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# In Vitro and In Vivo Experimental Studies of A Novel MR-Guided Method for Bipolar Radiofrequency Liver Ablation

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**ABSTRACT** This paper aims to investigate the feasibility of using a parallel method for MR-guided bipolar radiofrequency ablation. Experimental validations using fresh pig livers and rabbit livers were performed on a 0.35T open MR system with MR-compatible electrodes. The comparison studies of the proposed method and the conventional method were conducted. Experimental results showed that the parallel method offers better performance than the conventional method, which shortens the puncture durations and creates more spherical ablation zones. The bipolar radiofrequency ablation was carried out successfully without causing thermal damage and puncture injury. The proposed method significantly improved radiofrequency ablation, which has the potential to become a promising tool for liver tumor ablation.

**INDEX TERMS** Bipolar radiofrequency ablation, liver ablation, open MR-guided method.

## I. INTRODUCTION

Radiofrequency ablation (RFA) has been applied to destroy small liver tumors without surgery [1], [2]. Clinical trials have shown that the recurrence rates of cancer in early-stage treatment are less than 15% after RFA [3], [4]. Monopolar RFA is the most commonly available tool for existing RFA systems. However, this technique leads tumor recurrence if the tumor is larger than 3cm or close to large blood vessels [5]–[7]. To solve this challenge, bipolar RFA (B-RFA) approach was developed with two electrodes located at the boundary of the tumor tissues [8]–[11]. These two electrodes should be placed in parallel to generate an oval area with a diameter up to 7cm [12], [13]. If the electrodes arranged unparallelly, they might ablate irregular volumes [14].

Image guidance plays a key role in the precise and safe positioning of surgical electrodes [15]–[17]. Ultrasound (US) guided RFA and Computed Tomography (CT) guided RFA are the most commonly available methods for hepatocellular carcinoma. US-guided RFA is the most popular technique applied for tumors less than 3cm in diameter that are associated with hepatocellular carcinoma [18]. The technique provides real-time visibility of the electrode tip during

puncture and ablation process. However, the bubbles generated during ablation reduce the visibility of the ablation volume. CT-guided RFA has been applied by many doctors as it offers high sensitivity. However, it produces unsafe radiation, the differentiation between ablation volume and not the ablated tumor is invisible without using contrast agent injection [2], [6], [12], [17]–[18]. The ablation area and tumor size can be observed without using contrast agents [17], [19], which makes the MR-guided RFA become a safe and effective therapeutic tool for hepatic malignancies treatment [20]. MR imaging offers accurate monitoring of thermally-induced coagulation, which enables complete tumor coagulation in a single session [21].

The two electrodes used in image-guided B-RFA surgeries were added separately, while the US-dedicated handle helps to keep the electrodes parallel and reduces puncture duration in the US-guided B-RFA method [12]. In MR system, the puncture process is relatively complex and time-consuming due to the limited operational space. It is difficult to guarantee that these two electrodes are parallelly placed with suitable distance for ablation with good area [13], [22], [23]. To solve this problem, this paper

