Enhanced Intra-Operative Control During Cryoablation by Using the PRF Method: In Vivo Imaging and Histopathologic Correlation

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Introduction

Cryoablation is a promising minimally invasive therapy to effectively destroy localized tumors. Using MRI as the primary imaging modality for this procedure has multiple advantages. It not only provides excellent contrast between the ice and surrounding tissue, but also supports the accurate placement of the cryoprobes into the target tissue which is essential for complete tumor treatment. For enhanced intra-operative control during cryoablation, we propose to use the proton resonance frequency method (PRF) [1] to monitor the ice ball growth in the magnitude images and tissue temperature (relative to baseline) of adjacent regions in the phase images. By monitoring temperatures in close proximity to the region being ablated, procedure safety and efficacy can be increased. The purpose of this study was to demonstrate the value of online PRF temperature monitoring to 1) estimate the pattern of ice ball growth between multiple cryoprobes; and 2) prevent injury to adjacent structures. In this study, PRF imaging during *in vivo* cryoablation of porcine kidneys was compared to post-ablation imaging and histopathology.

Methods

In vivo swine experiments were approved by the institutional animal care and use committee and were performed on a 1.5T scanner (MAGNETOM Espree, Siemens Healthcare, Erlangen, Germany). For signal reception 6 elements of the body matrix coil were placed ventrally and were combined with 6 elements of the spine matrix dorsally to complete a 12 element array. Four swine were pre-anesthetized, intubated, maintained on isoflurane, and positioned head-first, supine in the scanner.

Freezing was achieved using an MRI-compatible cryotherapy system (Galil Medical, Yokneam, Israel) driven by pressurized Argon gas utilizing the Joule-Thomson effect. Both cryoprobe (17-gauge IceRod®, Galil Medical) placement and treatment monitoring were performed in the MR scanner. A custom real-time interactive spoiled gradient-echo sequence (BEAT_iRTTT, TE = 2.65ms, TR = 6.5ms, resolution = 2.3 x 2.3 x 10mm, flip angle = 20°) was used for probe placement into the kidney.

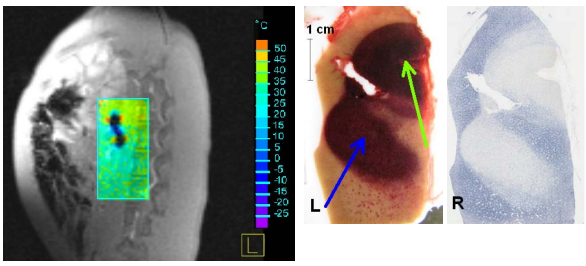
Cryoablation was performed using a double freeze-thaw cycle (15-5-10-5 minutes) scheme. Ice ball formation and dissolution was monitored in one minute intervals under breath hold conditions using a multiplanar PRF gradient echo sequence (TE = 5ms, TR = 51ms, resolution = 2.3 x 2.3 x 5 mm, flip angle = 25°), coupled to TMAP@IFE, a custom-built thermal therapy guidance application [2]. TE was set to 5ms as a tradeoff between temperature sensitivity (maximized when TE = T2*) and needle artifact size (increases with increasing TE). In two swine, a single cryoablation needle was used and in the other two swine, two needles were used in order to create a larger ablation zone and monitor the potential synergistic freezing effect of two adjacent probes. In all swine, a fiber optic temperature probe (Neoptix, Québec, Canada) was inserted into the kidney close to the expected ice ball border for ground truth temperature measurement.

Post-ablation imaging, including a T2-weighted TSE sequence (SPACE, effective TE = 146ms, TR = 4303ms, resolution = 0.4 x 0.4 x 0.8 mm), was performed when the kidney returned to body temperature after the end of the second freeze-thaw cycle. Following the procedure, the animals were immediately sacrificed, and the kidneys were harvested for histological evaluation (α-NADH staining for cell viability).

Results and Discussion

The PRF method has recently shown the ability to accurately measure tissue temperatures in close proximity to the ice ball [3]. It further can reliably support temperature monitoring for a multiple cryoprobe configuration. The spacing between probes needed to adequately cover the target lesion is not fully understood and can vary significantly depending on the tissue composition [4]. As demonstrated in Figure 1, cryoprobes separated by 2 cm in one porcine kidney did not create fully overlapping ice balls. In this example, the PRF images even after 1 minute of freezing provided an early indication of the pattern of ice ball growth. This information could be used to better shape the targeted cryoablation zone.

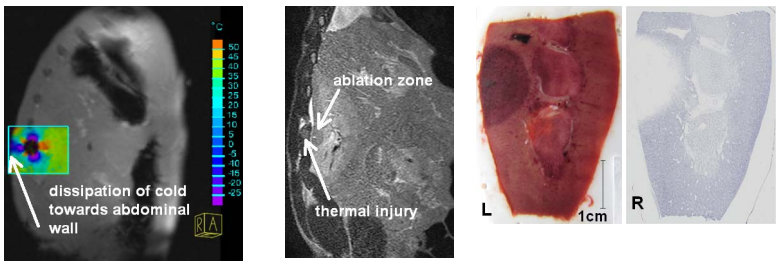
In addition, thermal injury to collateral structures is a known complication of cryoablation, and several protection techniques have been reported [5, 6]. An example where thermal injury was induced in the abdominal wall adjacent to the kidney is shown in Figure 2. Here, the PRF temperature images showed dissipation of cold towards the skin surface and demonstrate how PRF imaging could be used to monitor the effectiveness of these protection mechanisms and increase procedure safety.



A. PRF magnitude image of porcine kidney with temperature overlay after 1 min of freezing. Signal voids indicate the ice ball created by the two cryoprobes. The thermal map could be used to estimate the pattern of ice ball growth.

B. Corresponding tissue sample (L: unstained, R: α-NADH stained) to assess cell viability (dark blue). The staining suggests a non-overlapping cryoablation zone. The green arrow indicates the upper needle trajectory; the blue arrow marks the ablation zone created by the lower cryroprobe.

Figure 1: Ice ball formation between multiple cryo probes.



A. PRF magnitude image with overlaid temperature for a single cryo probe placed adjacent to the kidney capsule. Dissipation of cold was measurable as it extended towards the abdominal wall.

B. Post-procedure T2w TSE imaging confirmed the ablation zone and thermal injury.

C. Corresponding tissue sample (L: unstained, R: α-NADH stained). The viability stain suggests extension of ablation zone beyond the kidney capsule.

Figure 2: Thermal injury to collateral structure.

Conclusion

Online MR thermometry using the PRF method provides enhanced intra-operative control during cryoablation procedures. It not only helps to avoid damage to collateral structures but can also help optimize the spacing between multiple probes in order to create overlapping ablation zones.

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