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Current Density and Creation of Radiofrequency Ablation Lesions:

Relationship between Electrode Size and Power Efficiency

Technical Bulletin No. 1

INTRODUCTION

Atrial fibrillation (AF) is the most common arrhythmia encountered in clinical practice.[1] The rate of AF occurrence increases with age, from less than one percent of the population under age 60 to more than eight percent of the population age 80 and older. Catheter ablation has been accepted as a mainstream therapy for patients with AF.[2] Typical AF ablation approaches utilize radiofrequency (RF) energy delivered in a unipolar manner via the tip electrode of a transvenous catheter. The most common ablation strategies require the operator in a point-by-point process to create long contiguous lesions in the thin-walled left atrium, where undesirable side effects of surplus power delivery can lead to serious complications.[3] Since the majority of power delivered from conventional RF systems is lost to circulatory cooling, AF ablation techniques could benefit from technical improvements that minimize or eliminate the root causes of inefficient power delivery.

An innovative RF ablation system has been introduced that is designed to overcome many of the challenges reported using unipolar RF and tipped catheters to create left atrial lesions.[4] This system delivers user-defined combinations of unipolar and bipolar energy via relatively small cylindrical electrodes arranged in an array configuration [Figure 1]. This implementation allows the operator to create long, contiguous lesions with a single RF application, unlike typical hemispherical 4 mm and 8 mm ablation catheters that must be manipulated in a 'point-to-point' or 'dragging' manner to achieve similar lesion profiles. Early research with RF ablation proved that lesions greater than 7 mm in depth could be created using a hemispherical 6F/2 mm electrode and peak power of 10W.[5] In order to estimate the appropriate RF power settings for ablation with these smaller cylindrical electrodes, it was necessary to determine the equivalent current density used when creating lesions with conventional electrodes [Figure 2].

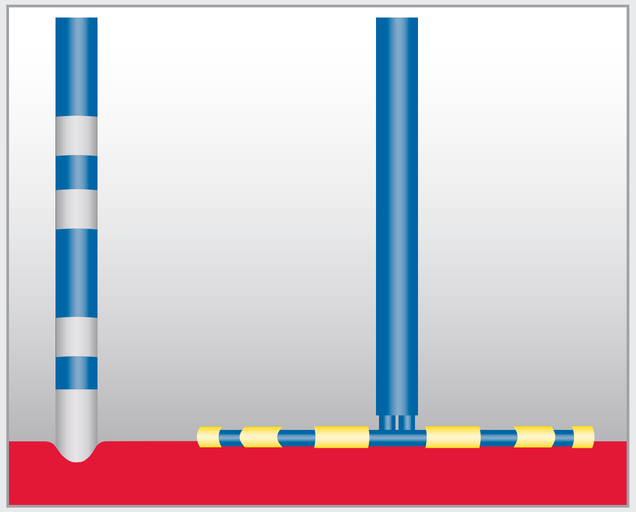

Figure 1: Comparison of 7F 4 mm hemispherical omni-directional electrode with Medtronic Ablation Frontiers PVAC® GOLD Pulmonary Vein Ablation Catheter® 3 mm, 9 electrode unidirectional array.

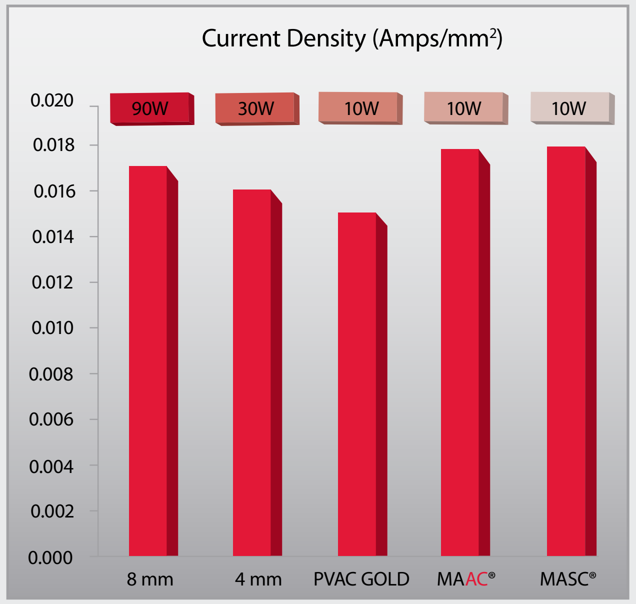

Figure 2: Equivalent current density can be maintained across various electrode sizes by titrating power. A smaller electrode requires less power to achieve equivalent current density.