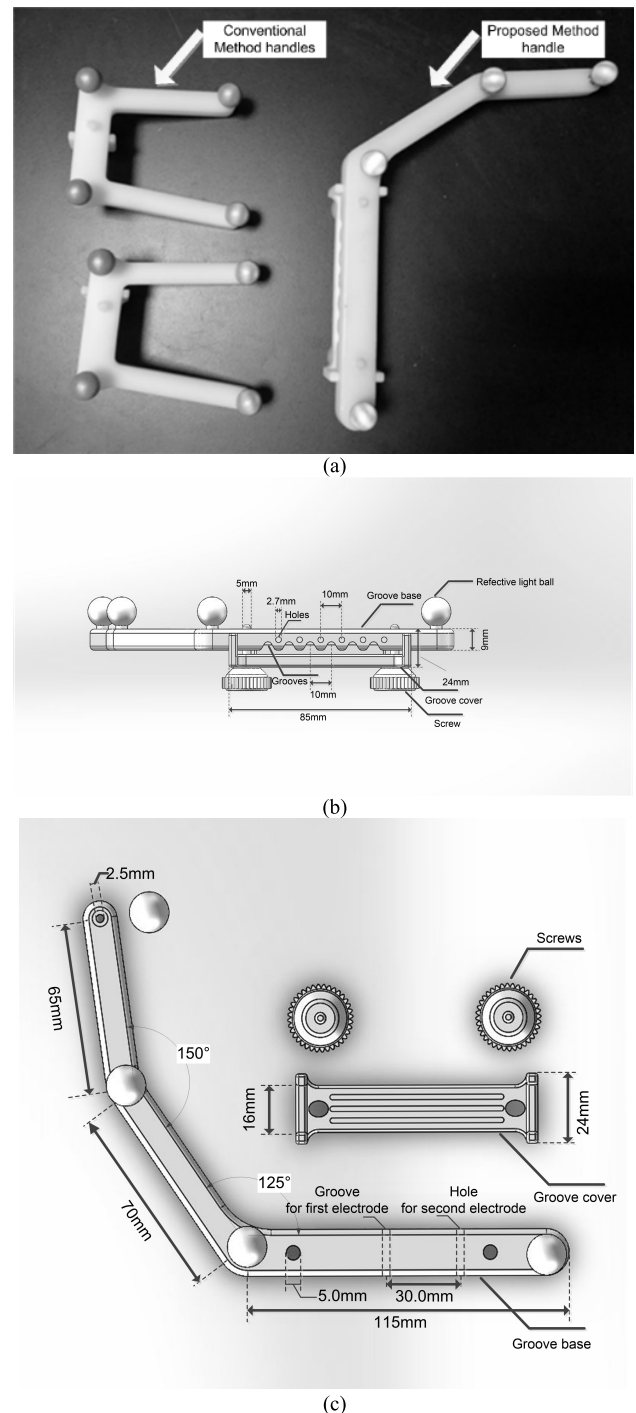
proposes a new parallel puncture method for MR-guided B-RFA of hepatic malignancies.

## II. MATERIAL AND METHODS

### A. CONVENTIONAL AND MR-GUIDED PUNCTURE METHODS

An optical tracking camera (NDI, Waterloo, Ontario, Canada) was used to guide the punctures in real-time tracking of the locations of the electrodes. The conventional puncture handles were used for puncture in the conventional method (see Fig. 1(a)). Four reflective light balls (NDI) were installed in the handle for optical tracking. After the electrodes were placed in two handles, they were inserted into the target location slowly with the assistance of real-time optical tracking and image guidance. The electrodes were displayed as a hypo-intense line acquired with a fast-low angle shot (FLASH) MRI sequence ( $TR/TE = 21.33\text{ms}/8.76\text{ms}$ , field of view [FOV] =  $256\text{mm} \times 256\text{mm}$ , matrix size =  $256 \times 256$ , slice thickness =  $5\text{mm}$ , slice gap =  $2\text{mm}$ , NEX = 1, acquisition time =  $5.4\text{s}$ ). These two electrodes were punctured inside of the target in parallel with a planned distance.

The conventional puncture method involves inserting the two electrodes individually, however, it is difficult to keep the electrodes parallel and with a predetermined distance. To improve efficiency of puncture for B-RFA, a handle (Fig. 1(a)) was designed to keep electrodes parallel. The handle was inspired by parallel puncture handle for US-guided B-RFA [13]. As shown in Fig. 1(b), the handle included a resin clamp with some grooves and holes was manufactured by the local supplier (Hefei Health Science and Technology Development Co, Ltd, Anhui, China). The construction of parallel grooves is similar to that of the conventional method. By tightening two resin screws, the first electrode can be firmly fixed in a groove between the groove cover and groove bottom. After that, the first electrode can be inserted into the tissue under MR guidance using this handle. The second electrode can be inserted through the small hole to ensure that it is placed parallel to first electrode and at a predetermined distance. The diameter of the hole is close to the diameter of the electrode, and the orientation of the holes is parallel with the grooves. Consequently, the two electrodes can be kept parallel during the puncture. The operators can grasp the handle easily, and the handle also ensures that the resin clamp will not block the second electrode during puncture. Guided by the NDI manual, four reflective light balls were installed in the three-section handle to reduce errors, and the proposed handles were designed to have an asymmetric structure with  $125^\circ$  and  $150^\circ$  angles (see Fig. 1(c)). The optical navigation system and control software can be used to update the angle and orientation of the two electrodes based on reflective data obtained from the handle [24]. Thus, all electrodes can be observed automatically in the MR images with the assistance of the proposed handle. The location of hole and groove for electrode punctures were selected based on tumor size and entry point of puncture. Fig.1 shows the key



