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Hybrid MR interventional imaging system: combined MR and angiography suites with single interactive table. Feasibility study in vascular liver tumor procedures

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Abstract. Our objective was to evaluate the feasibility of a hybrid system consisting of a high-field MR and fully equipped digital subtraction angiography (DSA) unit for MR-guided vascular interventions. In a newly built hybrid system, consisting of a high-field MRI and a fully equipped DSA unit, elective interventional hybrid procedures were performed. Between May 2000 and November 2001, 30 patients with liver tumors underwent MR-guided chemoembolization using the hybrid system. During the intervention accurate catheter position was monitored with real-time and dynamic MR imaging. Elective hybrid interventional vascular procedures were performed successfully in 23 patients with liver metastases and hepatocellular carcinoma (n=7). Patients could be transferred between the MRI and angiographic units on a carbon fiber tabletop within 10 s. Initial clinical trials demonstrated that in the chemoembolization of primary and secondary liver tumors the hybrid approach resulted in a change of catheter position in 40% of procedures. In combining high-field MR system and a fully equipped interventional vascular angiographic unit as backup, this hybrid system

improves the therapeutic capabilities of interventional vascular procedures in the liver.

Keywords. Magnetic resonance technology - Angiographic technology - MR interventional procedures - Liver tumors

Introduction

Magnetic-resonance-guided interventional procedures have gained major interest with the advent of new minimally invasive interventional techniques. The shift from open to closed procedures, and from extensive to reduced or percutaneous access, is universal and is observed in nearly every field of medicine and for all organ systems.

Open-MR scanners are usually operated at 0.2-1.0 T. Vascular interventional procedures, such as transarterial embolization, percutaneous transluminal angioplasty, or stenting, however, require high spatial resolution and optimized real-time imaging to control the interventional process. Radiological hybrid systems are of great interest in the field of interventional radiology, and some systems have already been established in clinical routine. The majority of hybrid systems thus far in use combine CT and digital subtraction angiography (DSA) units. These settings are most useful for the diagnostic and interventional approach to liver tumors and bony lesions [*1*]. This combination has been extended to other applications, including percutaneous spine biopsy [*2*]. Other hybrid systems thus far installed combine MRI with C-arm fluoroscopy [*3*, *4*].

We present here a new hybrid system, combining high-field MRI and a fully equipped high-end DSA unit in separate rooms, with a newly constructed table for transferring patients between the units. The system can be used both for standard clinical imaging and in interventional procedures with additional advanced functionality. Interventional vascular procedures in the liver were performed in this study, and the results are presented herein.

Materials and methods

In a newly built suite with fully equipped MR and C-arm DSA units, elective interventional hybrid procedures were performed successfully in 30 patients.

The MR imager is a new-generation 1.5-T unit (Magnetom Symphony Quantum, Siemens, Erlangen, Germany) with power gradients and a bore length of 160 cm [gradients 30 mT/m each axis; field of view (FOV) 50 cm). The system is equipped with a standard MR table and an in-room monitor (size: 15 in., shielded TFT display) for in-room control of interventional process as well as in room scanning control. The overall working space for the MR room is 36 m^2 (Fig. 1). The MR system allows the use of all high-field MR capabilities (e.g., contrast-enhanced MR angiography, dynamic imaging, MR fluoroscopy, perfusion imaging) without compromise or limitations. Additionally, the system allows MR fluoroscopy through advanced real-time imaging (up to five images/s) with a true fast imaging with steady precession (FISP) sequence.

