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Electrical isolation during radiofrequency ablation: 5% dextrose in water provides better protection than saline

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***Abstract*—We quantify the ability of 0.9% NaCl (saline) and 5% dextrose in water (D5W) to protect tissues during RF ablation. Using computer simulations and phantom experiments, we determined that D5W provides significantly more electrical isolation than saline, which reduces unwanted heating of the adjacent tissue. Saline actually increased the amount of RF current in the adjacent tissue. Based on these results, we conclude that D5W is preferable to saline as a protective fluid.**

I. INTRODUCTION

RADIOFREQUENCY (RF) ablation has quickly gained acceptance as a treatment option for tumors of the liver, kidney, lung and bone [1-6]. Recent advances in RF ablation technology, such as multiple-electrode systems and multi-prong electrodes, have enhanced physicians' ability to treat large tumors [7, 8]. However, because of the limited volume of the human liver, many large tumors are located at or near the surface of the liver. Superficial tumors present a unique challenge for ablative therapies because the zone of ablation in the tumor can cause unintended thermal injury to adjacent tissues (e.g., diaphragm, bowel). Complications from unintended thermal injury have been reported and can be life-threatening, making tumor proximity to sensitive structures a relative contraindication for RF ablation [9-11].

Several techniques and devices to displace and protect adjacent tissue from thermal damage have been proposed, including gas-filled balloons [12], carbon-dioxide insufflation [12-14] and fluid infusion [15-20]. Balloons can be relatively invasive and may require several separate balloons to adequately move the adjacent tissue. Carbon-dioxide can be difficult to control once introduced and must be removed manually after ablation is complete. More importantly, because gases are poor conductors of sound, injected gas or gas-filled balloons make the use of ultrasound guidance during the ablation procedure very difficult. Fluid-based techniques allow ultrasound guidance and may be easier to control than gases.

Solutions of 0.9% NaCl (saline) and 5% dextrose in water (D5W) have been proposed for fluid induction because they are readily absorbed by the body and can be introduced with spinal needles less than 1 mm in diameter. However, saline is ionic and encourages RF current flow, which can increase local heating or cause unpredictable heating patterns [21]. Indeed, saline infusion is used in some RF electrodes as a means to increase the zone of ablation [22-26]. For this reason, it has been proposed that D5W may be a better fluid for protection of adjacent structures during RF ablation [27]. This hypothesis has been supported by recent preclinical and clinical studies which showed that while both saline and D5W can reduce heating of the adjacent tissue and improve pain scores in human patients, D5W is significantly more effective [16, 28]. This is likely because D5W has a substantially lower electrical conductivity than saline and, thus, creates a high-impedance path between the RF electrode and protected tissue. We believe that D5W redirects the current to a path away from the protected tissue, thereby preventing RF heating of the tissue.

The goal of our study was to measure the electrical and thermal protection of saline and D5W via computer simulations and phantom tissue model experiments as described in the following sections: II. Experimental methods, III. Results and IV. Conclusions.

II. EXPERIMENTAL METHODS

A. Computer modeling

To numerically examine the protective effects of saline and D5W, we used commercial finite-element method software (Comsol Multiphysics 3.2a; Burlington, MA) to predict current flow through the protective fluid layer and temperature profiles in liver tissue during ablation by solving the time-dependent heat equation

$$\rho C_p \frac{\partial T}{\partial t} = k_T \nabla^2 T + \mathbf{J} \cdot \mathbf{E} \qquad (1)$$

where ρ is density (kg/m^3), C_p is specific heat capacity (J/kg·K), T is temperature (K), k_T is thermal conductivity (W/m·K), $\mathbf{J}$ is current density (A/m^2) and $\mathbf{E}$ is electric field intensity (V/m). The term $\mathbf{J}\cdot\mathbf{E}$ represents the heat generated and, using the relationship $\mathbf{J} = \sigma\mathbf{E}$, may also be written as $\sigma|\mathbf{E}|^2$ where σ is electrical conductivity (S/m). We used a two-dimensional computational domain for in-plane current flow with four subdomains defined for 1) the primary liver tissue, 2) the fluid layer 3) adjacent ("protected") liver tissue and 4) the electrode (Fig. 1). Thermal and electrical properties of each subdomain were defined using the values in Table 1. The electrode was assumed to be connected to a constant 2.0 A current source and ground return paths were created at the tissue boundaries on both sides of the fluid to mimic clinical RF ablation, where several current paths exist in the body between the electrode and grounding pads.

Numerical studies were carried out in two steps: 1) to calculate the current distribution at $t = 0$, before heating

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begins, and 2) to simulate time-dependent heating of the tissue. The first step demonstrates the amount of electrical protection afforded by the fluid layer while the second step also includes protection caused by the physical displacement and thermal buffer created by the fluid layer. Note that the thermal properties of saline and D5W are the same. We simulated several setups by varying the electrode-fluid spacing (*d)* from 0.5-2.0 cm and the fluid thickness (*D*) from 0.5-2.0 cm, which covers the range of clinically-feasible options.

