Review

Development of instruments to assist accurate puncture of liver tumors for MRI-guided microwave ablation –From a simple spacer to a motorized robot–

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Abstract

In MR-guided microwave ablation of liver tumors, real-time MR images including the needle path and the target tumors were essential for accurate puncture. An optical tracking system, integrated in the MR system, played a very important role for the interactive scan plane control. The optical tracking system, however, had some limitations caused by the line of sight between the LEDs and detectors. In addition, the LEDs were slightly ferromagnetic. To solve the problems of this tracking system, we prepared various adaptors for the hand piece. Then, we procured less magnetic LEDs with compatible performance and created new original hand pieces. A hybrid tracking system with optical and electromagnetic detections was also constructed and seamless navigation was enabled. Finally, an MR-compatible motorized robot was developed to chase the preset target point automatically. With these devices to track the target, more convenient and accurate puncture of liver tumor was realized under MR image guidance.

Key words: liver tumor, microwave ablation, MR image guidance, interactive scan plane control, surgical robot

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Introduction

Since 2000, MR image-guided microwave ablation of liver tumors has been performed in 280 cases using an open-configuration MR scanner ¹⁾. In X-ray fluoroscopic guidance, projection images are used, but in MR image guidance, tomographic images of specific slices are used to navigate interventional procedures. Therefore, the image plane should accurately include both the target and the needle path; otherwise, MR images will be useless. For this purpose, an optical tracking system was integrated in this MR system ²⁾. Image planes were interactively controlled by surgeons beside the patient with the hand piece and real-time MR images including the needle path were acquired. The MR images were shown on in-bore displays for the surgeons and they inserted MR-compatible puncture needle and microwave electrode while monitoring their tip position. The combination of MR image guidance and microwave ablation was quite feasible. Clear real-time MR images without interference could be observed even during microwave irradiation, and temperature changes of the tissues during microwave ablation could be monitored with 2-dimensional MR temperature maps using proton resonance frequency method ³⁾. MR image guidance

brought a new breakthrough for microwave ablation of liver tumors.

The open-configuration MR system with interactive scan plane control by an optical tracking system is fine as it is, but some practical problems and limitations also exist. To solve such problems and to increase the usability of this system, we have created new devices and instruments. In this paper, our developed devices and instruments for the accurate puncture of liver tumors are presented.

Instruments

MR images were acquired with a double-donut-type open-configuration MR scanner, 0.5 T Signa SP/2 (GE Healthcare, Waukesha, WI) (**Fig. 1A**). In this MR system, an optical tracking system, FlashPoint model 5000 (Boulder Innovation Group, Boulder, CO), was integrated. Its hand piece had a needle guide at the center and 3 LEDs on the 3 pedicles (**Fig. 1B**). Infrared light from the LEDs was received by 3 detectors on the ceiling of the magnets and the position and orientation of the needle were calculated. Real-time MR images of inplane 0 and inplane 90, both of which include the needle path, were acquired with a spoiled gradient echo (SPGR) se-

Figure 1

A: A double-donut-type open-configuration MR scanner, 0.5 T Signa SP/2. Two surgeons can access the patient from both sides through the gap between the magnets. B: Hand piece of an optical tracking system having 3 LEDs (arrows) on the 3 pedicles for interactive scan plane control. Scan planes of inplane 0 and inplane 90 including the needle path are usually used.

Figure 2 Adaptors for the hand piece of the optical tracking system

- A: A simple spacer to hold the hand piece stable with some distance from the body surface.
- B: A spherical adaptor and a handle to hold the hand piece stable with one hand and to adjust the angle of puncture.
- C: An offset-type adaptor having a needle guide with some distance from the LEDs to maintain the visibility of LEDs during surgical manipulation.
- D: A torch-type adaptor for puncture from the lateral side of the patient.

quence within 2 s. Under the guidance of these images, liver tumors were punctured with an MR-compatible 14G needle (Invivo, Schwerin, Germany, or Hakko Medical, Chikuma, Japan) and an MR-compatible microwave electrode was inserted through it. Microwave ablation was performed at 60 W for 3 min as one session with a microwave coagulator, Microtaze OT-110M (Alfresa, Osaka, Japan), operated at 2.45 GHz.

Adaptors for the hand piece of the optical tracking system

The optical tracking system was very useful and it played a very important role. However, it had some problems. The LEDs were slightly ferromagnetic and caused signal loss in MR images around them. Therefore, surgeons were required to hold the hand piece stable keeping it several centimeters away from the body surface and, at the same time, maintaining the visibility of all LEDs. Initially, a simple acrylic tube was used as a spacer and the hand piece was placed on it (**Fig. 2A**). Several shapes of spacers were prepared for the punctures at various angles. The hand piece could be kept stable with the spacer, but both hands of the assistant were occupied to hold the hand piece and the visibility of LEDs was easily blocked. It was inconvenient, because only two surgeons had access to the patient. Then, a spherical

