Journal of Interventional Cardiac Electrophysiology 4, 295–300(2000)

Microwave Radiometric Thermometry and its Potential Applicability to Ablative Therapy

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Abstract. ***Introduction:*** **Current techniques for estimating catheter tip temperature in ablative therapy for cardiac arrhythmias rely on thermocouples or thermistors attached to or embedded in the tip electrode. These methods may reflect the electrode temperature rather than the tissue temperature during electrode cooling so that the highest temperature away from the ablation site may go undetected. A microwave radiometer is capable of detecting microwave radiation as a result of molecular motion. In this study, we evaluated microwave radiometric thermometry as a new technique to monitor temperature away from the electrode tip during ablative therapy utilizing a saline model.**

Methods and Results: **A microwave radiometer antenna and fluoroptic thermometer were inserted in a test tube with circulating room temperature saline kept constant at 23.5°C while the surrounding saline bath was heated from 37°C to 70°C. For every degree rise in the warm saline bath placed either 5 mm or 8 mm from the radiometer antenna, the radiometer temperature changed 0.26°C and 0.14°C respectively while the fluoroptic temperature probe remained constant at 23.5°C. The radiometer temperature was highly correlated with the warm saline bath temperature (R^2 = 0.997 for warm saline 5 mm from the antenna, R^2 = 0.991 for warm saline 8 mm from the antenna).**

Conclusions: **Microwave radiometry can estimate distant temperatures by detecting microwave electromagnetic radiation. The sensitivity of the microwave radiometer is also distance-dependent. The microwave radiometer thus serves as a promising instrument for monitoring temperatures at depth away from the catheter-electrode tip in ablative therapy for cardiac arrhythmias.**

Key Words. **radiometer, microwave, temperature, ablation**

Introduction

Catheter ablative therapy has become a central element in the treatment of patients with cardiac arrhythmias [1–6]. The recording and control of catheter electrode temperature have been important in guiding catheter ablation and preventing impedance rises [7]. Thermocouples or thermistors attached to or embedded in the tip electrode have been used to estimate the temperature at the electrode–tissue interface. However, saline cooling of the electrode tip with saline interferes with the thermocouple's ability to record the highest temperature away from the electrode–tissue interface [8].

Radiometric thermometry is a technique in which the electromagnetic radiation resulting from the motion of molecules is measured in order to estimate temperature [9]. Because electromagnetic radiation can be detected over distance, radiometric thermometry may be used to estimate a temperature at depth even if the surface temperature is low. Therefore, we propose microwave radiometric thermometry as a novel technique to monitor temperatures away from the electrode–tissue interface during the presence of saline cooling.

Methods

Description of Microwave Radiometry System

In this study, a microwave radiometer utilizing a helical coil antenna measured microwave radiation resulting from molecular motion at a frequency of 4 GHz. The voltage output from the radiometer was recorded digitally using an analog-digital converter (National Instruments)

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Received 13 July 1999; accepted 9 September 1999

and input into a PC computer (Labview 5.0 software, National Instruments). The voltage outputs were converted to microwave radiometer temperatures using the calibration technique described below.

Test Apparatus

A saline environment was used to evaluate the ability of the microwave radiometer to assess temperature changes five and eight millimeters away. The microwave radiometer was placed within a test tube filled with saline of either constant or varying temperatures. The test tube and its contents were then surrounded by a warm saline environment (Bath A) heated between 37°C and 70°C (Fig. 1). Test tubes of differing diameters were used. The test tubes (Kimax-51, N51A borosilicate glass) had either an outer diameter (O.D.) of 10 or 16 mm.

The radiometer antenna was placed at the center of the saline-filled test tube 28 mm from floor of the warm saline bath. Four fluoroptic temperature probes (755 Multichannel Thermometer, Luxtron model #755G) were calibrated each day. All the fluoroptic temperature probes were placed at the same level as the radiometer's antenna tip, 28 mm from the floor of the warm saline bath. One fluoroptic temperature probe was placed alongside the radiometer antenna within the test tube. The remaining three fluoroptic temperature probes were placed at the inside edge of the surrounding warm saline bath.