**FIGURE 1.** The structure of the conventional and proposed handle. (a) Picture of the conventional and proposed handle, (b) front view of the proposed handle, and (c) top view of the proposed handle.

dimension parameters of the handle that consists of 6 grooves and holes, and the maximum distance between each two electrodes is 6-7cm. When punctures were carried out through holes and grooves with the proposed handle, operators could easily keep two electrodes in parallel with a predetermined distance. The handle could make MR-guided B-RFA more efficient than the conventional method.

## B. BIPOLAR RFA SYSTEM AND TEMPERATURE MEASURING SYSTEM

A self-made B-RFA apparatus was used for liver ablation, which generated 400KHZ of RF energy. The necrosis was caused by using two 17-gauge titanium alloy electrodes with lengths of 15cm. A T-type thermocouple was embedded in the RF electrode to measure the temperature of the electrode tip each second. The temperature of the ablation process can be assumed to be equal to the temperature of the electrode tip [25]. The B-RFA apparatus and temperature monitor (Jinko808, Jinko, Jiangsu, China) were placed in the operator room. RF energy and temperature signals were filtered through passive low-pass filters to overcome RF interference for the MR images.

## C. EVALUATION OF THE EFFICIENCY OF THE PROPOSED PUNCTURE METHOD

Two experiments by using the conventional and parallel methods were conducted and results were compared. 40 fresh pig livers were purchased from the local supermarket and they were placed in a saline solution at room temperature. All pig livers were randomly divided into two groups. The conventional method was used for group A, and the proposed parallel method was used for group B. The spacing interval of the two electrodes was 20.0mm, the lengths of the exposed tube and the sharp tip of the electrodes were 20.0mm and 5.0mm, respectively. The ablation power was maintained at 40W to ablate the livers for 10 minutes for both groups. The times for inserting the two electrodes into the liver tissue under MR guidance were recorded and compared.

The T1W spin echo (SE) sequence was performed to confirm whether the two electrodes reached the appropriate location (TR/TE = 400ms/15ms, the field of view (FOV) = 256mm × 256mm, matrix size = 210 × 192, slice thickness = 6mm, slice gap = 0mm, number of excitations (NEX) = 3, acquisition time = 154s), and the parallelity was described by the included angle between two extended lines for electrodes in T1W SE images.

## D. MORPHOLOGICAL AND PATHOLOGIC EVALUATION OF ABLATED AREA

The temperatures of electrode tips were collected to monitor the ablation status during ablation. After ablation, the longitudinal and transverse ablation diameters of ablated area were measured for area of necrosis (white coagulation zone) after cutting the liver along the electrodes. The ratio of longitudinal and transverse ablation (Dt/Dl) was also determined. The shape of ablation volume was characterized by Dt/Dl. The ideal ablation volume had a Dt/Dl ratio close to 1.

## E. EVALUATION OF THE EFFECTS AND COMPLICATIONS FOR IN VIVO EXPERIMENTS IN THE RABBITS

Experimental validation was performed with ethical approval from China Animal Ethics Association of the University of Science and Technology (USTCACUC1701002). Six New

Zealand healthy rabbits (male, 2.5-3.5kg) were used for the in vivo experiments. Anesthesia was performed by subcutaneous administration of 4mL of 3% sodium pentobarbital, which can keep the animals under anesthesia for at least two hours. Rabbits were placed on the operating table in the supine position 30 minutes after anesthetizing, and they were found to have no corneal reflex. Then, two 10.0mm incisions for electrodes puncture were made in the abdomens of the rabbits. The space between two incisions was 15.0mm.

Rabbits were placed on a 0.35T (Time Medical Systems, PICA, Hong Kong, China) home-made MR coil for puncturing. In the interventional therapy, the operators punctured the RF electrodes into the rabbit liver by using the proposed method. The interval distance between the two electrodes was 15mm, and the lengths of the exposed tube and the sharp tip of the electrodes were 15mm and 5mm, respectively. The distance of 15mm was selected for the ablation electrodes as the liver tissue was relatively small. The ablation power was maintained at 40W for 10 minutes after puncture.