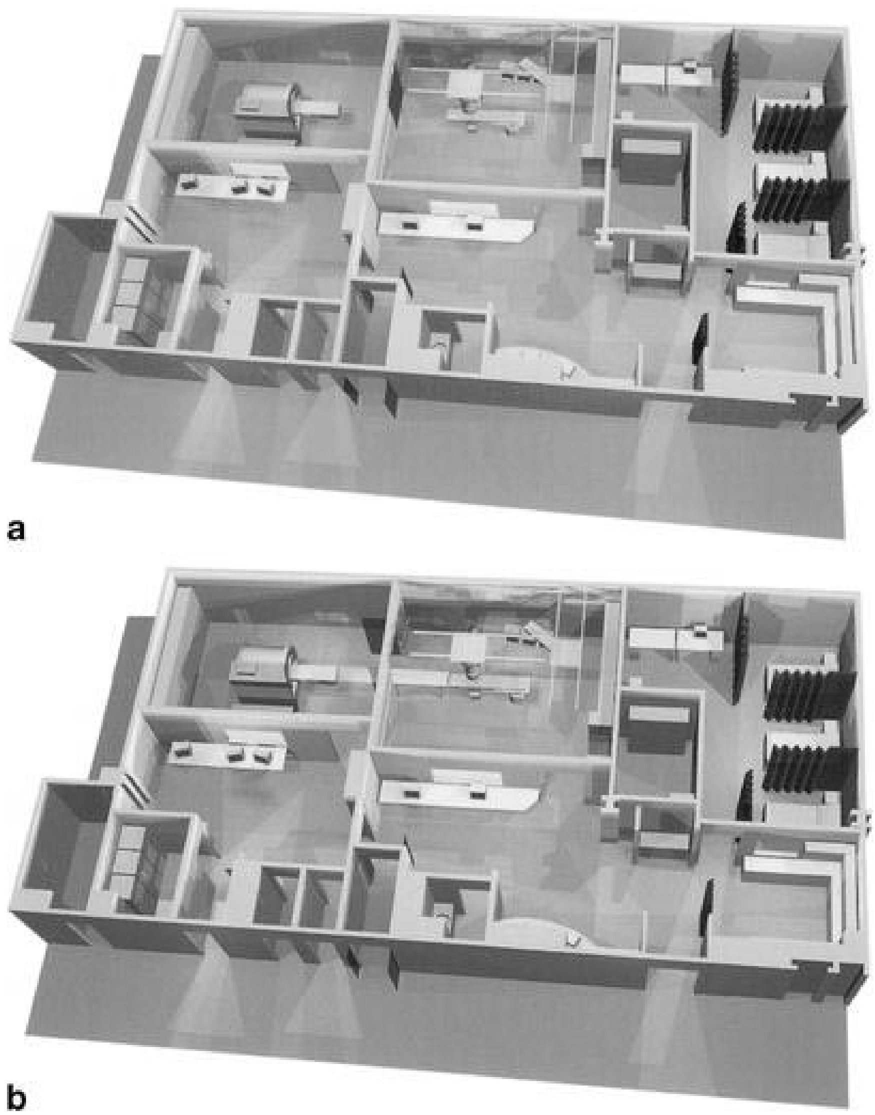

Fig. 1a, b. Combined MR and angiography suite in the interventional center (University Hospital Frankfurt, Germany). **a** Stand-alone use of both modalities. **b** Hybrid use with interactive table

The DSA unit (Multistar Plus, Siemens Erlangen, Germany), installed in a room of 42 m^2, is a commercial system with a double C-arm construction, allowing rotation of the entire C-arm (X-ray tube and image intensifier) at speeds up to 25°/s. The angiographic unit includes special options for rotational angiography, automated digitally subtracted peripheral stepping, and CO_2 angiography. Additional features include techniques for reduction of X-ray exposure, such as pulsed fluoroscopy; graphics-based radiation-free collimation in last-image hold; and automatically inserted spectrum filters to reduce soft skin radiation. The system is equipped with three monitors: one for the examination; the second for roadmap or last-series view; and the third for patient monitoring (Fig. 2).