The degree of current redirection was quantified using a ratio of currents, I_2/I_1, where I_2 is the current through the fluid layer ground pad and I_1 is the current through the electrode-side ground pad. A lower I_2/I_1, ratio indicates more current redirection. Both fluid layers were compared to a control simulation, where the fluid layer properties were identical to the surrounding tissue (i.e., no electrical protection). Total current flow through each ground pad, current density maps and temperatures were recorded in 30 s time steps from 0-900 s during the simulated heating cycle.

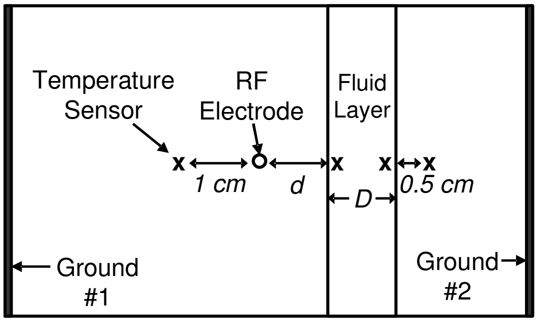

Fig. 1. Setup for computer simulations and phantom experiments. Temperatures were measured in the positions marked with an 'X.

TABLE 1
ELECTRICAL AND THERMAL PROPERTIES USED IN NUMERICAL STUDIES

Property		Units	Liver	Saline	D5W
Relative Permittivity	ε_r		2600	78	68
Electrical Conductivity	σ	S/m	0.146	0.72	0.05
Thermal Conductivity	k_T	W/m·K	0.564	0.6	0.6
Specific Heat	C_p	J/kg·K	3300	4128	4128
Density	ρ	kg/m^3	1050	1000	1000

B. Phantom experiments

To verify our computer simulations and test our hypotheses in a controlled environment, we used tissue-equivalent phantoms in a setup similar to that of the computer models (Fig. 1). We prepared gel phantoms using the technique of Solazzo et al., (a solution of 5% agar, 3% sucrose and 0.3% saline in distilled water) to mimic the electrical properties of liver tissue [29]. Similar to the numerical study, we tested fluid layers 0.3-0.9 cm thick in 0.3 cm intervals and electrode-fluid spacings of 0.5 cm and 1.0 cm. The control group had no fluid layer.

The electrical impedance through each ground pad was measured before each ablation using the impedance check provided with the RF generator (Valleylab Cool-tip™; Boulder, CO). Ablation was performed for 2 min in manual mode with a constant generator output of 2.0 A to measure temperature changes without excessively melting the phantom material. To observe how current was redirected by the fluid layer, we measured current flow through each ground pad at $t = 0$ s, 60 s and 120 s during ablation. Temperatures were also measured constantly at the points shown in Fig. 1 using a fiberoptic thermometry system (Luxtron; Santa Clara, CA) to determine the actual thermal protection provided by each fluid. In the control group, temperatures were measured at the point 1 cm away from the electrode on the non-fluid side and at a point *d* cm away from the electrode on the fluid side to reflect the fact that without fluid there is no displacement of tissue. Generator data such as output current, voltage, power, total circuit impedance and electrode tip-temperature were also collected continuously.

III. RESULTS

A. Simulation results

The results of our computer modeling clearly demonstrate that D5W is superior to saline for redirecting current from and, thus, preventing unwanted heating of the adjacent tissue (Fig. 2). D5W decreased the I_2/I_1 current ratio 32-55 percent when compared to controls, indicating that D5W effectively shields the adjacent tissue from current flow. It is interesting to note that saline actually enhanced current flow through the adjacent tissue branch when compared to the control. Consequently, simulated temperatures in the adjacent tissue were up to lower for D5W than saline or controls, indicating that D5W is theoretically superior for protecting adjacent tissues during RF ablation.

B. Phantom results

Results from the phantom experiments mirror those of the computer simulations. As expected, the impedance measured through the fluid layer was highest for the D5W group and increased with fluid layer thickness while a slight decrease in impedance was noted in the saline group (Fig. 3). Correspondingly, temperatures on the protected side of the fluid layer were lowest when D5W was used (Fig. 4). The increased impedance seen with D5W resulted in a marked increase in protection with thicker layers so that very little heating of the adjacent tissue was observed with a 0.9 mm thick D5W layer. Temperatures measured when saline was used were also lower than controls because saline at least provided tissue displacement and a thermal buffer.

