Magnetic Resonance–Monitored Coaxial Electrochemical Ablation—Preliminary Evaluation of Technical Feasibility

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ABSTRACT

Purpose: To evaluate the technical feasibility of a coaxial electrode configuration to rapidly create a mechanically defined electrochemical ablation zone monitored by magnetic resonance (MR) imaging in real time.

Materials and Methods: A direct current generator supplied the nitinol cathode cage and central platinum anode for coaxial electrochemical ablation. Safety and efficacy were evaluated by measuring local pH, temperature, and current scatter in saline solutions. Ablation zone diameters of 3–6 cm (n = 72) were created on ex vivo bovine liver and verified by gross pathology. Feasibility of MR monitoring was evaluated using 8 swine livers to create ablations of 3 cm (n = 12), 4 cm (n = 4), and 5 cm (n = 4) verified by histology.

Results: Local pH was 3.2 at the anode and 13.8 at the cathode. Current scatter was negligible. Ablation progress increased relative to local ion concentration, and MR signal changes corresponded to histologic findings. In the ex vivo model, the times to achieve complete ablation were 15 minutes, 20 minutes, 35 minutes, and 40 minutes for diameters of 3 cm, 4 cm, 5 cm, and 6 cm, respectively. Ablation times for the in situ model were 15 minutes, 35 minutes, and 50 minutes for 3 cm, 4 cm, and 5 cm, respectively.

Conclusions: The coaxial configuration mechanically defined the electrochemical ablation zone with times similar to comparably sized thermal ablations. MR compatibility allowed for real-time monitoring of ablation progress.

ABBREVIATIONS

DC = direct current, EChT = electrochemical treatment, NaCl = sodium chloride, PEEK = polyethylethylketone, TR/TE = repetition time/echo time, TSE = turbo spin echo, VIBE = volumetric interpolated breath-hold examination

Percutaneous ablation of malignant hepatic tumors is a widely accepted alternative in patients who are poor candidates for surgical resection. These techniques are increasingly used because of their low profile and lower cost and because they can be performed on patients who have contraindications to surgery (1). In thermal ablation, lesion size and location could result in incomplete ablation and

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complications secondary to thermal injury and heat sink effects (1,2).

The use of direct current (DC) electricity for selective ablation of tissue was originally explored for treatment of tumors and thrombosis of aneurysms (3,4). Although thermal ablation superseded this technique throughout the 20th century, more recent technologic developments and the emergence of irreversible electroporation inspired further investigations into the clinical utility of electrochemical treatment (EChT). EChT is a nonthermal percutaneous ablation technique that uses DC electricity to cause tumor necrosis by generating a strongly acidic microenvironment at the anode and strongly alkaline microenvironment at the cathode (5–7). Studies showed no effect on systemic pH; necrosis was due primarily to pH-mediated protein denaturation and secondarily to disruption of cell membranes and coagulation of local capillaries (8–12). Although thermal ablation relies on heat dispersion, which is susceptible to perivascular heat sink, the acids and bases of EChT penetrate into the surrounding tissues via diffusion and electrically driven migration (13,14). This feature results in a sharp ablation margin regardless of traversing vessels (11,12). The primary considerations for ablation size and rate for EChT is the level of current and electrode distance (11,12,15–18). Additionally, magnetic resonance (MR)–compatible electrodes can be used in EChT.

EChT has been used to treat lung, gastrointestinal, and soft tissue tumors with minimal local discomfort and morbidity (19,20). Reported 5-year survival was 39% for lung, 15% for primary liver, and 50% for breast carcinomas (13). However, EChT has not gained widespread clinical use in Western countries because of the lack of standardized treatment algorithms, the paucity of published clinical trials, and because ablations are time-consuming and difficult to contour with traditional EChT (11–13,19,20). We propose a novel approach to EChT using a coaxial configuration of the electrodes consisting of a central platinum anode with a peripheral nitinol cathode cage. The purpose of this study was to test the feasibility of a coaxial electrode configuration to mechanically define the ablation zone, amplify EChT by achieving ablation times comparable to other modalities, and allow for real-time monitoring of ablation progress with MR imaging.