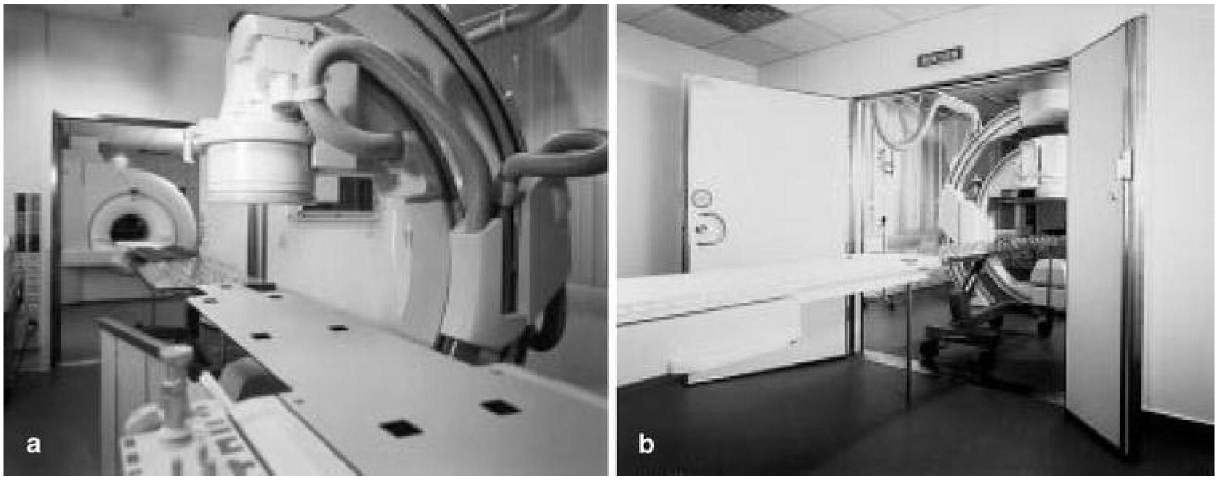

Fig. 2. View from inside the hybrid system **a** toward the MRI unit, or **b** out of the MR suite. A newly developed, mobile connecting table with integrated roller on the table top enables immediate positioning of the patient in either unit within 10 s without the need for transposition

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Between the MR scanner and the angiography unit, a double-wing door was installed, measuring 180 × 200 cm. Actual measurements of magnetic and radio fields showed that the minimum distance

between the MRI unit and the C-arm system should be 6.5 m so as to prevent imaging interference between the two systems during operation. This distance was determined by experimental measurements prior to setup of the hybrid system. The distance between the center of the magnet and the 0.5-mT line is 4 m in z direction and 2.5 m in the x direction. The door was constructed with shielding against the magnetic field on one side, and the X-ray environment on the other side.

A newly developed table with a length of 2.8 m can be positioned between the MR and DSA tables, allowing transfer of the patients on a carbon-fiber tabletop within 10 s.

The MR and angiography units are connected to an image reconstruction and evaluation workstation (Virtuoso, Siemens, Erlangen, Germany), which is used for secondary evaluation of images, image reconstruction, and image fusion. Image fusion is accomplished with software developed by SCR (Siemens Corporate Research, Princeton, N.J.). It enables overlapping of images from both modalities, thus increasing the information yield while enhancing navigation for MR-guided interventions.

Patients

Between May 2000 and November 2001 30 patients underwent MR-guided vascular intervention using the hybrid system. All patients gave written informed consent to the examination and hybrid intervention.

Histologically proven hepatocellular carcinoma (HCC; *n*=7) and colorectal liver metastases (*n*=23) were treated with transarterial chemoembolization (TACE). The average age of the patients was 61.0±9.0 years. The diagnosis had been based on percutaneous liver cutting needle biopsy (*n*=16) or biopsy obtained through laparoscopy (*n*=4) or on imaging follow-up (*n*=10). In 11 patients no clinical or radiological signs of cirrhosis were found. The TACE was performed in the absence of contraindications to the procedure.

In all patients, the aim of TACE was to achieve control of local tumor growth and prolong survival in the framework of a palliative therapy plan. In an interdisciplinary conference, all patients had previously been rejected as candidates for liver resection or transplantation on the basis of local tumor staging or poor general medical condition. Criteria for inclusion in the TACE group included nodal HCC growth as seen in investigative spiral-CT or MRI studies, with absent clinical and radiological evidence of extrahepatic involvement such as lymph node metastases, lung or bone metastases, or peritoneal carcinomatosis. For liver metastases, we included patients with colorectal cancer whose metastatic lesions were five or fewer in number, and 50-90 mm in diameter. Partial or complete thrombosis of the main portal vein was a further exclusion criterion for the procedure. Follow-up studies were performed with plain and contrast-enhanced spiral-CT.