The tip temperatures and T2 FSE sequences (TR/TE = 2000ms/110ms, FOV = 256 × 256mm, matrix size = 128 × 128, slice thickness = 6.5mm, slice gap = 0, NEX = 1, acquisition time = 34s) were collected for monitoring of ablation. After ablation, the T2 FSE sequences were performed (TR/TE = 2000ms/110ms, FOV = 256mm × 256mm, matrix size = 128 × 128, slice thickness = 6.5mm, slice gap = 0mm, 3 averages, acquisition time = 102s). The longitudinal and transverse ablation diameters of the ablated area were measured in the T2 FSE images. The electrodes were pulled out after the longitudinal and transverse diameters of the ablated volume were measured. The operators sutured the rabbits' wounds and injected ceftiofur sodium (5mg/kg) as an anti-inflammatory.

The authors checked the rabbit bleeding on 3.0T MR system (Discovery750, GE, USA) on operation day, and the authors also recorded food-intake for the following three days. The livers were removed when the rabbits were euthanized on the 4th day. The injuries to the liver lobes and the damages to the stomach, intestine, and gallbladder were recorded. The longitudinal and transverse ablation diameters of the ablated liver volume were measured after cutting the liver along the holes left by the electrode insertion.

The ablated liver tissue was cut into multiple samples, and placed in a 10% formalin solution for fixation. After 48 hours, the samples were processed into a paraffin section and stained with hematoxylin and eosin (H&E) to analyze the histology of the ablated area through optical microscopes. In this way, the irreversible cellular injury caused by RF energy could be determined.

## F. STATISTICAL ANALYSIS

The measurements were expressed as mean values with standard deviations. The in vitro experimental measurements were analyzed using SPSS Statistics 6.0. P values were calculated by the Students t-test. P values less than 0.05 was considered to be statistically significant.

**TABLE 1.** The parameters of the group A and group B for in-vitro pig liver in MR-guided bipolar RFA

| Pig liver | Group A |        |       |        |        |       | Group B |        |       |        |        |       |
|-----------|---------|--------|-------|--------|--------|-------|---------|--------|-------|--------|--------|-------|
|           | TM1(s)  | TM2(s) | Angle | Dt(mm) | Dl(mm) | Ratio | TM1(s)  | TM2(s) | Angle | Dt(mm) | Dl(mm) | Ratio |
| 1         | 22      | 69     | 2.84  | 31.5   | 26.4   | 0.84  | 21      | 19     | 1.23  | 30.7   | 27.8   | 0.91  |
| 2         | 25      | 82     | 2.81  | 30.2   | 26.0   | 0.86  | 23      | 20     | 1.20  | 29.1   | 27.2   | 0.93  |
| 3         | 26      | 52     | 2.77  | 32.5   | 25.5   | 0.78  | 24      | 16     | 1.18  | 31.3   | 26.4   | 0.84  |
| 4         | 29      | 68     | 2.76  | 31.2   | 26.3   | 0.84  | 24      | 16     | 1.16  | 30.1   | 26.6   | 0.88  |
| 5         | 23      | 85     | 2.63  | 33.3   | 27.4   | 0.82  | 26      | 25     | 1.07  | 32.2   | 28.4   | 0.88  |
| 6         | 24      | 74     | 2.69  | 34.2   | 27.1   | 0.79  | 27      | 21     | 1.09  | 33.3   | 27.4   | 0.82  |
| 7         | 25      | 64     | 3.01  | 32.3   | 26.5   | 0.82  | 23      | 23     | 1.15  | 32.4   | 28.3   | 0.87  |
| 8         | 32      | 73     | 2.79  | 31.2   | 27.3   | 0.88  | 26      | 17     | 1.08  | 30.5   | 27.9   | 0.91  |
| 9         | 31      | 83     | 3.32  | 30.2   | 30.1   | 1.00  | 27      | 18     | 1.01  | 30.1   | 27.3   | 0.91  |
| 10        | 27      | 66     | 3.39  | 31.7   | 24.3   | 0.77  | 23      | 27     | 1.22  | 32.3   | 28.9   | 0.89  |
| 11        | 30      | 55     | 2.48  | 33.1   | 29.1   | 0.90  | 22      | 21     | 1.04  | 30.7   | 27.4   | 0.89  |
| 12        | 26      | 82     | 2.97  | 31.4   | 25.9   | 0.82  | 21      | 19     | 1.23  | 32.6   | 28.8   | 0.88  |
| 13        | 23      | 68     | 2.77  | 32.4   | 25.7   | 0.79  | 25      | 24     | 1.11  | 31.2   | 27.5   | 0.88  |
| 14        | 28      | 94     | 3.02  | 33.7   | 26.4   | 0.78  | 23      | 24     | 1.34  | 33.7   | 29.6   | 0.87  |
| 15        | 24      | 64     | 2.15  | 31.8   | 25.8   | 0.81  | 25      | 23     | 1.06  | 32.8   | 28.4   | 0.86  |
| 16        | 26      | 53     | 2.45  | 32.7   | 26.8   | 0.82  | 29      | 30     | 1.24  | 30.1   | 27.9   | 0.92  |
| 17        | 24      | 56     | 2.75  | 30.7   | 28.9   | 0.94  | 28      | 16     | 1.08  | 30.9   | 26.8   | 0.87  |
| 18        | 25      | 76     | 2.67  | 33.6   | 26.2   | 0.78  | 27      | 28     | 1.15  | 32.7   | 27.4   | 0.84  |
| 19        | 32      | 83     | 3.07  | 31.5   | 25.8   | 0.82  | 23      | 24     | 1.06  | 31.7   | 27.8   | 0.88  |
| 20        | 23      | 59     | 2.67  | 32.4   | 25.3   | 0.78  | 27      | 23     | 1.02  | 32.1   | 26.9   | 0.84  |