Microwave Radiometer Calibration

The microwave radiometer was calibrated between 22°C and 35°C. During calibration runs saline was pumped from Bath A into the test tube to maintain the same temperature as the surrounding bath. The fluoroptic probes' temperatures and radiometer's voltage outputs were continuously recorded. Once all four temperature probes reached the same temperature during the calibration (e.g. at 22°C, 23°C... 35°C), the first 10 radiometer voltage outputs at that corresponding temperature was recorded and then averaged. The average voltage values for each

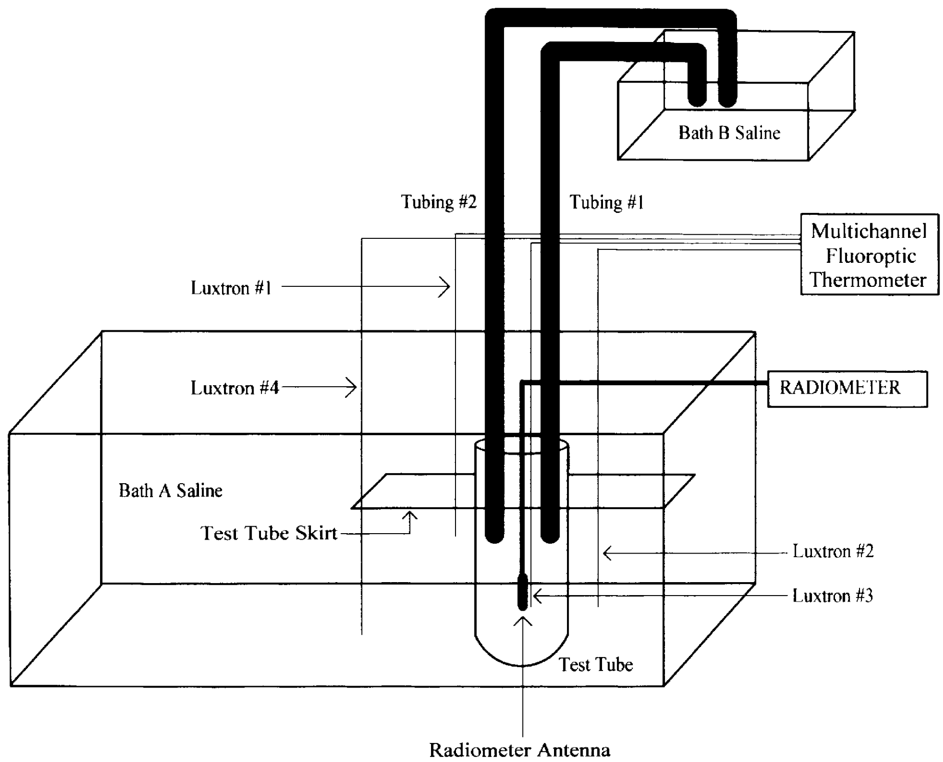

Fig. 1. *Design for microwave radiometer calibrations and experimental runs. Bath A saline was heated from 22°C to 35°C for calibrations and from 37°C to 70°C during experimental runs. The radiometer antenna tip was placed at the center of the test tube studied (10 mm O.D. or 16 mm O.D.) 28 mm from floor of Bath A. The clear vinyl test tube skirt (19 cm L×18 cm W) was attached 2 cm below opening of each test tube. Rubber tubing #1 pumped saline from Bath A into the test tube while rubber tubing #2 was left unused during calibrations. Rubber tubings #1, 2, and Bath B saline were used to maintain a saline temperature of 23.5°C inside the test tube during experimental runs. All four fluoroptic temperature probes were placed at same level as the antenna's tip inside Bath A during calibration and experimental runs.*

degree Centigrade were then averaged from all calibration runs conducted for the day. A standard curve was constructed with the average values and utilized to convert experimental radiometer voltages into temperature equivalents for experiments conducted later that day.

Experimental Measurements

A total of thirty experimental runs (n = 15 with 10 mm O.D. test tube; n = 15 with 16 mm O.D. test tube) were conducted. Calibration of the microwave radiometer was performed prior to and following each experimental run. A “radiometer calibration standard curve” was created for data analysis of experimental runs described previously.