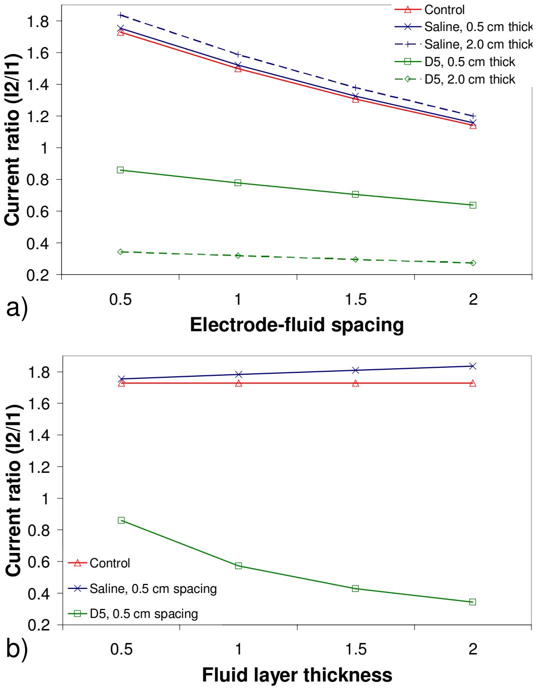

Fig. 2. Ratio of current flow through the protected tissue to current flow through the unprotected tissue (I2/I1) versus a) electrode-fluid spacing and b) fluid layer thickness. The low ratios observed with D5W indicate that D5W more effectively protects the adjacent tissue. Thicker layers of D5W result in less current flow through the protected tissue. D5W also seems less dependent on electrode-fluid layer spacing than saline in reducing current flow.

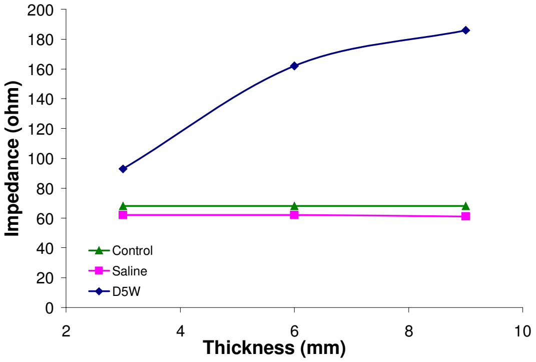

Fig. 3. Initial impedance to RF current flow through the protected tissue versus fluid layer thickness using a 0.5 cm electrode-fluid spacing. As seen in our numerical study, thicker layers of D5W resulted in larger impedances and, hence, less current flow through the protected layer. Conversely, increasing the thickness of the saline layer slightly decreased the impedance.

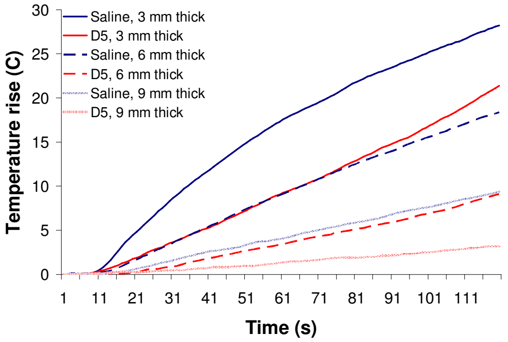

Fig. 4. Temperature rise observed in the protected tissue for various fluids and thicknesses. D5W is more effective at reducing temperatures for all thicknesses and nearly eliminates heating at a thickness of 9 mm. The electrode-fluid spacing in this series was 0.5 cm.

IV. CONCLUSIONS

To our knowledge, this work represents the first investigation of the electrical and thermal protective ability of D5W during RF ablation. Our results show that D5W redirects current flow away from the site of fluid induction better than saline and, therefore, reduces the likelihood of excessive heating of the protected tissue. Numerical simulations indicated that smaller electrode-fluid layer spacings cause more current flow through the protected tissue when saline is used. This indicates that placing the electrode too close to saline may increase unwanted heating. We also found that increasing the thickness of a D5W fluid layer provides additional electrical protection but that increasing the thickness of a saline fluid layer does not. These important findings indicate that 1) thermal buffering caused by physical displacement is the only protection provided by saline and 2) increasing the thickenss of a D5W layer will increase the protective ability of the fluid infusion. Thus, we note that while both fluids do reduce heating of the protected tissue by providing a thermal buffer between the electrode and protected tissue, the effect is magnified when an electrically insulating fluid, like D5W, is used.

With these results, we cannot accurately predict a minimum electrode-fluid layer spacing or fluid layer thickness that should be used in a clinical setting to avoid any adjacent tissue damage. However, our data does suggest that a fluid layer thickness of 1.0 cm may be adequate, even with the relatively small electrode-fluid spacing of 0.5 cm. Additional experimentation and translation into a tissue model is ongoing to better define the role of electrode-fluid layer spacing and fluid layer thickness.

The clinical implications of our findings are that D5W should be used in lieu of saline for protecting surrounding tissues during RF ablation whenever possible. We see no reasonable benefit to using saline and caution that, due to its high electrical conductivity, saline may actually lead to unpredictable heating patterns if used in contact with, or in close proximity to, the electrode.

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