TM1, TM2: the times for the MR-guided puncture from the beginning of the insertion to the end of the test for the first and second electrodes.

Angle: the included angle between the two extended lines for the first and second electrodes in T1W SE images.

Dl, Dt: the longitudinal and transverse diameters of the ablated area measured by rulers in gross examination; Ratio: Dt/Dl.

### III. RESULTS

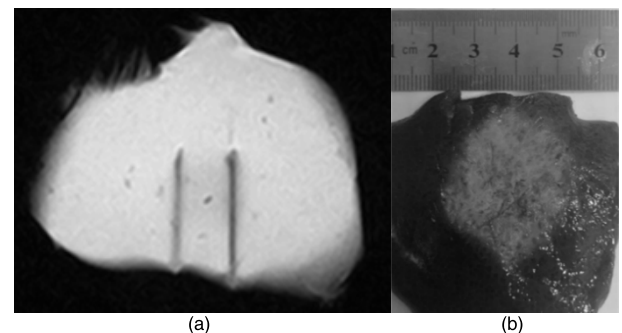
#### A. EFFICIENCY FOR PARALLEL METHOD

The ablation electrodes were successfully inserted into the middle of the liver tissue with the assistance of an optical tracking system and with MR image guidance for the in vitro pig liver experiments. The two electrodes were kept parallel. The puncture duration for the first electrode was similar for group A and group B ( $26 \pm 3$ s for group A vs.  $24 \pm 4$ s for group B;  $P > 0.05$ ) (see TABLE 1), but the second electrode puncture duration of group A was longer than that of group B ( $71 \pm 10$ s vs.  $20 \pm 3$ s;  $P < 0.05$ ). The angle of the two electrodes was measured using the T1W SE image ( $3.26 \pm 0.9^\circ$  for group A vs.  $1.09 \pm 0.12^\circ$  for group B;  $P < 0.05$ ). The angle of group B was smaller than that of group A (see Fig. 2(a)). Both electrodes can be identified in the image of group B, but the electrodes can be identified in the image of group A after manual adjustment.

#### B. EVALUATION OF THE RESULTS OF ABLATION

In the in vitro pig liver experiments, the angle and orientation of the two electrodes stayed constant during the whole process of ablation. Temperature measurements were made continuously, and the mean temperature values of the two electrode tips in the two groups were over  $60^\circ\text{C}$  after 4 minutes. The tip temperatures showed a similar steady increase for 10 minutes for both groups.