The microwave antenna was placed along side a fluoroptic thermometer in the center of a test tube filled with saline kept at a constant temperature of 23.5°C. This warm saline environment (Bath A) was heated in 1°C increments between 37°C and 70°C. A cool saline reservoir (Bath B) ensured that the test tube saline environment remained constant throughout each experimental run. During experimental runs saline was pumped from Bath B into the test tube to maintain a constant saline temperature of 23.5°C. This temperature was selected to represent room temperature saline used for an irrigated ablation electrode. The test tube had a plastic skirt 2 cm below the opening of the test tube affixed to prevent incoming cold saline from flowing along the sides of the test tube where the radiometer’s antenna might be sensing the surrounding warmer environment. Saline temperatures and corresponding radiometer voltage outputs were continuously recorded.

Radiometric voltages and cold saline temperature readings within the test tube were recorded for every single degree rise of the surrounding warm saline bath (e.g. at 37°C, 38°C . . . 70°C). Once all of the fluoroptic temperature probes immersed in the warm saline bath reached the same temperature, the first 10 corresponding radiometer voltages and the fluoroptic temperature readings within the cold saline test tube were recorded and then averaged. These average radiometer voltage values in each run were then converted to experimental radiometer temperatures at each degree rise in the surrounding warm saline bath utilizing the standard curve previously constructed.

Statistical Analysis

Standard deviations (at 1 S.D., 15 experiments total for each test tube) were calculated for radiometer temperatures for each degree rise in the outer warm saline bath (from 37°C to 70°C). Regression analysis was used to compare the radiometer temperature with the outer warm saline bath temperature. R^2 value for each regression analysis demonstrated a high degree of correlation if greater than 0.9.

Results

During calibration of the microwave radiometer, the microwave radiometric voltage increased linearly as the saline-filled test tube and the saline bath were heated simultaneously (Fig. 2). The increase in voltage reflects the increase in microwave radiation produced by molecular motion due to heating. A change of 1 volt represented a 6.4 degree Celsius change in the saline bath temperature.

During the experimental measurements, the temperature inside the test tube was kept at a constant at 23.5 ± 0.1°C. For every degree of increase in the saline bath temperature, the radiometer-estimated temperature changed 0.26°C and 0.14°C for the 5 mm and 8 mm distances, respectively. The temperature predicted by radiometric thermometry correlated well with the temperature measured in the saline bath by the fluoroptic probes with an R^2 value of 0.997 and 0.991 for distances of 5 mm and 8 mm, respectively (Fig. 3).

Discussion

Utilizing thermistors and thermocouples to monitor surface temperature at the electrode–myocardial interface has been shown to improve the control and efficacy of lesion formation during radiofrequency catheter ablation [7,10]. Moreover, radiofrequency energy delivery in the temperature control mode is associated with a threefold reduction in the development of coagulum, and a more than fivefold reduction in the incidence of developing an automatic power shutdown due to an impedance rise or an electrode temperature greater than 100°C [7]. However, the utilization of thermistors and thermocouples at the tip electrode does not permit temperature measurements at depth away from the electrode–myocardial interface where the hottest tissue temperature may be found, particularly during electrode cooling. Cooling of ablation electrodes with saline irrigation to prevent impedance rise and to increase energy delivery further prevents an accurate measurement of the hottest temperature within the myocardium. Nakagawa et al demonstrated that the tissue temperature during radiofrequency ablation with saline irrigation can be significantly higher than in applications without irrigation, even though the tip

