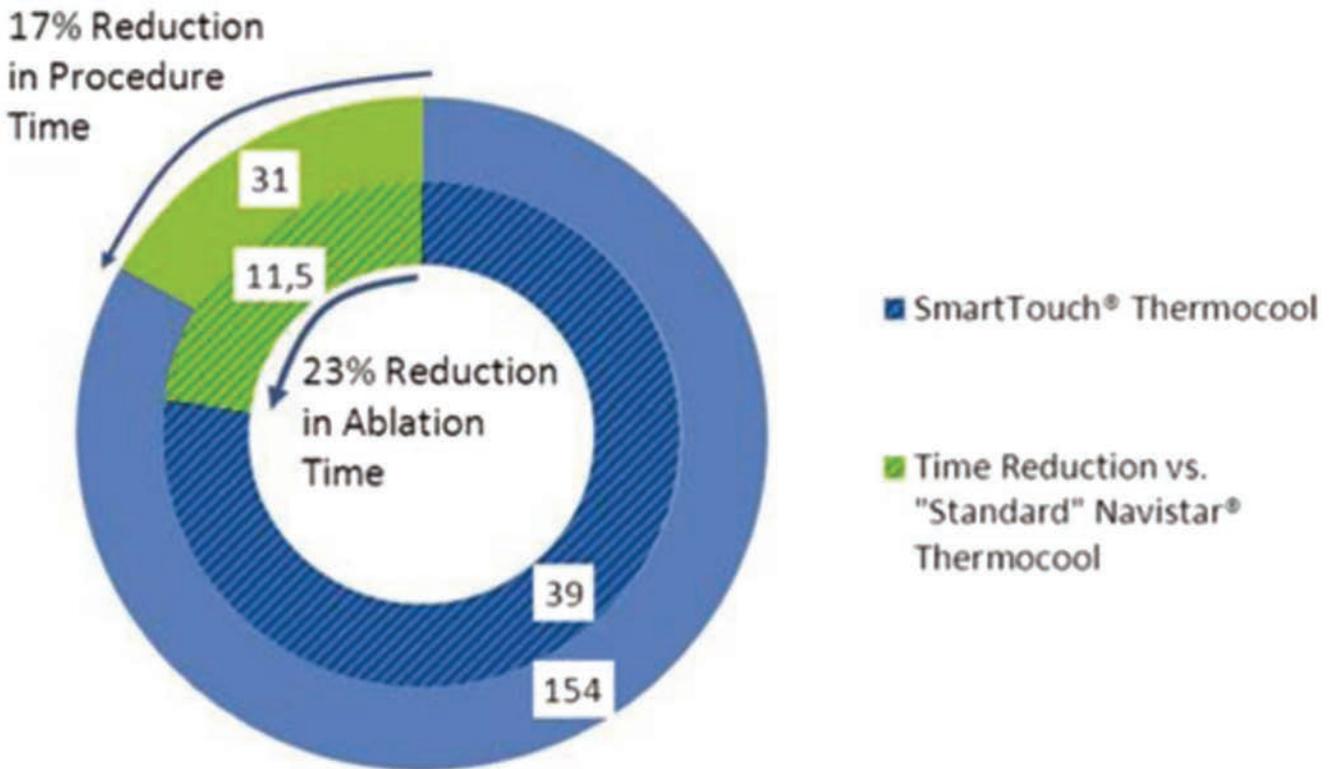PV reconnection remains common at repeat procedures, and may occur because of atrial injury which is either