TACE protocol in the hybrid system

The interventional procedure was started in the DSA unit with a transfemoral access and placement of a 5-F sheath (Terumo, Frankfurt, Germany) followed by an intra-arterial survey DSA of the abdominal aorta employing a 5-F Pigtail (Cordis, Haan, Germany). Angiographic evaluation continued with selective intra-arterial DSA of the superior mesenteric artery (SMA) and the celiac trunk as well as common hepatic artery using a 4-F Cobra catheter (Terumo, Frankfurt, Germany). During intra-arterial DSA of the SMA an indirect portography was performed, outlining the portal circulation in the venous phase. The 4-F Cobra catheter was placed in the celiac trunk and advanced beyond the gastroduodenal artery. Depending on the size, location, and the arterial supply of the tumor and its satellites, the tip of the catheter was advanced further into segmental arteries for superselective DSA.

Under angiographic control, an MR-compatible Cobra 4-F (Somatex, Berlin, Germany) was superselectively positioned via guide wire into the tumor-bearing segmental artery. This catheter had no braiding but a radiopaque tip which produced a slight signal void in MRI thus easing tip identification in real-time MR imaging. The patient was then positioned in the MR unit. Twenty milliliters of a Gd-enhanced NaCl solution (concentration 1:20) was manually injected (flow approximately 3 ml/s) via the catheter into the hepatic artery and dynamic MRI was performed using a fast low-angle shot (FLASH) 2D sequence with a 110-ms TR and a 6-ms TE, matrix size 256 $\times$ 256, and flip angle 90°. The acquisition time per sequence was 12.09 s; 12 images were obtained per minute over 5 min. The segment involved was visualized. Catheter position was assumed as optimal if the segmental perfusion during dynamic imaging matched involved liver segments (either right or left liver lobe) to 80% as compared with preinterventional contrast-enhanced MRI.

In 1 patient (Fig. 3) a transbrachial approach was used with the 4-F Cobra catheter. Depending on the results of the dynamic MR images, the catheter was repositioned and the segmental perfusion was re-controlled to allow immediate embolization after transferring the patient to the angiographic suite.