MATERIALS AND METHODS

Electrochemical Equipment

A B&K Precision 1901 adjustable (0–32 V) DC power supply (Yorba Linda, California) served as the electricity generator. An 18-gauge (1.024-mm-diameter) 99.9% pure platinum wire (T.B. Hagstoz, Philadelphia, Pennsylvania) was cut into 20-cm-long pieces to serve as the anode. A 16-gauge (1.291-mm-diameter) medical-grade (ASTM F2063) nitinol wire (Fort Wayne Metals, Fort Wayne, Indiana) was cut into ten 20-cm-long pieces to serve as the cathode cage.

In Vitro Model

In vitro experiments were conducted in saline solutions of 0.45%, 0.9%, 1.8%, 2.7%, and 3.6% weight/volume sodium chloride (NaCl) titrated to a pH of 7.5 to evaluate EChT ablation with respect to local ionic content. The cathode cage was constructed by arranging the ten 16-gauge nitinol electrodes into a regular 3-cm-diameter cage using a custom-designed polyethylethylketone (PEEK) needle guide. A single platinum anode was placed in the isocenter of the cage. All electrodes had a 2-cm active tip. The DC power supply was connected and set to constant voltage of 32 V with variable current (**Fig 1**).

Temperature and local pH were measured using an Accumet AR15 pH probe (Thermo Fisher Scientific, Inc, Waltham, Massachusetts) on the surfaces of the anode and cathode. Local current was measured within the cathode cage using an 80 Series V True-RMS multimeter (Fluke Corp, Everett, Washington). Current scatter was measured in 1-cm intervals from the exterior of the cathode cage up to a maximum of 6 cm.

MR compatibility was tested on a 1.5% agarose gel composed of 0.9% weight/volume NaCl with phenol red—a visual pH indicator with red indicating alkaline pH and yellow indicating acidic pH (21). Ten nitinol electrodes were arranged in a 5-cm diameter using the PEEK needle guide block, and a single platinum anode was placed in the isocenter. The gel was loaded onto a Siemens Avanto 1.5-tesla clinical MR imaging system using a Tx/Rx CP transmit-receive head coil

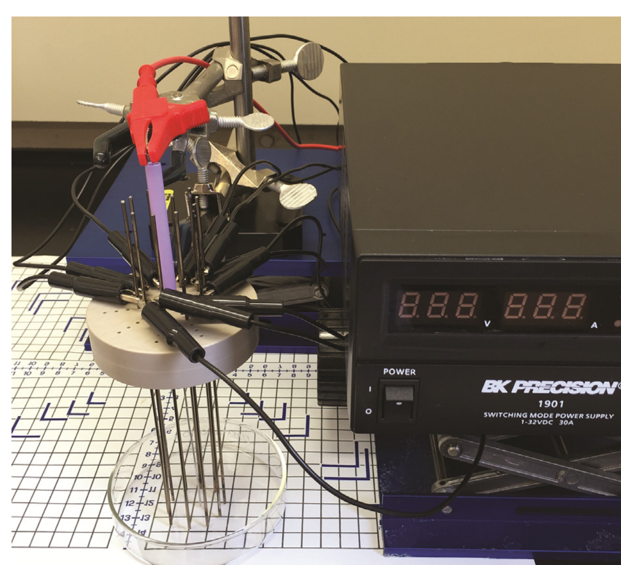

Figure 1. Coaxial electrochemical ablation system. The coaxial ablation system consists of an 18-gauge platinum anode loaded into the center of a needle guide. A cage consisting of ten 16-gauge nitinol cathodes was arranged around the anode. The anode and cathodes were connected to a DC generator.