Figure 3: Clinical impact of an open-irrigated radiofrequency catheter with direct force measurement on atrial fibrillation ablation. Absolute reduction in ablation (inner circle) and procedure duration (outer circle) in minutes and percentages. (Reproduced with permission from[13]).
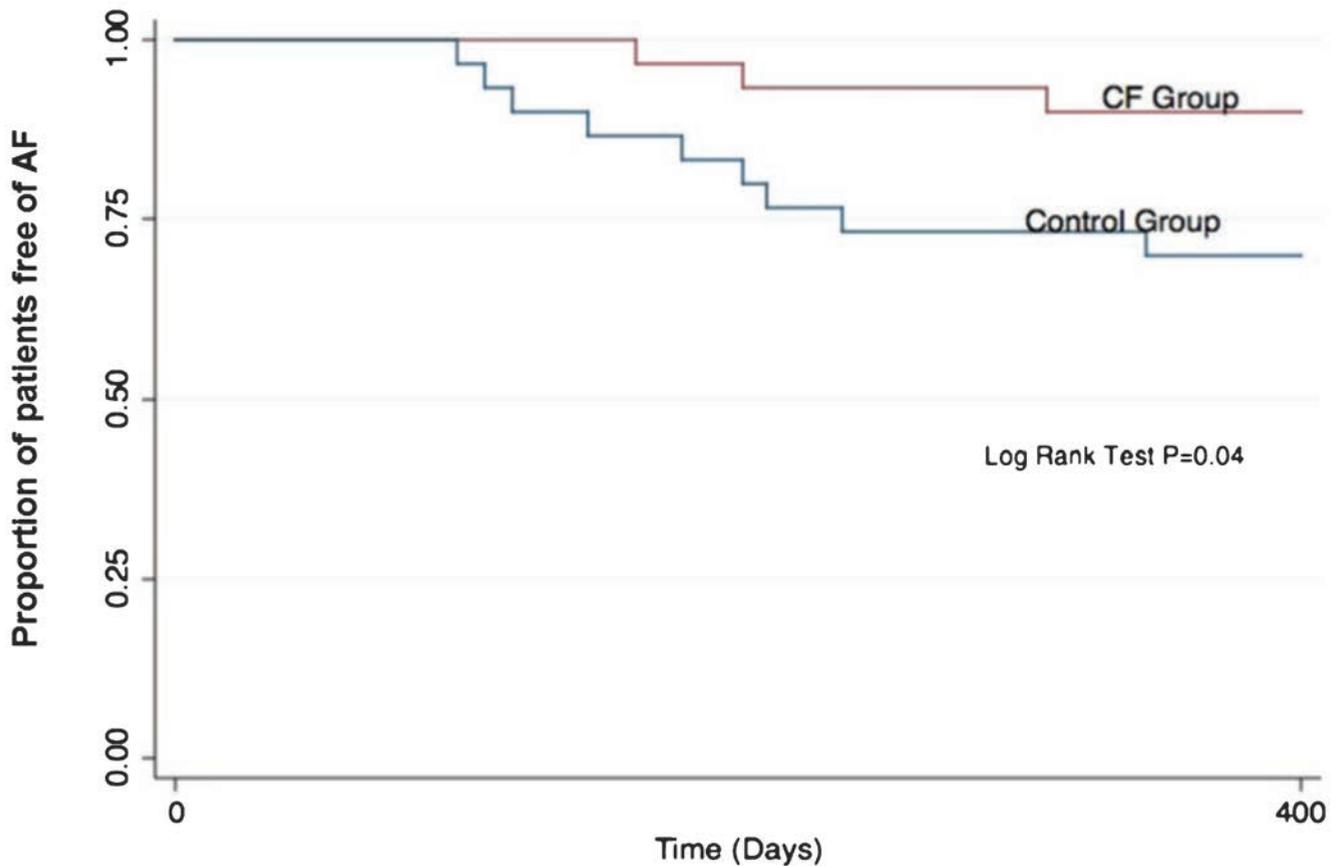
Figure 4: Real-time contact force sensing for pulmonary vein isolation in the setting of paroxysmal atrial fibrillation (AF): procedural and 1-year results. Kaplan–Meier survival curve—proportion of patients free of AF during the 12-month follow-up (3-month blanking period). (Reproduced with permission from[26]).
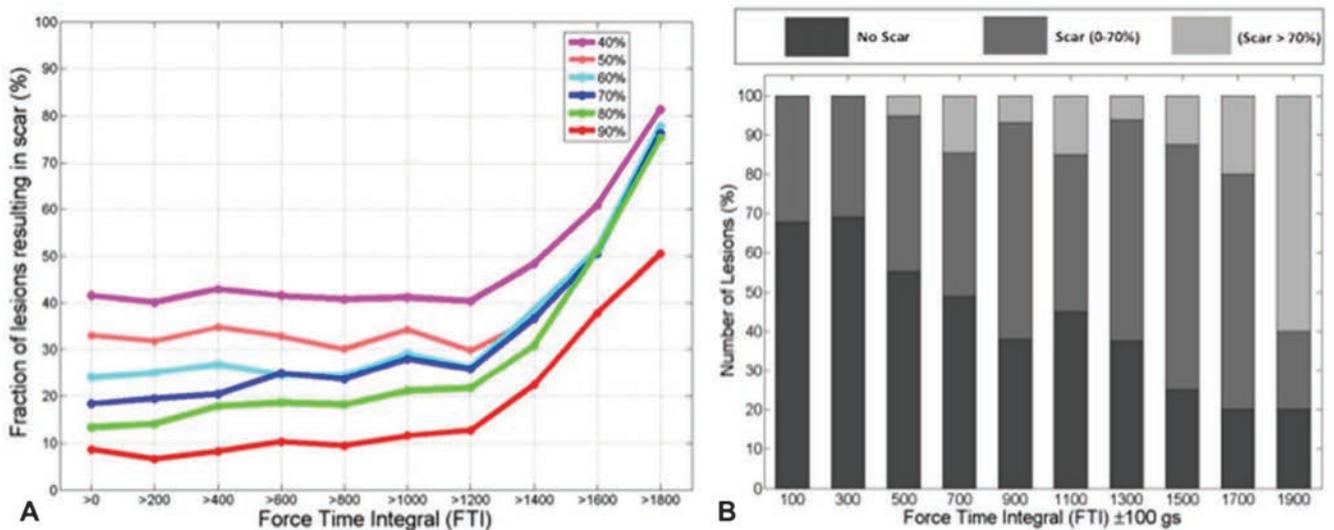