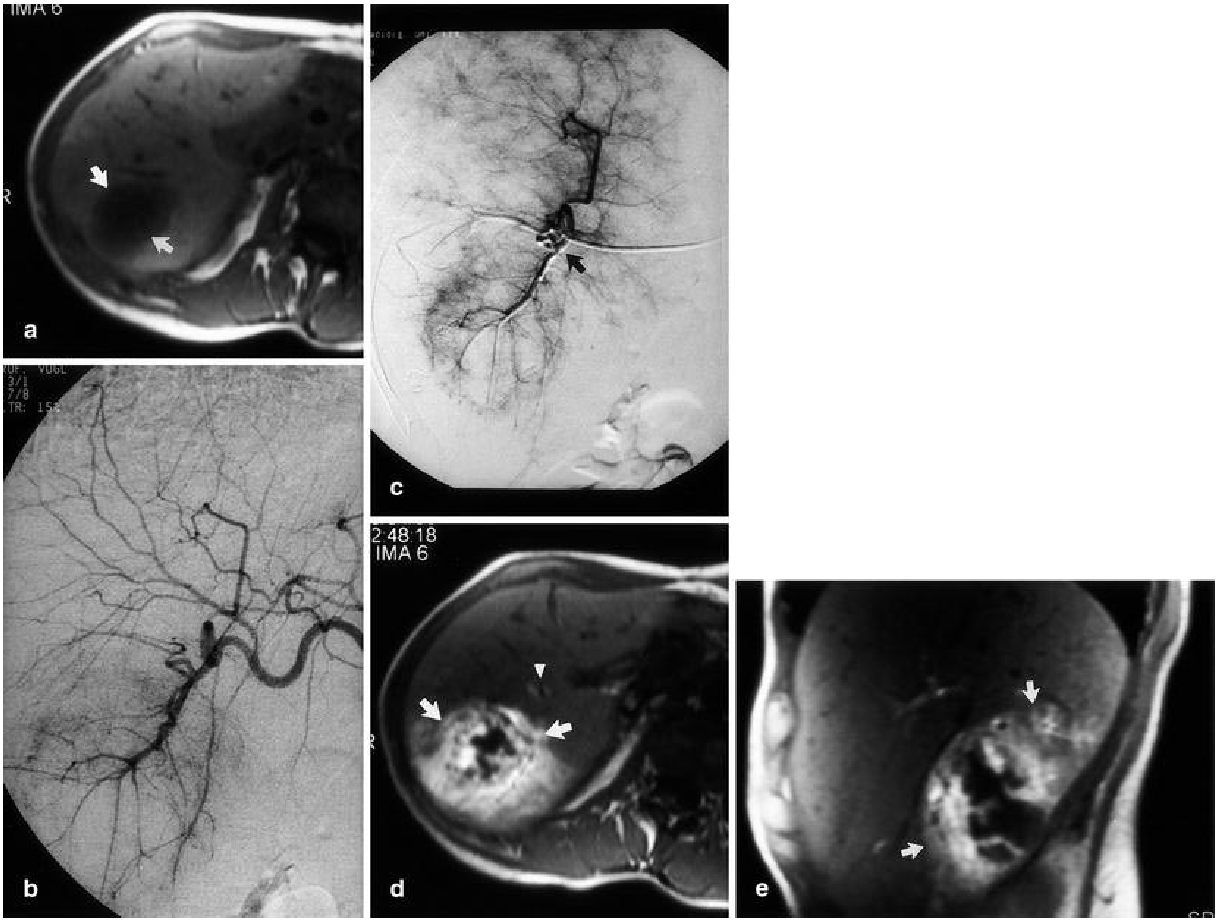

Fig. 3a-d. Hybrid chemoembolization from a transbrachial approach with multinodular metastatic liver infiltration. **a** Gradient-echo-sequence pre-embolization demonstrating multinodular infiltration of the right liver lobe. **b**, **c** Angiographic evaluation reveals an accessory hepatic supply of the right liver lobe via the superior mesenteric artery (**b**). **d** Gradient-echo-sequence, 40 s post intra-arterial injection of contrast medium, reveals the regional perfusion via the positioned catheter

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The embolization suspension consisted of 8-mg/m^2 body surface Mitomycin C, and 10-ml iodised oil (Lipiodol, Guerbet, Sulzbach, Germany), followed by injection of 2- to 10-mg microspheres (Spherex, Pharmacia, Berlin, Germany). After TACE, the reduced tumor perfusion was confirmed by an additional DSA study of the hepatic artery.

Imaging protocol

All patients received a plain and bi-phasic (arterial and venous phase) spiral-CT (Somatom plus 4, Siemens, Erlangen, Germany) examination of the liver prior to and every 3 months after intervention during the first year and twice yearly thereafter as staging and re-staging examination. Additionally, all patients received plain spiral CT of the liver every 24 h after TACE in order to determine the Lipiodol distribution within the liver and the tumor. All patients were additionally imaged with a unenhanced and contrast-enhanced hepatic MRI protocol (MR Symphony Quantum, Siemens, Erlangen, Germany) during intervention in order to more accurately access the segmental distribution of the liver tumors and therapeutic changes.

Results

Preliminary clinical results demonstrate the practical use of this hybrid system in a clinical setting. Transferring the patient from the angiographic suite to the MR unit is achieved in 35 s or less, with a mean value of 25±10 s until the first MR image is obtained. Repositioning of the patient with the carbon-fiber tabletop from the MRI setting to the workspace outside the 5-gauss field for X-ray angiographic procedures is achieved even faster, in a mean time of 14±8 s. The mean value for patient repositioning during intervention was 3±2 times (maximum 6 repositionings, minimum 1 repositioning).

Dynamic MRI using the above-described protocol and intra-arterial contrast injection revealed a rapid and high signal increase in the perfused regions. In the metastases we observed a strong signal increase in the peripheral parts of the lesion and the adjacent liver parenchyma (Fig. 4d). In the central parts of the tumor, no early enhancement was observed, presumably due to necrotic tumor components. In 62% of the lesions, delayed contrast enhancement of the central parts was noted.