After ablation, the in vitro pig livers were cut along the line between the two electrodes. The ablated livers were soft white and oval (See Fig. 2(b)). The longitudinal and transverse diameters of the ablated shape were measured for both groups (See TABLE 1). The average ratios of Dt/Dl were entirely



**FIGURE 2.** T1W SE image and gross examination for group B. (a) T1W SE image for checking parallelity. (b) Gross examination for measuring the ratio of the longitudinal and the transverse diameters.

different for groups A and B ( $0.84 \pm 0.06$  vs.  $0.89 \pm 0.03$ ;  $P < 0.05$ ). The Dt/Dl ratios for group B were closer to 1, so they tended to have more spherically-shaped ablation zones.

#### C. EVALUATION OF THE EFFECTS AND COMPLICATION FOR THE IN VIVO RABBIT EXPERIMENTS

For the in vivo rabbit experiments, the puncture durations for the two electrodes were  $57 \pm 6$ s and  $48 \pm 7$ s, respectively. The included angle between the two electrodes was  $1.01 \pm 0.06^\circ$ . Thus, the two electrodes were almost parallel (See Fig. 3(a) and TABLE 2). The temperature changes for the in vivo tests were similar to those for the in vitro tests, and the mean temperature values of the two electrodes tip were over  $60^\circ\text{C}$  after 4 minutes. After ablation, the longitudinal and transverse diameters of the ablated liver volumes, as measured in T2 FSE

**TABLE 2.** The parameters of the in vivo rabbit experiments for MR-guided bipolar RFA.

|   | TM1(s) | TM2(s) | Angle | Dt1(mm) | Dl1(mm) | Ratio1 | Dt2(mm) | Dl2(mm) | Ratio2 | PT-complications |
|---|--------|--------|-------|---------|---------|--------|---------|---------|--------|------------------|
| 1 | 62     | 54     | 1.07  | 20.0    | 17.0    | 0.85   | 32.7    | 21.2    | 0.65   | Gallbladder      |
| 2 | 58     | 45     | 1.09  | 24.2    | 18.3    | 0.76   | 46.8    | 15.2    | 0.32   | Gallbladder      |
| 3 | 50     | 50     | 0.97  | 21.2    | 17.5    | 0.83   | 40.4    | 21.6    | 0.53   | Gallbladder      |
| 4 | 52     | 43     | 1.04  | 22.4    | 16.4    | 0.73   | 32.1    | 22.9    | 0.71   | Gallbladder      |
| 5 | 65     | 58     | 0.96  | 20.6    | 16.9    | 0.82   | 35.6    | 16.5    | 0.46   | Gallbladder      |
| 6 | 56     | 39     | 0.93  | 23.7    | 16.3    | 0.68   | 45.5    | 15.6    | 0.34   | Gallbladder      |

TM1, TM2: times for the MR-guided puncture from the beginning of the insertion to the end of the test for the first and second electrodes.

Angle: the included angle between the two extended lines for the first and second electrodes in T1W SE images.

Dl1, Dt1: the longitudinal and transverse diameters of the ablated area measured by rulers using the T2 FSE images; Ratio1: Dt1/Dl2.

Dl2, Dt2: the longitudinal and transverse diameters of the ablated area measured by rulers in gross examination; Ratio2: Dt1/Dl2.

PT-complications: complications for puncture injury or thermal damage of critical anatomical structures.

images, were  $22.02 \pm 1.70$ mm and  $17.07 \pm 0.74$ mm, respectively (See Fig. 3(c)). The ratio of the Dt/Dl was  $0.78 \pm 0.06$ .

There were no severe bleeding complications for any of the rabbits on the day of the operation. On the second day, they were recovered enough to eat. They were euthanized on the fourth day, and after the autopsies, we recorded the thermal damage and puncture injury to adjacent structures. There were two ablated liver lobes for each rabbit, and the gallbladder was destroyed for all rabbits, but there were no burn injuries to their stomachs, intestines, or skin in the in vivo experiment.

The rabbit livers were cut along the holes left with the two electrodes. The longitudinal and transverse diameters of the ablated livers were recorded, and the measured values were  $38.85 \pm 6.38$ mm and  $18.83 \pm 3.43$ mm, respectively. The average Dt/Dl ratio for vivo experiment was  $0.53 \pm 0.12$ . The average Dt/Dl ratio of rabbit liver experiment was different from average Dt/Dl ratio of pig liver experiment due to two electrodes were inserted in different liver lobes.

