LABORATORY INVESTIGATION

MR Coagulation: A Novel Minimally Invasive Approach to Aneurysm Repair

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ABSTRACT

Purpose: To demonstrate a proof of concept of magnetic resonance (MR) coagulation, in which MR imaging scanner–induced radiofrequency (RF) heating at the end of an intracatheter long wire heats and coagulates a protein solution to effect a vascular repair by embolization.

Materials and Methods: MR coagulation was simulated by finite-element modeling of electromagnetic fields and specific absorption rate (SAR) in a phantom. A glass phantom consisting of a spherical cavity joined to the side of a tube was incorporated into a flow system to simulate an aneurysm and flowing blood with velocities of 0–1.7 mL/s. A double-lumen catheter containing the wire and fiberoptic temperature sensor in 1 lumen was passed through the flow system into the aneurysm, and 9 cm^3 of protein solution was injected into the aneurysm through the second lumen. The distal end of the wire was laid on the patient table as an antenna to couple RF from the body coil or was connected to a separate tuned RF pickup coil. A high RF duty-cycle turbo spin-echo pulse sequence excited the wire such that RF energy deposited at the tip of the wire coagulated the protein solution, embolizing the aneurysm.

Results: The protein coagulation temperature of 60°C was reached in the aneurysm in ~12 seconds, yielding a coagulated mass that largely filled the aneurysm. The heating rate was controlled by adjusting pulse-sequence parameters.

Conclusions: MR coagulation has the potential to embolize vascular defects by coagulating a protein solution delivered by catheter using MR imaging scanner–induced RF heating of an intracatheter wire.

ABBREVIATIONS

HSA = human serum albumin, MT = magnetization transfer, RF = radiofrequency, SAH = subarachnoid hemorrhage, SAR = specific absorption rate

Intracranial aneurysms occur in an estimated 1%–6% of the population (1), with the most common presentation being subarachnoid hemorrhage (SAH) (2). Current treatment methods consist of (*i*) microvascular neurosurgical clipping (3); (*ii*) endovascular coil embolization (4), which may be combined with temporary caging for wide-necked aneurysms (5); and (*iii*) embolization with the use of a coagulable material such as Onyx (Micro Therapeutics, Irvine, California) (6) or recently developed polymeric foams (7). Neurosurgical clipping is highly invasive because it entails clipping the aneurysm at its base via an open surgical approach to prevent rupture. Additionally, in clinical trials, clipping presents less favorable outcomes than coil embolization (8,9). Although it is minimally invasive, a disadvantage of coil embolization is a possible reopening of the aneurysm that may be caused by impaction of the coils (8). Finally, embolization with coagulable materials yields improved packing compared with coil embolization but requires the injection of possibly immunogenic foreign materials.

The present study describes a novel minimally invasive embolization method, magnetic resonance (MR) coagulation, that does not require the permanent implantation of artificial objects (eg, coils) or foreign materials (eg, Onyx, polymeric foams) to achieve embolization, and does not necessarily require temporary occlusion of normal blood flow. Instead, a biomaterial that can be coagulated by mild

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heating is injected into the aneurysm and coagulated by using the heat generated by the MR imaging scanner. The scanner also provides the necessary intraprocedural image guidance and assesses the efficacy of the repair. The MR imaging scanner permits fine control and real-time monitoring of the coagulation process and significantly simplifies the embolization procedure.

In this report, egg white, a conveniently available protein solution, is used as the biomaterial. In clinical practice, the use of a more human-compatible material such as human serum albumin (HSA), a naturally present blood protein that is nonthrombogenic and nonimmunogenic, is envisioned. The MR coagulation concept is illustrated in **Figure 1**. The potential of MR coagulation is demonstrated via electromagnetic simulations and phantom experiments that mimic typical conditions encountered in in vivo aneurysms.

MATERIALS AND METHODS

Electromagnetic Simulation and Model Description

The feasibility of the proposed technique for directing RF energy from the scanner's body RF coil to the aneurysm was tested by numeric simulation of two device configurations using an electromagnetic finite-element solver (HFSS; Ansys, Canonsburg, Pennsylvania). In one device configuration, a standalone wire was used to harvest the RF energy from the scanner. The standalone wire was a polytetrafluoroethylene-insulated 24-gauge (American wire gauge) wire with 0.5 cm exposed at the tip. In the second configuration, an RF coil tuned to the scanner's Larmor frequency was used in conjunction with the wire. The aneurysm was modeled as a 15-mm-diameter sphere. The sphere's dielectric properties were set to those of blood (10,11).

