Temperature-Controlled Cooled-Tip Radiofrequency Ablation in Left Ventricular Myocardium

Avoidance of Steam Pop During Ablation

Ichiro Watanabe,1 MD, Min Nuo,1 MD, Yasuo Okumura,1 MD, Kimie Ohkubo,1 MD, Sonoko Ashino,1 MD, Masayoshi Kofune,1 MD, Tatsuya Kofune,1 MD, Toshiko Nakai,1 MD, Yuji Kasamaki,1 MD, and Atsushi Hirayama,1 MD

Summary

Steam pop and intramural charring have been reported during cooled-tip radiofrequency catheter ablation (RFCA). We studied the feasibility of temperature-controlled cooled-tip RFCA in the canine heart. An internally cooled ablation catheter was inserted into the left ventricle. A custom-made radiofrequency (RF) generator capable of controlling the tip-temperature at the preset level by slow increases in the power was used. Temperature-controlled cooled-tip RF applications were performed at a target temperature of 40°C for 90 seconds.

Acute study: Intramyocardial temperature was measured at the ablation site in 10 dogs by inserting a fluoroptic probe. Chronic study: Lesion depth and volume were measured in 5 dogs after 3 weeks of survival. In the acute study, no pop or abrupt impedance rise was observed. Maximum intramyocardial temperature was 72.4 ± 14.4°C at 2-4 mm above the endocardium. No coagulum formation, craters, or intramural charring were observed. Maximum lesion depth was 6.7 ± 1.5 mm, and lesion volume was 404 ± 219 mm$^3$. In the chronic study, maximum lesion depth was 5.9 ± 1.1 mm, and lesion volume was 281 ± 210 mm$^3$.

Temperature controlled RFCA is feasible with a cooled-tip catheter and an RF generator that slowly increases the RF power until the preset catheter-tip temperature is reached. (Int Heart J 2010; 51: 193-198)

Key words: Cooled-tip ablation, Temperature control, Intramyocardial temperature, Ventricular myocardium, Steam pop, Thrombus

Radiofrequency (RF) ablation destroys myocardial tissue via thermal injury. Resistive heating occurs in a small zone adjacent to the catheter tip, while the surrounding myocardium is passively heated by conduction. Tissue temperatures > 50°C are necessary to produce irreversible injury.1,2 Excessive heating > 100°C leads to coagulation of blood proteins and charring of surface tissue.3 At the electrode-tissue interface, this layer of coagulum and char acts as an insulator, preventing further energy transfer and causing a rise in electrical impedance. To avoid overheating of the tissue, delivery of RF power is adjusted to maintain temperatures well below 100°C. Measured electrode temperature is typically restricted to 60-70°C due to the discrepancy between the temperature at the electrode, which is cooled by circulating blood, and the tissue temperature.4-6

A saline-irrigated or “cooled” RF catheter circulates saline through the electrode tip, cooling the distal electrode and tissue interface and allowing greater energy delivery before coagulum formation and charring set in. Larger ablation lesions can thereby be created.4,6 There is, however, an even greater discrepancy between measured electrode tip temperature and actual tissue temperature than with a standard ablation catheter; this creates greater potential for unrecognized excessive heating within the myocardium. This overheating results in boiling of the tissue’s water and the formation of steam, which erupts through the tissue surface and is heard as a pop. The final result is charring within the myocardium.4-7 These events are undesirable, are associated with a risk of perforation, and may occur during cooled-tip RFCA while “low” temperatures are recorded from the catheter. We previously reported that steam pop and intramyocardial charring occurred when the temperature of the catheter tip used for cooled RF ablation exceeded 45°C.7 The aim of this study was to investigate the rationale for testing the slow onset algorithm results in delay between heating of the electrode-tissue interface and heating of the thermocouple used to measure temperature in in vivo experiments.

Methods

The care of all animals in this study conformed to the Position of the American Heart Association on Research Animal Use and was conducted in accordance with ac-
Acute experiments: The heart was exposed via a median sternotomy and suspended in a pericardial cradle. Anesthesia was maintained with pentobarbital sodium (100 mg between 5-15 mV). Left ventricular intramyocardial temperatures recorded at serial depth from the ablation catheter were measured by inserting a fluoroptic thermal catheter (4 probes, 2.5 mm apart, Fluoroptic Thermometer 3100, Luxtron Co, Santa Clara, CA, USA) above the endocardial surface. Endo indicates endocardium; Epi, epicardium; and LV, left ventricle. Measurement of lesion size. The lesion volume was calculated by using the formula for an oblate ellipsoid by subtracting the volume of the ellipsoid extending above the surface of the muscle.