Histologic examination showed that the features of sections for vivo experiments were similar. The stained sections under the microscope can be divided into three parts (see Fig. 4): clear boundary of the peripheral bleeding area, central necrotic area, and healthy tissue area. All tissues were destroyed in the central necrotic area.

#### IV. DISCUSSION

MR-guided B-RFA has been successfully applied for clinical trials with the conventional puncturing method with electrodes inserted into the target area separately [13], [23]. This method is time-consuming and unreliable when puncturing in a limited space. It is difficult to ensure that the two electrodes are parallel, and electrodes that are not parallel result in an irregular ablation area.

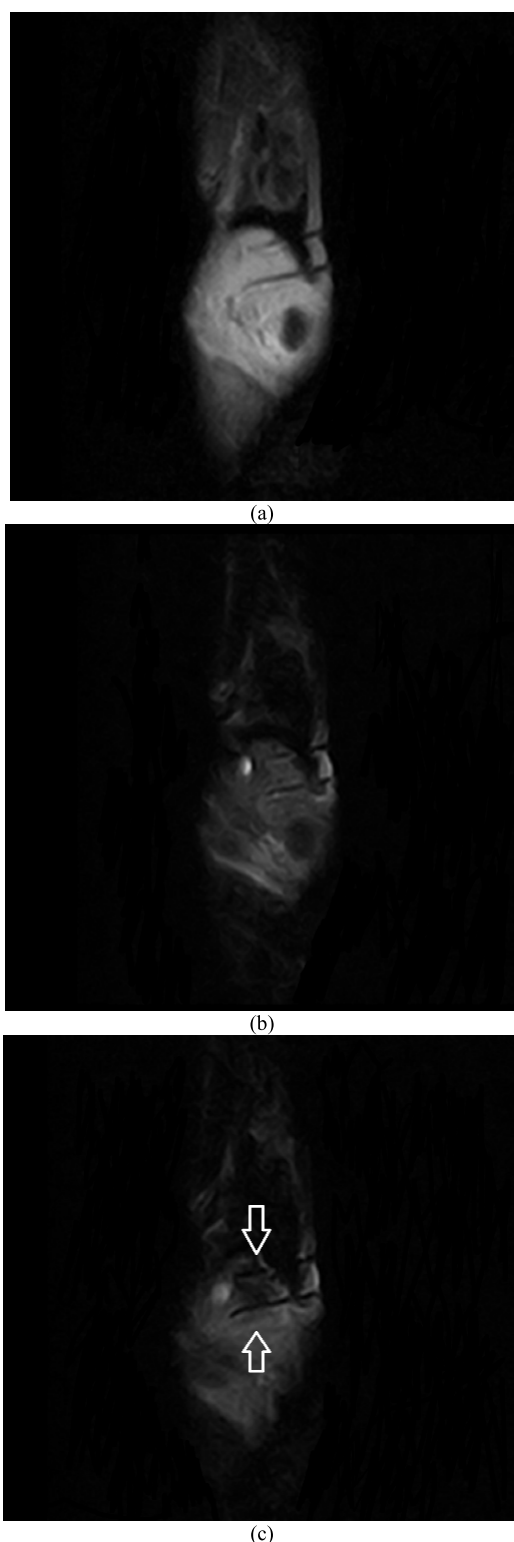
In order to solve this problem, we proposed a fast and stable parallel method for puncture with open MR guidance. The in vitro experimental results demonstrated that the proposed method and device could reduce the puncture time by approximately one minute (see Figs. 1). The proposed method offers a fast and reliable puncture process, which has the potential to ensure the electrodes placed in parallel and helps to create a regular shape for ablation volume. Moreover, the MR machine able to automatically select the scanning

plane according to the positions of the two electrodes. It could show the electrodes continuously in the same image during surgery. The operator could observe and adjust the two electrodes in real-time. Thus the deviation from the predefined trajectory could be reduced.

Tumors usually have longitudinal and transverse diameter ratios of close to 1. Thus it is best to have an ablation area as close to 1 as possible. For B-RFA, the Dt/Dl ratios were determined by the spacing interval of the two electrodes and the lengths of the tip exposure, which included the exposed tube and sharp tip of the electrodes. In our in vitro studies, the spacing interval was 20mm, and the length of the tip exposure was 25mm. After ablation, the Dt/Dl ratios of the ablated area in group B ( $0.89 \pm 0.03$ ) were much closer to 1 than that of group A ( $0.84 \pm 0.06$ ). There may be two reasons for the irregularity of the ablation areas for B-RFA. The in vitro experimental results demonstrated that the electrodes for conventional method were less likely to be parallel than the proposed parallel method. The distance between the electrodes was difficult to set to the planned value in the conventional method.