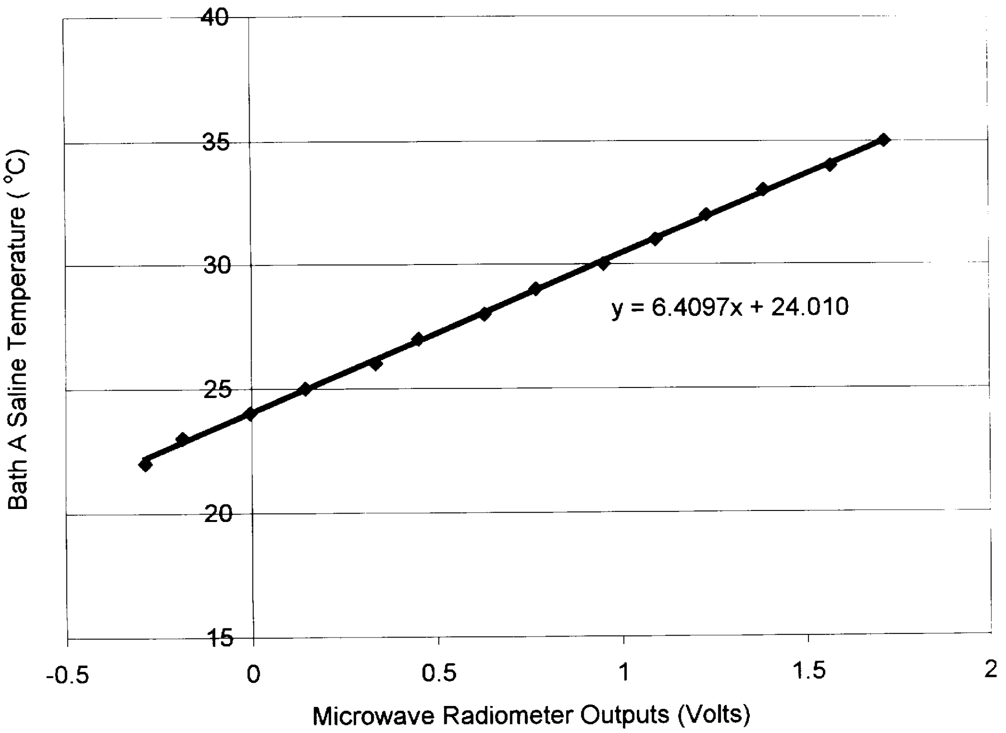

Fig. 2. *Sample radiometer calibration standard curve. The equation* $y = 6.4097\,x + 24.010$ *(*y *= bath A saline temperature,* x *= average radiometer voltage) is a best-fit line through the data points.*

electrode temperature was lowest with saline irrigation [8].

It is known that molecular motion results in microwave radiation that may be detected with sensitive instruments, particularly at the 4 GHz frequency range. Therefore, microwave radiometric thermometry may be a method of detecting minute changes in temperature. The microwave energy may be measured at a distance, leading us to hypothesize that microwave thermometry may be used to estimate temperature at depth. It is important to note that the radiometer is not a thermometer. The complex interactions of the electromagnetic fields surrounding the radiometer are detected by the radiometer as a function of distance. The microwave energy measured by the radiometer represents the sum of energy from all distances from the probe with the contribution decreasing at increasing distance. Therefore, two different temperatures at two different distances may generate the same signal at the probe thus direct temperature measurement is not achievable with this apparatus. Rather the radiometer detects the entire contributions of the surrounding environment to estimate regional temperatures.

We demonstrated that microwave radiometric thermometry was able to detect the higher temperature in the saline bath, even though the saline fluid surrounding the antenna remained constant at a considerably cooler temperature. The microwave thermometric measurement was highly correlated with the temperature in the outer saline bath, not the adjacent local temperature. We observed that the greatest change in radiometric temperature was at the closest distance. This is in agreement with the fact that the receiving antenna detects microwave energy, which is the summation of radiation from each of the many contributing spheres, surrounding the antenna. The amount of radiation from each of the surrounding spheres decreases as a function of distance. Therefore as expected, the change in microwave thermometric measurements was greatest with the smaller test tube.