**Ablated lesion volume** was calculated by means of the following formula for an oblate ellipsoid by subtracting the volume of the ellipsoid extending above the surface of the muscle (“missing cap”): 

\[ \frac{0.75 \pi (B/2)^2 (A-C)}{2} - \frac{0.25 \pi (D/2)^2 (A-2C)}{6} \]

where \(A\) = maximal depth, \(B\) = maximal diameter, \(C\) = depth at the maximal diameter, and \(D\) = lesion surface diameter.\(^6\)

**Chronic experiments:** A cooled ablation catheter was passed from the right carotid artery to the LV under fluoroscopic guidance. Catheter contact with the endocardium was assessed by the ST-T elevation of the catheter-tip unipolar electrograms between 5-15 mV. Closed-chest cooled RF ablation was performed at 4 to 6 separate sites. The lesion depth and volume were measured after 3 weeks of survival by the same formula used in the acute experiments.

**Cooled RF ablation system:** The internally cooled ablation catheter was constructed with a pair of inner lumens through which room temperature saline could be circulated under constant pressure by a motor-driven injector pump maintaining a steady flow of 0.66 mL/sec to cool the catheter tip throughout the delivery of RF current. A custom RF generator capable of controlling catheter-tip temperature at a preset level ≥ 30°C automatically by slowly increasing the voltage (maximum voltage = 70 volts; the rate of increase in voltage = 1 volt/sec; time to reach the preselected temperature = around 40 seconds, Japan Lifeline Co./Central Kogyo Co. (Tokyo) was used. Temperature-controlled cooled-tip RF applications at a target temperature of 40°C were performed for 90 seconds each.

**Histological analysis:** In the acute experiments, animals were killed 1 hour after the last cooled RF ablation. Lesions were identified upon gross examination by the presence of light brown areas surrounded by grey spots. In the chronic experiments, lesions were identified upon gross examination by the presence of well-demarcated fibrous scars. Tissue sections from grossly detectable lesions were fixed in 10% formalin, dehydrated, embedded in paraffin, sectioned at 5-μm thickness, and stained with hematoxylin and eosin for the acute experiments, and with hematoxylin and eosin and Masson’s trichrome stains for the chronic experiments.

**Statistical analysis:** Values are expressed as the mean ± SD. Differences in continuous variables were analyzed by unpaired Student’s t-test. A \( P \) value of < 0.05 was considered statistically significant. StatView 5.0 software (SAS Institute, Cary, NC, USA) was used for data analysis.

**Results**

**Lesion sizes**

**Acute experiments:** Thirty-four lesions were created in 10 dogs. LV endocardial lesion depth was 6.7 ± 1.5 mm (4.5-10 mm), and LV volume was 404 ± 219 mm³ (147-1027 mm³). No audible pop, abrupt impedance change, or abrupt catheter-tip temperature change was noted during RF current application. Maximum intramyocardial temperature was 72.4 ± 14.4°C (n = 34, 49.0-97.1°C). Maximum temperature was achieved at the first (distal) temperature probe in 8 experiments, at probe 2 in 14 experiments, at probe 3 in 11 experiments, and at the fourth (proximal) probe in 1 experiment. Intramyocardial temperature profiles and myocardial lesions are shown in Figure 2-5. Maximum temperature was
achieved at probe 2 in one experiment (Figures 2, 3), but maximum temperature was achieved at probe 3 in another experiment (Figures 4, 5). In one experiment in which RF power, RF voltage, and catheter-tip impedance were measured, maximum RF power was 32W and maximum impedance fall reached 43Ω (Figures 6, 7). Figure 8 shows the relationship between maximum intramyocardial temperature among 4 intramyocardial probes during RF ablation and lesion depth and volume.

Chronic experiments: Twenty lesions were created in 5 dogs. LV endocardial lesion depth was 5.9 ± 1.0 mm (4.0-7.5 mm), and LV volume was 264 ± 198 mm³ (81-931 mm³). Results of a chronic experiment are shown in Figures 9 and 10. The catheter-tip temperature decreased from 38°C to 24°C by perfusion of the catheter tip with saline. The catheter-tip temperature was increased gradually and maintained at 40°C during RF energy application for 90 seconds. Bipolar electrogram amplitude at the catheter-tip decreased to 25% of the control value. No steam pop was observed during ablation. The maximum depth of the lesion was 4.8 mm, and the lesion border was clearly demarcated. In the present experiments, lesion depth and volume were smaller in the chronic experiments (P = 0.039 and P = 0.023, re-
spectively). Smaller lesion depth and volume in the chronic experiments might be explained by the shrinkage of the lesions by replacement of the myocardium by collagen tissue and also the different experimental conditions (open-chest in acute experiment and closed-chest experiment in chronic experiment).

Discussion

Previous experimental and clinical studies showed that cooling the electrode during RF energy applications allows greater energy delivery and produces lesions larger than those produced by noncooled RF applications in normal and infarcted hearts. A multicenter study of cooled RF ablation of ventricular tachycardia in patients with structural heart disease showed that such ablation can be performed with high initial success. Although the safety of this trial was relatively good, the risk of excessive heating with steam pop explosions remains an important concern because studies in in vitro and in vivo models have shown that steam formation can cause rupture of overlying myocardial tissue either into the myocardial cavity or outward into the pericardium, and parameters for guiding ablation have not been adequately defined.