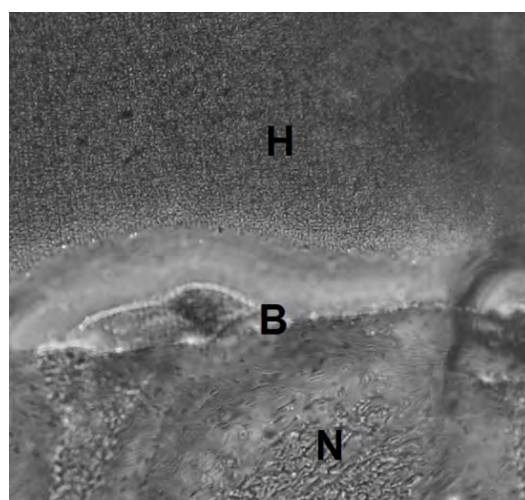
For B-RFA, the temperatures were homogeneous throughout the heated region [26], [27]. Therefore the mean temperature of the two electrodes tips during B-RFA can be used to represent the temperature of the entire ablation region. In this paper, we proposed a new low-magnetic T-type thermocouple to measure the temperature of the electrode tips. The RF interference that was induced by the temperature measurement acquisition monitor can be reduced by four temperature filters. For RFA, the tissues begin to be ablated when the temperature reaches  $60^\circ\text{C}$ . In all experiments, the temperature exceeded  $60^\circ\text{C}$  for over 3-4 minutes. If the temperature exceeded  $100^\circ\text{C}$ , we could infuse saline to prevent carbonation.

In vivo experiments, the puncture and ablation avoided damaging critical anatomical structures. The experimental results confirmed that the proposed method can be used for in vivo animals, and the results can be used to predict its precision and safety. For the conventional method, the operators should not only ensure that the second electrode is kept at a predetermined distance from the first one during the puncture, but the operators must also keep the two electrodes parallel. If these things are not done correctly, the efficiency



**FIGURE 3.** T1 SE image and T2 FSE image for in vivo experiment. (a) T1 SE image for checking parallelity. (b) T2 FSE image of a rabbit before ablation. (c) T2 FSE image of the rabbit after ablation. The arrows show the ablated area.

of the ablation can be much lower. However, the electrodes are more likely to be parallel with correct distance for the proposed method, which improves the efficiency of puncture in vivo. The puncture time of the two electrodes was similar



**FIGURE 4.** Microscope image of the liver areas ablated by the RF machine in vivo. Healthy tissue (H), necrotic area (N), and boundary of the peripheral bleeding area (B).

( $57 \pm 6$ s,  $48 \pm 7$ s), while the puncture time of second electrode is likely to be much longer than first one by using the conventional method. The puncture durations may be longer in clinical operation, but when the proposed parallel method is used for malignant tumor treatment, it may help to reduce the pressure on operators and blood loss of patients by shortening the puncture durations of the second electrode. The puncture efficiency could be improved and ablation area could be more regular, which is very important for patients. In addition, MR T2 FSE images and the ablation dimensions determined from gross examination were commonly used to compare ablation area [28]–[30]. A small difference between MR images and gross examination was observed for longitudinal and transverse diameters of the ablated livers.

Previous studies showed that most of the complications of RFA were related to thermal damage and puncture injury to adjacent structures, especially the stomach, intestines and skin. After rabbits were euthanized for autopsy these complications were recorded. The important structures were not damaged significantly apart from liver and gallbladder.

The major limitation of this study is that only healthy rabbits were involved. Animals with implanted tumors need to be used to re-evaluate the effectiveness of the system. The respiratory-gated device could not be applied to rabbit liver ablation which caused respiratory artifacts especially in the axial direction. The proposed method improves the efficiency of liver ablation, which has the potential to become a useful clinical tool for RF ablation of liver tumors. Future studies will be carried out with the respiratory-gated device.

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