the laparoscope works normally in the MR environment, the scopist can control the laparoscope as in conventional laparoscopic surgery even in the MR environment, and its use in MR image-guided laparoscopic surgery does not affect MR image quality. It is necessary to evaluate image quality in terms of imaging artifact related to EMI, which is generated by electric signals passing through the long cable that connects the CCD and the processor, in addition to artifact related to the susceptibility of the laparoscope.

Artifact resulting from EMI was not detected, even when the distally mounted CCD approached the image plane. Other MR-compatible laparoscopes have the CCD at the proximal side of the scope, and consist of rigid relay lenses, an object lens, and an eyepiece [3–6]. It is comparatively easy to shield a laparoscope of this design for EMI because the camera head and optical coupler can be eliminated from the MRI gantry; however, we adopted differential signaling because it is impossible to eliminate the CCD from the MRI gantry using a laparoscope with a distally mounted CCD. It is very important that an artifact resulting from EMI is not found even if the distally mounted CCD were to be placed at the center of the magnetic field: this indicates that an issue in the development of flexible-tip versions of the MR-compatible laparoscope has been solved. The scopist cannot freely control the laparoscope in laparoscopic surgery under intraoperative MRI because of the confines of the narrow space. A flexible MR-compatible laparoscope is required to enable the surgeon to obtain a wide range of laparoscopic vision using MRI, as in conventional laparoscopy. Our concept of newly developed MR-compatible laparoscope with a distally mounted CCD will assist in the development of a flexible MR-compatible laparoscope and will enable laparoscopic surgery to be performed more easily under intraoperative MRI. Furthermore, one report has found that a laparoscope with a distally mounted CCD was superior in terms of consistently clear image quality because there is no honeycomb effect from the fiber bundle when compared to a conventional laparoscope, in which the CCD is placed on the proximal side of the scope [9]. The diameter of our scope can become smaller because the CCD is able to perform well even with less light. Therefore, our new MR-compatible laparoscope may be superior to existing MR-compatible laparoscopes with proximally mounted CCD.

The distally mounted CCD caused susceptibility artifact; however, according to the results of the susceptibility experiment, artifact does not occur when the CCD is more than 4 cm from the image plane. A previous report evaluated tissue interaction in a simulation using a turkey as a phantom [10]; however, distortion without signal loss cannot be assessed with such a phantom. Distortion would not be detected even if the MR image of a turkey phantom were distorted because the signal intensity is identical in all parts. We consider that distortions that are not visible on the turkey phantom could cause misplacement of image information in actual MR imaging. We were able to evaluate this invisible distortion using a grid phantom. In the present study, susceptibility artifact had little affect when the phase encoding direction was set in the R-L direction.

We confirmed that the laparoscope was MR-safe by testing with a handheld magnet. Although this test is very simple, it is useful as a preliminary test to evaluate the attraction of an unknown instrument to the MR magnet [11]. In the present study, the scopist could easily control the laparoscope in the magnet and it had no affect on near real-time MR imaging in the in vivo experiment. We consider that the laparoscope came no closer than 4 cm to the MR image plane because the scopist controlled the laparoscope in order to confirm placement of the RFA probe, other forceps, and the puncture site of the liver. MR-compatibility for medical devices is described in detail by Woods [12], who stated that a device is MR-compatible unless the amount and location of artifact affects the region of interest to the clinician, and that a complete absence of artifact is not always desirable. It was confirmed that our laparoscope produced image artifact in phantom experiment, but near real-time MR imaging was not affected by the use of our scope during MR image-guided laparoscopic RFA. Therefore, it is feasible to apply this MR-compatible laparoscope prototype to MR image-guided radiofrequency ablation therapy. Importantly, MR-compatibility depends on the MR conditions [8]. The laparoscope should be retested before use in different MR conditions, for example in a higher magnetic field.

All punctures were successfully performed by RFA probe using our laparoscope with near real-time MR imaging and 3-D navigation. RFA is usually performed percutaneously under ultrasound (US) guidance; however, laparoscopic or thoracoscopic RFA has advantages over the percutaneous approach because the subphrenic area or free surface of the liver can be punctured safely and easily [13,14]. US is the standard guidance modality for RFA, but it has a relatively low sensitivity in detecting hepatocellular carcinoma (HCC) with liver cirrhosis [15,16]. It is reported that the computed tomography (CT) guidance has limitations such as radiation dose [17,18]. MR image-guided laparoscopic RFA using our MR-compatible laparoscope solves all of the above issues. MRI guidance provides the surgeon with image verification of the probe at all times, as with US guidance, and the image plane can be obtained in any orientation. MR fluoroscopy delivers no radiation dose. In our in vivo experiment, the surgeon was able to easily guide the probe close to the mimic tumor on the first attempt using 3-D navigation; the true positions of the target and probe could then be confirmed, and the puncture could be completed via near real-time MR imaging. We consider that MR image-guided laparoscopic RFA is safer and more effective and precise than percutaneous RFA performed under US or CT.

Previous studies report that MR image-guided laparoscopic surgery is feasible for other procedures in addition to local ablation treatment for tumors. Lauro et al. [5] performed intraoperative MR-cholangiography using fast spin echo during laparoscopic cholecystectomy. Intraoperative MRI will ameliorate safety issues in laparoscopic cholecystectomy because MR-cholangiography is much less invasive for patients compared to conventional cholangiography [19]. Recent research reports MR imaging for lymph nodes [20, 21]. Our MR-compatible laparoscope, near real-time MR imaging, and 3-D navigation is likely to be used to assist the surgeon dissecting lymph nodes under intraoperative MRI.

In conclusion, we have developed a new MR-compatible laparoscope that incorporates a distally mounted CCD. We performed MR image-guided laparoscopic RFA more safely, effectively, and precisely than percutaneous RFA performed under US or CT. This MR-compatible laparoscope with distally mounted CCD is useful in laparoscopic surgery under intraoperative MR image guidance; use of this laparoscope will improve the safety of conventional laparoscopic surgery.

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