Our data provides strong evidence for the ability of microwave thermometry to record temperatures at depth by measuring the microwave energy released from molecular motion. Because of this unique ability to measure temperatures at depth, microwave radiometric thermometry may be particularly well suited for recording temperatures during catheter ablation. Radiometric methods may be used to estimate the temperatures at depth even in the presence of electrode cooling. Temperature monitoring using this technique may make cooled ablation safer by

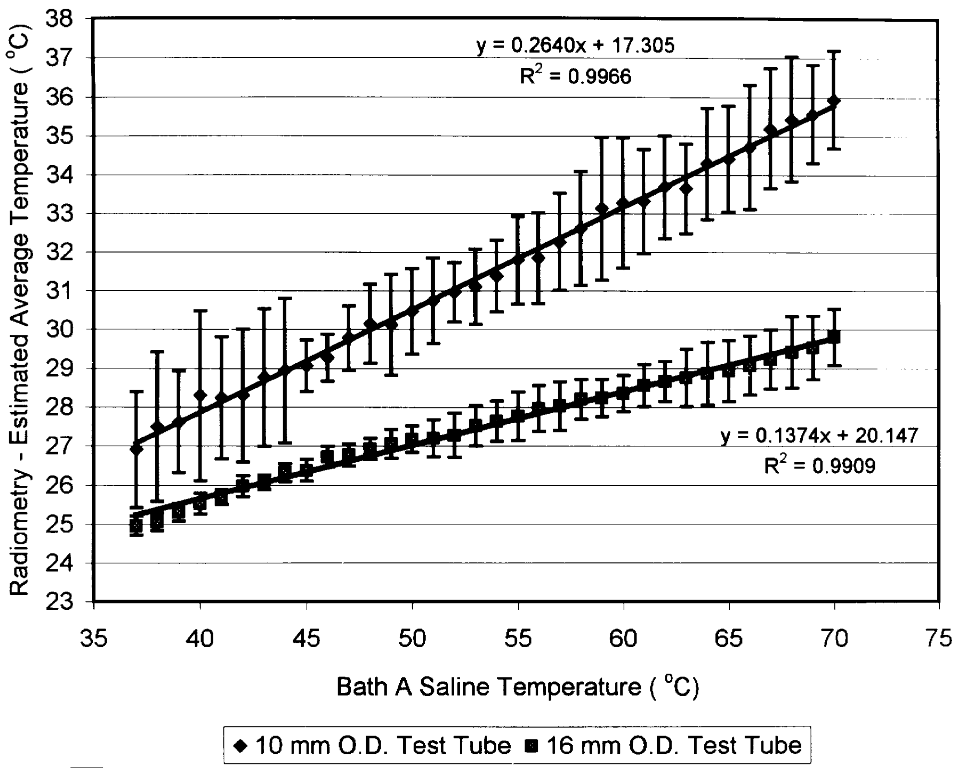

Fig. 3. *Graph of average microwave radiometer temperatures (measured inside a 10 mm O.D. and a 16 mm O.D. test tube with cold saline surrounded by warm bath A saline, n = 15 experiments for each test tube) as surrounding bath A saline was heated from 37 °C to 70 °C. The equations $y = 0.2640x + 17.305$ ($R^2 = 0.9966$) and $y = 0.1374 + 20.147$ ($R^2 = 0.9909$) represented average radiometer temperature versus bath A saline temperature plots for 10 mm O.D. and 16 mm O.D. test tubes, respectively. Standard deviations (1 S.D., y-bars) of average microwave radiometer temperatures for each degree rise in surrounding warm bath A saline are shown.*

preventing “super heating”, “pops”, and coagulation formation.

Study Limitations

We did not examine additional distances between the radiometer antenna and the surrounding warm saline. The results reported are from only one antenna rather than a range of microwave antennas. The study was also not conducted using living tissue under ablative conditions, however at the frequency chosen to measure the microwave radiation, the dielectric properties of saline and myocardium are very similar [11,12]. Radiometric thermometry was not tested at temperatures greater than 70°C because with this test apparatus heating such a large volume of saline at high temperatures was problematic. Furthermore, we did not perform finite element analysis to model the microwave field.

Conclusions

Microwave radiometric thermometry is able to detect temperatures at depths of 5 mm or more. This technique has promise for monitoring temperature measurements away from the catheter-electrode tip during catheter ablation of cardiac arrhythmias.

Acknowledgments

This publication was made possible by Grant Number 2 R44 HL46580-02A3. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NHLBI or the NIH.

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