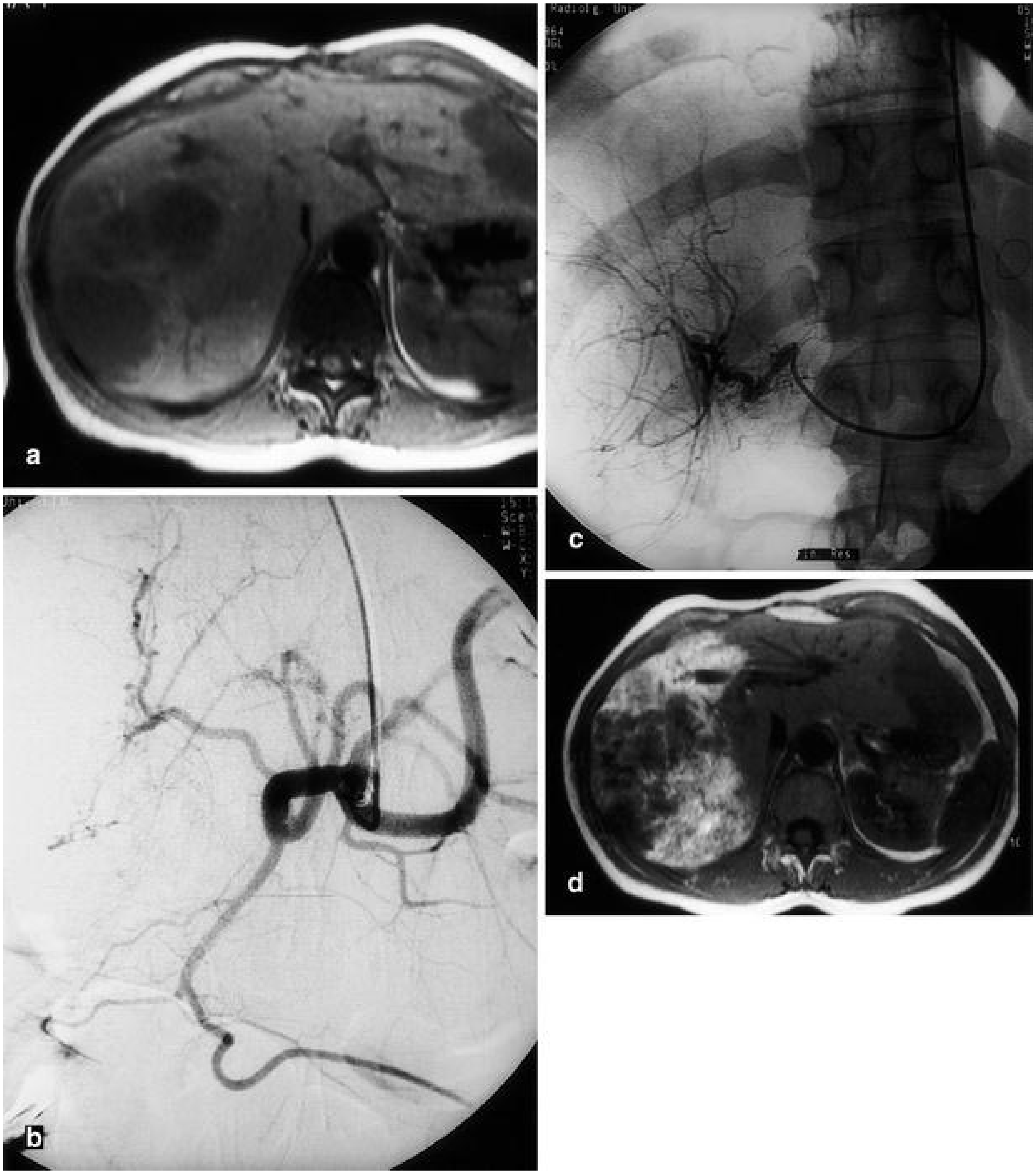

Fig. 4. Hybrid intervention for transarterial chemoembolization of liver metastases. Hybrid procedure for chemoembolization in a patient with an irresectable liver metastasis in segment 7. **a** Gradient-echo-sequence (fast low-angle shot, FLASH; TR/TE=110 ms/6 ms, flip angle 90°). Pre-chemoembolization visualization of the lesion with low signal intensity (*arrows*). **b**, **c** Digital subtraction angiography via 4-F catheter (MR compatible) which is placed in the right hepatic artery. In the parenchymal phase of the angiography a slightly hypervascular metastasis is verified in the right lower portion of the liver in the angiographic survey (**b**). Thereafter, the catheter was superselectively positioned in the periphery (**c**). Note the tip of the catheter (*arrow*). Afterward, the patient is transferred to the MR unit via the connecting table. The localization of the placed catheter is performed with a 2D gradient-echo sequence in sequential slice orientation. **d** The dynamic Gd-DTPA