Previously, we showed the catheter-tip temperature at
the onset of popping and abrupt impedance rise to be 54 ± 5°C (48-60°C) and 59 ± 10°C (50-75°C), respectively, during cooled-tip ablation in in vivo experiments. Cooper, et al also showed in in vivo experiments that steam explosions are common when cooled electrode temperature exceeds 40°C and are not predictable from the drop in power and impedance drop. Thiagalingam, et al compared the incidence of pops and thrombus formation in ex vivo experiments and showed that there was a significantly greater incidence of pops and thrombus formation at a constant power of 20W or 30W than under temperature control. The incidence was also greater under impedance control (drop of up to 20Ω) than under temperature control (42°C) at a maximum power of 40W or under impedance control at a drop of up to 10Ω. During cooled RF ablation, it is difficult to maintain a catheter-tip temperature of 40°C precisely by automatic temperature control mode with commercially available RF generators that rapidly increase the power, because the catheter-tip temperature changes rapidly.

In addition, it generally takes several seconds to reach the preset temperature with the current commercially available RF generators. Before conducting this experiment, we did experiments in which constant power was applied using closed-loop cooled-tip catheters under the same experimental condition. In the present experiment and the former experiment, catheter contact with the endocardium was assessed by the ST-T elevation of the catheter-tip unipolar electrograms between 5-15 mV. Recent studies demonstrated that not only the power setting, but also the contact force of the catheter-tip is an important factor to predict tissue temperature, lesion depth, popping, and crater formation experimentally.

In the previous experiments, a 30W constant power and mean RF delivery duration of 105 ± 17 seconds resulted in a mean maximum catheter-tip temperature of 42 ± 5°C, mean lesion volume of 514 ± 104 mm³, and mean lesion depth of 8.2 ± 1.2 mm. We observed popping in 1 out of 6 cooled-ablations. We did not observe popping and an abrupt impedance rise when the catheter-tip temperature < 45°C. However, popping during cooled-tip ablation resulted in serious myocardial damage due to intramyocardial steam-pop. Thus, in this series of experiments, we set the catheter-tip temperature at 40°C, and slow power increase because more accurate catheter-tip temperature control was possible.

Actually, when popping or an abrupt impedance rise did not occur during power-controlled cooled-tip ablation, lesion volume and depth were similar or greater with a conventional RF generator system. In the previous experiments, we performed closed-loop, cooled-tip catheter ablation with different power settings, such as 20W, 30W, 40W, and 50W for 120 seconds, and found that the incidence of popping and abrupt impedance rise was observed in 0/11 experiments with 20W, 1/22 using 30W, 13/25 using 40W, and 6/6 using 50W. All popping and impedance rises were observed at a catheter-tip temperature of ≥ 45°C. We speculated that a rapid increase in the RF power might increase the likelihood of intramural steam pop during cooled RF ablation because of the rapid increase in myocardial temperature. Therefore, we designed an RF generator that would reach the preset temperature between 30-40 seconds after the onset of RF delivery. Thus, we kept RF delivery time to 90 seconds. In our acute and chronic experiments, there was no steam pop or rapid impedance rise. Furthermore, no obvious thrombus was noted at the catheter-tip and the ablated tissue in the acute experiments. Yokoyama, et al used a closed-loop irrigation catheter with a fixed power of 20W or 30W in a canine thigh muscle preparation. They found that in the presence of blood flow (0.5 m/seconds), thrombus occurred with a catheter electrode temperature ≥ 43°C, and the highest incidence of thrombus occurred with temperatures ≥ 50°C. To the best of our knowledge, only one previous study has presented subacute phase lesion dimensions at 4-7 days after RF ablation by saline irrigated catheter. However, no previous study has compared acute and chronic phase lesion dimensions.

Study limitations: This study has several limitations. Only one condition was tested (40°C for 90 seconds), whereas a variety of protocols are seen in clinical practice. Thus, different temperatures and different RF times are needed to compare the lesion depth and volume. Similarly, we studied only a closed-loop cooled-tip catheter with one saline temperature and one irrigation flow rate, those that are recommended for the clinically available internally irrigated catheter, although varying the irrigation flow rate and saline temperature have not been shown to have a significant effect on lesion size, but we did not conduct the same catheter-tip temperature control experiments with a conventional RF generator and open-irrigated catheter, which might result in different lesion size. Electrode orientation and blood flow also have important effects on temperature and were not studied due to limits in being able to quantitate or control these parameters in an in vivo beating heart model. We did not compare the temperature control experiments with conventional rapid increased power in the present experiments. The contact force of the catheter-tip also affects steam pop and thrombus formation in an open-irrigated ablation, therefore contact force also should be measured.

Conclusion: Temperature-controlled cooled-tip RFCA is feasible without “steam pop” and an abrupt rise in impedance using an RF generator that slowly increases the power to reach the preselected catheter-tip temperature.

References