TECHNICAL INSIGHT

Irreversible thermal injury to cardiomyocytes has been shown to occur at temperatures above 50 °C, yet soft thrombus can form at just 80 °C and the potential for "steam pops" occurs above 100 °C.[6] Thus a desirable RF lesion will be created within the temperature limits of 50 → 80 °C. The biophysical mechanism of lesion formation is based on resistive and conductive heating, thus a comparison model can be created by assessing the current density delivered to the tissue.

As current flows through tissue, power is dissipated and thus heat generated via resistive heating. Joule's Law defines the quantity of power (*P*) delivered through a resistive medium as the product of the resistance or impedance (*R*) and the square of current flow (*i*), Equation 1 [Figure 3].

Rearranging the equation [Figure 3] to calculate total current delivered gives Equation 2 [Figure 3]. For a given electrode configuration, the average current density [i_d] per unit area will be equal to the total current divided by the electrode surface area, Equation 3 [Figure 3].

As electrode size decreases, the size of the tissue "corridor" through which current may flow will get smaller, thus increasing the impedance. With all other factors constant, a smaller electrode will experience greater impedance and larger electrode less impedance.

Equation 1 $P = I^2 * R$

Equation 2 $i[A] = \sqrt{\frac{P\,[W]}{R\,[\Omega]}}$

Equation 3 $i_d\left[\frac{A}{mm^2}\right] = \frac{\sqrt{\frac{P\,[W]}{R\,[\Omega]}}}{SA_{electrode}[mm^2]}$

Figure 3: Joule's Law shows that power delivered through a resistive medium is equal to the square of current times the impedance. Rearranging and dividing by surface area gives the formula for Current Density based on the electrode size.

Table 1 shows the resultant calculations for Current Density using a matrix of typical electrode sizes at various powers, as well as for the 2 mm and 3 mm electrodes found on the Medtronic Ablation Frontiers Multi-Array Ablation Catheter® (MAAC), Multi-Array Septal Catheter® (MASC) and Pulmonary Vein Ablation Catheter® GOLD (PVAC GOLD). Note that this table represents average current densities assuming a homogeneous tissue medium with fixed impedance per unit volume [Figure 4].

These calculations demonstrate that equivalent current densities used in conventional large electrode delivery, can be achieved by delivering approximately 10W to a 2 mm or 3 mm cylindrical electrode.

Catheter size (F)	Electrode Length (mm)	Electrode Surface Area (mm²)	Impedance (Ω)	Current Density (A/mm²) — Power 10	20	30	40	50	60	70	80	90
MAAC & MASC	2	9	355	**0.018**	0.026	0.032	0.037	0.041	0.045	0.049	0.052	0.055
PVAC GOLD	3	14	225	**0.015**	0.022	0.027	0.031	0.035	0.038	0.041	0.044	0.046
7	4	32	100	0.010	0.014	**0.017**	0.020	0.022	0.024	0.026	0.028	0.029
8	8	63	60	0.006	0.009	0.011	0.013	0.014	0.016	**0.017**	0.018	0.019

Table 1: Comparison of current density between common electrode sizes and typical RF generator power settings. As electrode size increases, larger amounts of power must be delivered to maintain equivalent current density.

