MR Coagulation and Multiparametric Quantitative Imaging for Aneurysm Treatment and Monitoring of Repair

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Introduction

Aneurysms are abnormal focal ballooning of arteries causing substantial rates of morbidity and mortality. A cerebral aneurysm can put pressure on a nerve or surrounding brain tissue or may leak or rupture. Aneurysms can be repaired by embolization with energy-coagulable materials but monitoring the state of coagulation remains a challenge. Temperature measurements, for instance, reflect the heating but not the coagulation itself and may be affected by heat transport of flowing blood.

MR Coagulation (MRC) [1] is a novel embolization method whereby a biomaterial (human serum albumin) is injected into the aneurysm and coagulated using heat generated by the MRI scanner (**Figure 1**). Here we demonstrate the feasibility of directly monitoring the state of coagulation using fast multiparametric quantitative imaging. Improved monitoring enhances the safety of clinical embolization procedures and can therefore improve patient outcomes.

Methods

Phantom Experiments

Coagulation experiments were conducted in a spherical glass aneurysm phantom with a 15-mm outside diameter using a double-lumen catheter for injection of ovalbumin (egg white), a low-cost protein with coagulation properties similar to those of human serum albumin. The temperature was monitored by a fiberoptic temperature sensor inserted into one lumen of the catheter. A peristaltic pump provided a controllable pulsatile saline solution flow through the phantom.

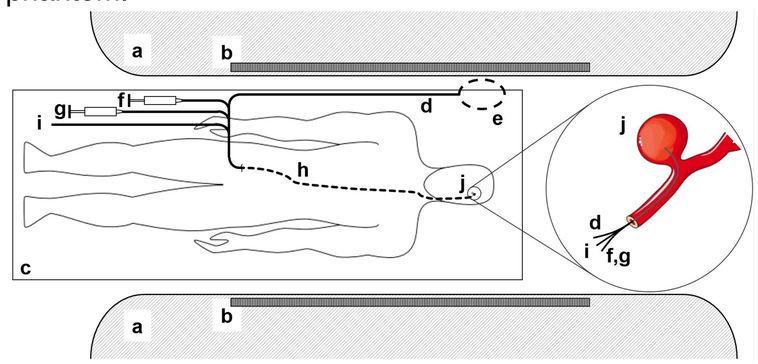

Figure 1: MRC concept. (a) MRI scanner magnet assembly. (b) Body RF coil. (c) Patient table. (d) Long wire RF pickup antenna magnetically coupled to body coil; RF pickup may be optionally enhanced with tuned RF pickup loop (e) connected to free end of wire. (f) Protein solution and (g) saline for flushing sharing one lumen of catheter (h) inserted percutaneously into femoral aorta. (i) Fiber optic temperature sensor sharing second lumen of catheter with wire. (j) Cerebral aneurysm.

MR Acquisition

Experiments were carried out in an Avanto 1.5-T scanner (Siemens, Erlangen, Germany) by using its built-in body RF coil for excitation. A high RF duty cycle turbo spin-echo sequence provided the necessary RF heating. The field of view was set to 300×300 mm^2 with a matrix size of 128×128 and a slice thickness of 5 mm. With the repetition time set to 300 ms, the total scan duration (heating time) was 2 min.

Quantitative Imaging

To find the optimal image contrast for monitoring the coagulation ovalbumin samples were scanned with gold-standard inversion-recovery (T1), CPMG (T2) and magnetization transfer (MT) pulse sequences. A heating system was used to regulate the temperature of the samples inside the magnet [2]. The ovalbumin was sequentially brought to equilibrium at seven temperatures (20, 30, 40, 50, 60, 70 and 37 °C). The T1 and T2 relaxation times and the full-width at half-max of the MT spectrum were measured at each temperature to determine the heating effect on each parameter.

Results

Coagulation

The temperature profile for a successful coagulation experiment and the resulting coagulum are shown in **Figure 2**. The coagulum adhered to the aneurysm walls and successfully disrupted the flow inside the aneurysm.

Tissue Mapping

Changes in the T1, T2 and MT properties of the ovalbumin for the different temperatures tested are shown in **Figure 3**. The T2 and MT parameters gave the most definitive indication of the change from uncoagulated albumin at low temperature to fully coagulated at 60 °C. In contrast, the water T1 showed only the expected gradual increase with temperature, and no response to coagulation. Sample MT weighted images acquired before and after coagulation (**Figure 4)** illustrate the potential for quantitative tissue mapping in monitoring and quantifying the extent of coagulation in a clinical setting.

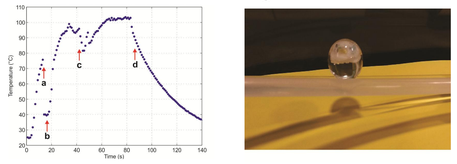

Figure 2: Temperature profile for a coagulation experiment under flow (left) showing injection of egg white bolus (a,c) and subsequent cooling (b,d) as well as the resulting coagulum in the aneurysm (right).

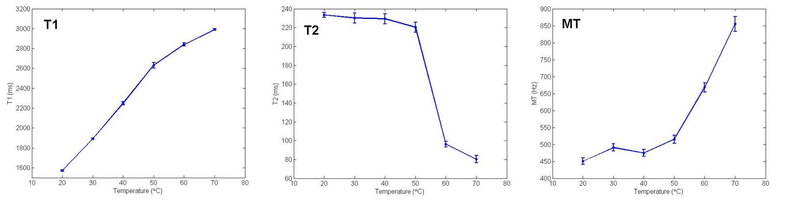

Figure 3: T1, T2 and MT parameters of the ovoalbumin solution as a function of the measured temperature. While the water T1 showed no response to coagulation, the T2 and MT parameters showed large differences between the uncoagulated (<60°C) and coagulated (>60°C) solution. The subsequent cooling to body temperature (37°C) is not shown.

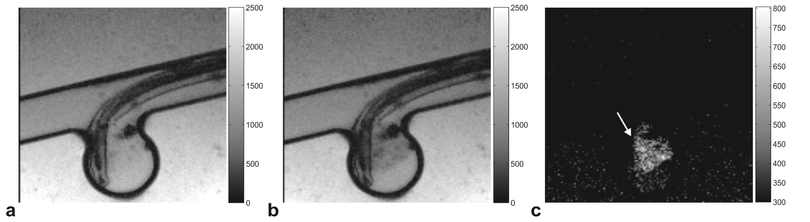

Figure 4: MT weighted images acquired before (a) and after (b) coagulation. The hyperintense regions in the difference image (arrow, c) indicate the location and morphology of the coagulum which enables intraprocedural monitoring of the progress of coagulation.

Conclusion

MRC is a minimally-invasive vascular embolization method offering complete integration with the MR scanner. MRI's high anatomic spatial resolution, soft tissue specificity, and ability to image unique parameters (e.g., tissue temperature, degree of coagulation) is combined with the ability to deliver spatially targeted energy in a controlled manner inherently synchronized with the imaging protocol.

Quantitative tissue maps can directly reflect the changes in tissue properties caused by coagulation and are unaffected by instrumental imperfections. The main drawback of conventional quantitative pulse sequences is their exceedingly long scan times that make them unsuitable for routine clinical use. Fortunately, much progress has been made in recent years in development of fast acquisition [3] and reconstruction [4] methods based on the MR fingerprinting [5] paradigm that can overcome these issues. These methods can potentially provide dynamic quantitative maps in seconds and thus enable near real-time tracking of the coagulation process.

Acknowledgements

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