adaptor and a handle were created (**Fig. 2B**). The hand piece could be kept stable by one hand keeping some distance from the body surface of the patient and the direction of the hand piece could be easily adjusted. The needle guide of this hand piece was located at the center of the LEDs and surgical manipulation of the needle always obstructed the line of sight between LEDs and detectors. To obtain the latest and correct information, the surgeon was required to withdraw his hand. Then, an offset-type adaptor (**Fig. 2C**) was created, in which the needle guide was located with some distance from the LEDs. With this adaptor, surgical manipulation did not disturb the visibility of the LEDs. Because the detectors were located on the ceiling, all the LEDs needed to face upwards and the hand piece could not be used for the puncture from the lateral side. To solve this limitation, a torch-type adaptor was created (**Fig. 2D**). With this adaptor, the direction of the needle guide was changed and lateral puncture was enabled. For the adaptors of **Fig. 2C** and **2D**, new tool files for the Flash-Point system were created and new needle position and direction controlled MR image planes. The efficacy of these adaptors has been reported elsewhere⁴⁾. They substantially improved the usability and availability of the puncture in MR image-guided procedures.

Figure 3 Effects of the hand pieces on the MR images of an agar phantom

Inplane 0 and 90 spoiled gradient echo images were acquired with the hand pieces.

A: Without the hand piece.

B: With the standard hand piece.

C: With an original hand piece using LEDs with ceramic base, CL-1CL3 (Kodenshi).

D: With an original hand piece using tip-type LEDs, HL601 (Kodenshi).

Production of new hand pieces with less ferromagnetic LEDs

Less ferromagnetic LEDs with the same performance as those used in FlashPoint were explored in Japan. We found 2 substitutive LEDs, CL-1CL3 (ceramic base, **Fig. 3C**) and HL601 (tip-type, **Fig. 3D**) (Kodenshi, Uji, Japan). In CL-1CL3, only the leads were magnetic and HL601 was completely nonmagnetic. Using these LEDs, we made new hand pieces with slightly smaller size and weight. Making new tool files, these hand pieces worked properly in the FlashPoint system and showed the same level of accuracy. In addition, the signal loss of MR images caused by the hand piece was much less with these hand pieces (**Fig. 3**). With the hand piece using HL601, artifacts on MR images completely disappeared. Procurement of compatible LEDs enabled us to make special hand pieces for the hybrid system and motorized robot described below.

Hybrid-type tracking system

The optical tracking system showed sufficient accuracy and prompt response, but limitations with regard to the line of sight were inevitable. An electromagnetic tracking system, EndoScout (Robin Medical, Baltimore, MD), was also available for interactive control of image planes in MR systems⁵. Its sensor had 3 pairs of coils in the X, Y, and Z axes (6 coils) and its position and direction were calculated from the inductive voltage caused by gradient pulses during MR scanning (**Fig. 4A**). With this system, line of site did not need to be considered, but response was slower than that of the optical system and the accuracy was guaranteed only in the central $40 \times 40 \times 40 \text{ cm}^3$ area. A hybrid tracking system was developed combining the advantages of the optical and electromagnetic tracking systems⁶. The hand piece (**Fig. 4B**) had 3 LEDs and a cubic electromagnetic sensor. Two sensor systems independently calculated the location and orientation of the needle

Figure 4

A: A cube sensor of an electromagnetic tracking system, EndoScout, having 3 pairs of coils in the X, Y, and Z axes (6 coils).
B: A hand piece of a hybrid tracking system having 3 LEDs for the optical system and a cube sensor for the electromagnetic system.

and the information of both systems was sent to our original navigation software, MRNavi, on an external PC ⁷⁾. The information from the optical tracking system was preferably utilized, but, when it was not available because of the obstruction of lines of sight, that from the electromagnetic tracking system was adopted. The selected information was sent to the MR system to control scan planes and effective information was continuously utilized. With this hybrid system, surgeons could interactively control the image planes without a break.

Motorized robot to chase the target automatically

In the MR-guided microwave ablation, many cases with liver tumors in the deep area, which were difficult to treat under the guidance with ultrasonography, were included. In such cases, it was time-consuming to choose the optimal puncture route. To assist this process, we developed a portable-sized MR-compatible robot with a capability to chase the determined target point automatically (**Fig. 5A**). The end effector (**Fig. 5B**) had a specially designed hand piece of the optical tracking system to control image planes. The hand piece

had passive unstrained 2 degrees-of-freedom (DOF) rotation and its direction was controlled by the surgeon. The orientation of the needle was calculated from the information by 2 optical angle sensors (Oshima, Tokyo, Japan). The end effector was fixed on an active 3-DOF base stage having 3 nonmagnetic ultrasonic motors (Shinsei, Tokyo, Japan) in X, Y, and Z axes (**Fig. 5C**). The virtual needle tip position was maintained at the determined target point with the 3 ultrasonic motors using remote-center-of-motion (RCM) control ⁸⁾ (**Fig. 6A**). For application for tumors in various locations of the liver, detachable adaptors were prepared. RCM control worked correctly with individual adaptors (**Fig. 6B-6D**). In these cases, a 15-cm-long needle was used, but we could apply any length of needle. During the procedure, the adaptor could be changed depending on the location of the tumor without recalibration of the robot. The role of this robot was only targeting and surgeons manually punctured the tumors.