Figure 5: Relationship between left atrial lesion formation (%) 3 months after pulmonary vein isolation and CF measured as FTI (gs). Increasing FTI correlated with increasing LGE signal intensity. For an FTI<1,200 gs, an increment in the FTI results in a small increment in scar, whereas for FTI>1,200 gs an increment in the FTI results in a large change in scar formation. The figure shows different curves depending on the definition of an effective lesion ranging from 40% to 90% of scar in a 5-mm^2 analysis zone. (b) Relationship between FTI and percentage of scar per analysis zone (no amount of scar versus < 70% scar versus >70% scar) indicating that the amount of scar per zone increases, whereas the amount of no scar decreases with increasing FTI. (Reproduced with permission from[15]).

transmural but non-permanent or permanent but non-transmural. Both patterns are inevitably associated with acute atrial edema and cannot be reliably distinguished by current CMR techniques within hours of an ablation procedure.[30,31] Finally, there is evidence of a good correlation between FTI and LGE MRI following catheter ablation of AF and it has been demonstrated that an FTI of 1.200 gs is associated with the formation of transmural atrial scar defined by CMR.[15] In addition, real-time FTI maps are feasible and may prevent inadequate lesion formation during catheter ablation for AF.[15]

Present limitations and future directions

Despite an ever-increasing number of parameters that are known to correlate with lesion formation,[32] we are still unable to consistently create permanent transmural contiguous lesions. This is perhaps in part due to the multiple factors that influence lesion formation in the *in vivo* setting, not all of which are currently measured or measurable. This has led to the development of technologies that can assess the actual lesion as opposed to factors, including CF, that are known to influence lesion formation. One group of technologies aims to measure intra-tissue temperature, as once the isotherm of irreversible tissue injury is reached a lesion is created. Microwave thermometry, which measures the radiated temperature from the cardiac tissue up to a depth of 3 mm has shown some promise in preclinical studies,[33] but there are no data on creating transmural lesions. MR thermometry has also been trialed, but in ventricular tissue only, as a way of assessing lesion formation in real time.[34] Ultrasound imaging does not suffer from the same spatial or temporal resolution problems and a variety of ultrasound methodologies have been assessed preclinically including photoacoustic imaging[35] and acoustic radiation force imaging.[36]

Near-field ultrasound

Owing to the variability in atrial tissue depth, indirect measurement of lesion formation alone cannot lead to transmural lesions unless one accepts as inevitable ablation extending beyond the cardiac border. Given the potentially catastrophic consequences of extracardiac ablation, namely atrial-esophageal fistula, direct assessment of tissue depth and lesion depth is required. Seminal work on pathological specimens has demonstrated that the posterior wall can vary in depth by more than fivefold between the left and right PV ostia and along the posterior wall.[37] The range of distances between the left atrium and the esophagus is similarly large (3.6–13.5 mm). Although a number of methods attempt to minimize the risk of esophageal damage, no technique has been demonstrated to reliably prevent fistula formation.

Titration of energy delivery so that the operator is in control of lesion growth is the aim of a combined RF ablation catheter that incorporates ultrasound transducers to visualize tissue depth at the catheter tip in real time. Initial work in an open chest model demonstrated that the change in tissue architecture with myocardial necrosis from RF energy delivery resulted in a change in ultrasound contrast which was highly correlated ($y=0.93x+0.18$ $r=0.72$ R^2 0.62), whereas the impedance drop had a poor correlation with lesion depth.[38] Further work has demonstrated that specific features during ablation can also be reliably detected, such as intramyocardial steam formation, prior to an actual steam pop.[39]

Conclusions

Interventional strategies for AF have evolved over the last two decades and recognize the importance of achieving permanent pulmonary vein isolation at the very least in a patient with paroxysmal or persistent AF. In parallel to this focus on ablation strategy has been the recognition of a need for precise titration of energy at the point of delivery and specific to that site of delivery. Creating permanent contiguous lesions has always been difficult, but through evolution of catheter tip design incorporating CF measurement this is becoming easier. An important hurdle yet to be overcome is visualization of lesion creation and assessment of the atrial tissue for every single lesion. MRI and ultrasound may offer a solution to this problem.

Acknowledgment

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