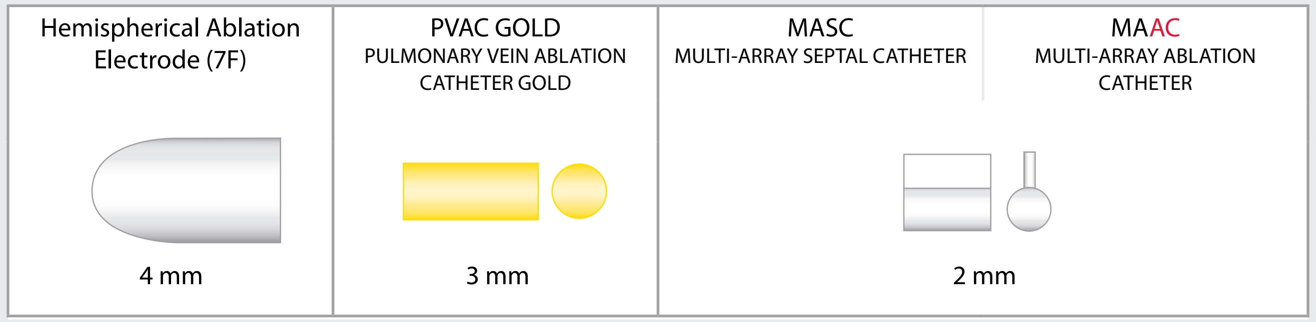

Figure 4: Relative size comparison for radiofrequency electrodes described in Table 1.

CLINICAL IMPLICATIONS

While small electrodes are able to provide equivalent current density and thus equivalent heating to larger electrodes, several other aspects of small electrode deployment may also help to alleviate the root causes of inefficient power delivery.

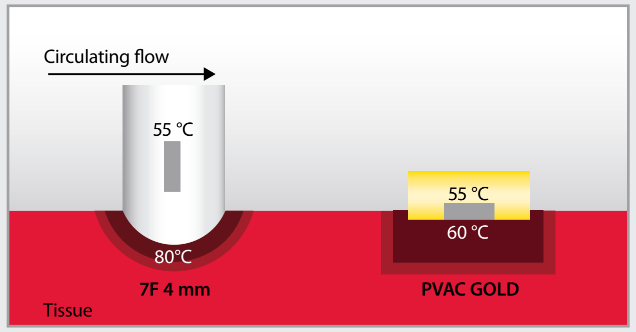

Figure 5: The geometry of the PVAC GOLD electrode array allows for thermal measurement predictably at the tissue interface (dark gray area represents location of the thermocouple). Also, the relative electrode surface in contact with the tissue is higher with a small electrode in the unidirectional configuration.

Unlike conventional tip catheters, which are designed for omni-directional use, these small electrodes are deployed on nitinol frames which only allow for unidirectional tissue contact [Figure 1]. The advantage to this configuration is that it localizes the temperature sensors at the endocardial surface [Figure 5]. By actively measuring temperatures at this junction, a more accurate tissue temperature is achieved because the cooling effect of circulating blood is minimized.

With greater accuracy between the measured and actual tissue temperature, the power delivery of a temperature driven system becomes more efficient.

The unidirectional configuration together with the pliability of the nitinol frame also allows the multi-electrode array to conform to the variable structures found within the left atrial chamber. This enhances the ratio of electrode-tissue contact that can be achieved when compared to larger electrodes. Since blood has approximately one-half the impedance of tissue, increasing the ratio of electrode surface in contact with the tissue will decrease the amount of current lost to blood flow and provide RF power efficiency improvement.

Successful and safe radiofrequency ablation relies on achieving target temperatures that achieve irreversible thermal injury without the consequences of overheating. Thus effective ablation is achieved by focusing on the primary objective – lesion creation – but can become safer and more efficient when considering all technical aspects of a temperature-driven radiofrequency circuit. The combination of small electrodes that can provide equivalent current density, pliable frames that achieve high electrode-tissue contact area and accurate temperature measurement make it possible to successfully create therapeutic lesions with relatively low power. [Figure 6]

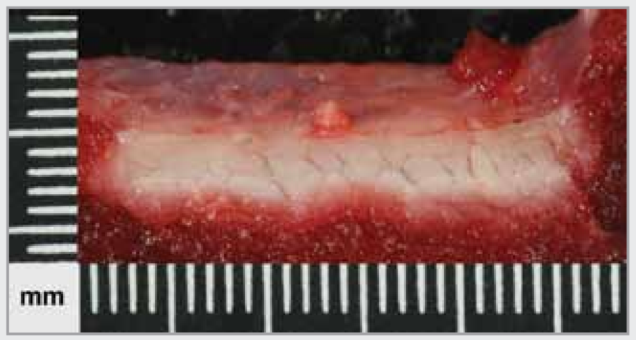

Figure 6: Typical in vitro lesion created by PVAC GOLD 4 electrode test catheter delivering radiofrequency (RF) to porcine thigh muscle for 60 seconds at target temperature of 60° C in 2:1 energy mode. The lesion is approximately 5 mm deep.