Pulsing Microwave Energy: A Method to Create More Uniform Myocardial Temperature Gradients

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Abstract. Microwave energy has been proposed as a possible technique to create large myocardial lesions. Achieving a uniform myocardial temperature gradient during microwave ablation may prevent excessive endocardial temperatures while maintaining temperatures at depth. The goal of the current study was to examine the ability of microwave (MW) pulsing to achieve a more uniform myocardial temperature gradient. Using an in-vitro ovine endocardial model, we measured tissue temperature at 0.5-mm, 2.0-mm, and 3.5-mm depths in a circulating saline bath. MW energy was delivered at 20 W at 915 MHz for 30 seconds. Pulse configurations of 1 second on–1 second off, 3 seconds on–3 seconds off, and 5 seconds on–5 seconds off, with 30 seconds of total MW time were compared with 30-seconds continuous. Maximum temperatures at 0.5 mm were significantly lower at 63.2 ± 5.89°C for the 1-second pulse compared with 83.5 ± 7.31°C for the continuous-energy delivery. Pulse configurations 3 seconds on–3 seconds off and 5 seconds on–5 seconds off also resulted in a significantly lower surface temperature than continuous-energy delivery. However, temperatures at the 2.0-mm and 3.5-mm depth created by the pulsing delivery were similar to those achieved during continuous-energy delivery. Thus, microwave pulsing achieves a lower endocardial temperature and results in a more uniform temperature gradient. These techniques may prevent the excessive endocardial damage that may result in an increased risk of thrombus formation and embolization.

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Microwave energy was delivered using a 915 MHz generator (Microwave Medical Systems, Acton, MA). The generator operated at a fixed load of 50 ohms and did not have variable impedance matching. The generator had a built-in system of measurement of forward and reflected power. Control of power for pulsed delivery was achieved using an automatic programmable algorithm using a data acquisition and control program (Labtech Notebook). The microwave antenna had a helical coil configuration and was 8 mm in length. The antenna was placed parallel to the endocardial surface.

Microwave energy was delivered at 20 watts in one of four protocols: 30 seconds continuous delivery; pulses of 1 second on, 1 second off; pulses of 3 seconds on, 3 seconds off; and pulses of 5 seconds on, 5 seconds off. Each protocol delivered 30 seconds of power in total. The protocol sequence was determined by random number assignment. Each protocol was repeated 10 times (5 times with temperature probes, 5 times without temperature probes).

Forward energy, reflected energy, myocardial temperature data, and thermocouple temperature were continuously sampled at 10 Hz by microcomputer using an analog-to-digital board (Real Time Devices, State College, PA). Measurements were recorded using a data acquisition program (Labtech Notebook) and were analyzed off-line using a data spreadsheet (Lotus 1-2-3, Lexington, MA).

After energy delivery the tissue was fixed in 10% buffered formalin. An observer (PJW) blinded to the protocols sectioned the lesions and measured length (L), width (W), and depth (D). Volume was calculated as the product of the length, width, and depth.

**Statistical analysis**

Statistical analysis was performed by Primer of Biostatistics (version 1.0, McGraw Hill). The maximum temperatures of the five trials were averaged for each protocol. The summarized results were expressed as a mean temperature ± standard deviation. At each depth, the mean of the maximum temperature values for the continuous delivery was compared with the mean value during the pulsing trials (1, 3, and 5 seconds).

Using the unpaired t-test, a value of p < 0.05 was considered statistically significant.

The mean lengths, width, and depths for the continuous delivery were compared with the mean dimensions of the pulsing deliveries using the unpaired t-test. An unpaired t-test was used to statistically analyze the effect of the temperature probe on the lesion size. Lesion dimensions produced by the continuous delivery with a probe were compared with the continuous delivery without a probe using unpaired t-test. The temperature gradient (0.5–2.0 mm, 2.0–3.5 mm, and 0.5–3.5 mm) was calculated by taking the slope of the lines connecting the temperatures at each of the three depths and was compared for pulsing and continuous delivery using the unpaired t-test. The temperature gradient over time was compared using the paired t-test. The change in temperature over time was compared for pulsing and continuous delivery using the unpaired t-test.

**Results**

**Temperature profiles**

During continuous energy delivery, at 0.5-mm depth a mean maximum temperature of 83.5 ± 7.31°C was achieved. This was significantly higher than the 0.5-mm maximum temperatures during the pulsing protocols: 63.2 ± 5.89°C for 1-second on-off (p = 0.001), 63.0 ± 9.78°C for 3-second on-off (p = 0.006), 59.6 ± 8.94°C for 5-second on-off (p = 0.002) (Fig. 1A). At the 2.0-mm and 3.5-mm depths, there was no statistical difference between the maximum temperatures during continuous-energy delivery and any of the pulsing protocols (Fig. 1B and 1C). Maximum temperatures at the 2.0-mm depth were 47.5 ± 4.05°C for continuous-energy delivery, 53.3 ± 4.22°C for the 1-second on-off pulse, 51.2 ± 9.64°C for the 3-second on-off pulse, and 45.9 ± 5.85°C for the 5 second on-off pulse (p = ns; Fig. 1B). At 3.5-mm depth, maximum temperatures were 47.0 ± 11.29°C for the continuous delivery, 41.6°C ± 1.97°C for the 1-second on-off pulse 43.1 ± 2.61°C for the 3-second on-off pulse, 40.4 ± 2.00°C for the 5-second on-off pulse (p = ns; Fig. 1C).

During continuous-energy delivery, there was a large difference in temperature at the various depths, with the greatest temperature at 0.5 mm (Fig. 2A). The temperature increased to a maximum at the end of energy delivery and decreased gradually after termination of energy delivery. At a 2.0-mm depth, a much lower maximum temperature was achieved and both heating and cooling occurred slowly. At a 3.5-mm depth, the temperature rise is very slow and minimal, continuing after energy delivery has ceased. For the 1-second on-off pulse, the 0.5-mm and 2.0-mm depths had similar temperatures and rose slowly (Fig. 2B). For the 3-second and 5-second pulses, the temperature rose even more slowly (Fig. 2C and 2D).

**Forward and reflected power**

While there was a statistically significant difference between forward power during continuous-energy delivery and pulse delivery in the 1-second on-off, and 3-second on-off (p = 0.017 and p = 0.017, respectively; Table 1), the magnitude of this difference is not clinically significant (0.04–0.12 watts). Similarly, while the reflected watts were significantly different during the continuous-energy delivery compared with all pulsing trials (1 second, p = 0.002; 3 seconds, p = 0.003; 5 seconds, p = 0.001), the magnitude of the difference (0.60–0.68 watts) is not clinically significant.