After confirmation of safety issues, validation of errors and careful simulation studies with phantom and volunteers, we started clinical study with this robot (**Fig. 7**) ⁹⁾. The robot was used for 34 nodules in S3 – S8 of 23 patients and all the tumors were successfully punctured without any compli-

Figure 5

- A: A portable-sized MR-compatible robot to chase the determined target point automatically.
- B: An end effector having a specially designed hand piece of the optical tracking system. Its direction can be changed with passive unstrained 2 degrees-of-freedom (DOF) rotation and its orientation is monitored by 2 optical angle sensors (arrows).
- C: An active 3-DOF base stage having 3 nonmagnetic ultrasonic motors (arrowheads) in X, Y, and Z axes to maintain the needle tip position at the target point.

Figure 6 Remote-center-of-motion (RCM) control of the robot

The needle tip positions are maintained at the predefined target point (A) without an adaptor, (B) with a 45° adaptor, (C) with a 60° adaptor, and (D) with a 90° adaptor.

Figure 7 Clinical use of the motorized MR-compatible robot in the double-donut-type open MR system for patients with liver tumor

cations during the procedure. Thoracoscopic assistance¹⁰⁾ was also combined in 8 cases. During microwave ablation, repeated punctures and ablations for one tumor were usually required. The robot led to the sequential puncture points immediately and remarkably reduced the workload of the surgeons. With this robot, the number of surgeons was reduced to one, but this robot sufficiently played a role as a reliable assistant.

Conclusion

Various adaptors for the hand piece were prepared to

improve the usability of the optical tracking system. New original hand pieces using less magnetic LEDs and a hybrid tracking system with optical and electromagnetic detections were also created. Finally, an MR-compatible motorized robot was developed to chase the preset target point automatically. With these devices to track the target, more convenient and accurate puncture of liver tumor was realized under MR image guidance.

References

- 1) Morikawa S, Inubushi T, Kurumi Y, Naka S, Sato K, Tani T, Yamamoto I, Fujimura M: MR-guided microwave thermocoagulation therapy of liver tumors: initial clinical experiences using a 0.5 T open MR system. *J Magn Reson Imaging* **16**: 576-583, 2002
- 2) Silverman SG, Collick BD, Figueira MR, Khorasani R, Adams DF, Newman RW, Topulos GP, Jolesz FA: Interactive MR-guided biopsy in an open-configuration MR imaging system. *Radiology* **197**: 175-181, 1995
- 3) De Poorter J, De Wagter C, De Deene Y, Thomsen C, Ståhlberg F, Achten E: Noninvasive MRI thermometry with the proton resonance frequency (PRF) method: in vivo results in human muscle. *Magn Reson Med* **33**: 74-81, 1995
- 4) Morikawa S, Inubushi T, Kurumi Y, Naka S, Sato K, Tani T, Haque HA, Tokuda J, Hata N: New assistive devices for MR-guided microwave thermocoagulation of liver tumors. *Acad Radiol* **10**: 180-188, 2003
- 5) Naka S, Kurumi Y, Morikawa S, Shiomi H, Tani T: MR guided microwave surgery for liver tumor with MR gradient-based tracking system. *Proc Intl Soc Mag Reson Med (ISMRM)* **14**: 1434, 2006
- 6) Morikawa S, Haque HA, Naka S, Murakami K, Kurumi Y, Tani T, Inubushi T: An optical and electromagnetic hybrid tracking system for MR image guided interventional procedures. *Proc Intl Soc Mag Reson Med (ISMRM)* **17**: 4418, 2009

- 7) Sato K, Morikawa S, Inubushi T, Kurumi Y, Naka S, Haque HA, Demura K, Tnai T: Alternate biplanar MR navigation for microwave ablation of liver tumors. *Magn Reson Med Sci* **4**: 89-94, 2005
- 8) Hata N, Tokuda J, Hurwitz S, Morikawa S: MRI-Compatible Manipulator With Remote-Center-of-Motion Control. *J Magn Reson Imaging* **27**: 1130-1138, 2008
- 9) Morikawa S, Naka S, Murakami K, Kurumi Y, Shiomi H, Tani T, Haque HA, Tokuda J, Hata N, Inubushi T: Preliminary clinical experiences of a motorized manipulator for magnetic resonance image-guided microwave coagulation therapy of liver tumors. *Am J Surg* **198**: 340-347, 2009
- 10) Shiomi H, Naka S, Sato K, Demura K, Murakami K, Shimizu T, Morikawa S, Kurumi Y, Tani T: Thoracoscopy-assisted magnetic resonance guided microwave coagulation therapy for hepatic tumors. *Am J Surg* **195**: 854-860, 2008