Phantom, Flow, and Catheter System

A spherical glass aneurysm phantom with a 15-mm outside diameter was manufactured (Yankee Glassblower, Concord, Massachusetts). A glass phantom was chosen because it is made of an MR-compatible material, is easily shaped, and allows visualization of the coagulum. The smoothness of the glass walls ensured that successful adhesion of the coagulum in vitro would be successful in vivo as well. A peristaltic pump (Cole-Parmer, Vernon Hills, Illinois) provided a controllable pulsatile saline solution flow through the phantom. Hemostatic Y-valves permitted the insertion of a DuraFlow 14-F double-lumen catheter (AngioDynamics, Latham, New York) while preventing the introduction of air bubbles into the system. A 26-gauge Teflon-insulated silver-plated solid copper wire (Alpha Wire, Elizabeth, New Jersey) was connected to a 30-cm × 30-cm square RF loop coil tuned to the Larmor frequency. The RF loop coil was placed against the scanner's inner bore. The other end of the wire and a Luxtron fiberoptic temperature sensor (LumaSense Technologies, Santa Clara, California) were inserted into one lumen of the catheter and positioned such that the wire and sensor tips emerged by approximately 5 mm from the catheter tip. The catheter assembly was guided into the aneurysm. Temperatures were sampled at 1-s intervals.

Chicken egg white, a low-cost protein solution source, was used as the coagulable biomaterial. Ovalbumin, a protein with coagulation properties similar to those of HSA, is the major protein constituent in egg white.

MR Imaging and MR Coagulation

Experiments were carried out in an Avanto 1.5-T scanner (Siemens, Erlangen, Germany) by using its built-in body RF coil for RF excitation. A high RF duty cycle turbo spin-echo

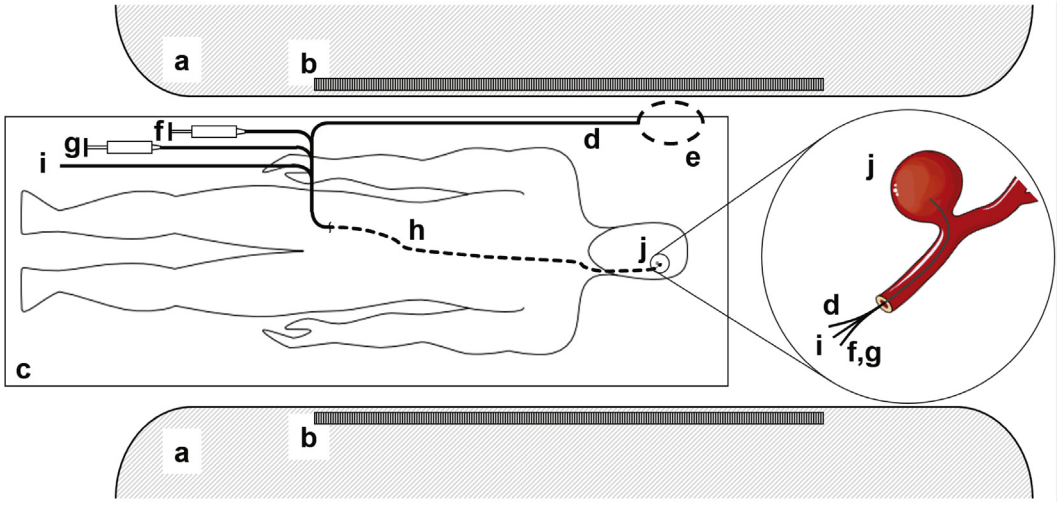

Figure 1. MR coagulation concept: (*a*) MR imaging scanner magnet assembly, (*b*) body RF coil, and (*c*) patient table. (*d*) Long wire RF pickup antenna is magnetically coupled to the body coil; RF pickup may be optionally enhanced with a tuned RF pickup loop (*e*) connected to the free end of the wire. (*f*) Protein solution and (*g*) saline solution for flushing share one lumen of the catheter (*h*) inserted percutaneously into the femoral aorta. (*i*) Fiberoptic temperature sensor shares the second lumen of catheter with the wire. (*j*) Cerebral aneurysm.