enhanced T1-weighted FLASH sequence (TR/TE=110 ms/6 ms; *arrows*) reveals an early and marked blush in the vascular bed peripheral to the catheter tip (*arrowhead*), thus proving the optimal positioning of the catheter for the embolization procedure. Enhancement both in the peripheral tumor region and the surrounding liver parenchyma. **e** Dynamic MRI evaluation with hyperintense demarcation of the metastasis in segment 6-7 (*arrows*) in sagittal orientation

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Magnetic resonance monitoring resulted in a repositioning of the catheter tip in 30% of embolization maneuvers, with the embolization being performed under angiographic guidance (Fig. 4). In 15 patients of the metastases group dynamic MR revealed incomplete uptake of the contrast medium in the malignant area, so that parts of the tumor were not perfused via the angiographically positioned catheter (Fig. 4d, e). In 8 patients (15%) we found an insufficient contrast uptake in the peritumoral liver parenchyma, thus allowing no sufficient safety zone for the embolization. In all patients above, the catheter was repositioned under angiographic control, the new position evaluated with MRI, and embolization was successfully performed. In 2 patients the repeated MRI study revealed again the incomplete perfusion of the tumor, so that a second course of embolization with a completely different catheter position had to be carried out 4 weeks later. In both cases major parts of the tumor were fed by branches from the left liver artery and not, as angiographically assumed, by the right liver artery. The second TACE was carried out with catheter position in the branches of the left liver lobe artery.

In 7 patients with hepatocellular carcinoma, involvement of the liver was visualized in the angiographic survey. All 22 lesions were clearly hypervascularized, allowing exact pre-embolization positioning of the catheter tip in 5 patients in a superselective maneuver. An MRI control demonstrated the areas of tumor with a marked and early enhancement during the arterial phase. In 2 patients a repositioning of the catheter had to be performed according to the information obtained from dynamic arterial enhanced MRI.

The image fusion allowed more easily identification of the branching of tumor feeding vessels in 90% of the patients, thus enabling an easier positioning of the catheter for embolization. In all 9 patients with catheter repositioning image fusion also eased the correct identification of the alternate vessel branch for TACE.

Discussion

Interventional radiology demands sophisticated imaging equipment, and yet the needs of interventionalists are not yet satisfied. A present goal is the creation of a multifunctional image-guided therapy room [*3*, *4*]. Combined CT and angiographic suites have been described that help to guide biopsy and drainage procedures, or to perform selective embolization [*1*]. Other hybrid systems consisting of MRI and C-arm fluoroscopy do not provide either real-time imaging or high-resolution DSA [*3*, *4*].

The hybrid system presented here for the first time forms the basis for the performance of interventional vascular procedures using a high-field MR system with power gradients and a fully equipped DSA unit ideally configured for interventional procedures. This system was designed to allow efficient performance of both examinations with minimal repositioning times for the patient, and to perform interventional high-field MR procedures with the backup of an angiographic unit in case of complications; thus, complementary diagnostic and therapeutic procedures can be performed almost simultaneously, saving time and permitting various selective arterial and venous catheterizations. Additionally, both modalities can also be used separately.

Some disadvantages have been encountered with this combined system. Two independent wall outlets for oxygen, pressure, and vacuum may need to be installed in order to allow an independent performance in both suites. Nursing staff and technicians must be trained to be aware of the possible dangers inherent in having access to a high-field MRI system and interventional (X-ray) suites [*4*, *5*].

Magnetic resonance imaging, with its superior soft tissue contrast, multiplanar imaging capabilities, and specific vascular applications, is the ideal method for interventional monitoring or treatment planning [*6*, *7*]. Especially vascular interventions, such as percutaneous transluminal angioplasty, stent implantation, or arterial chemoembolization require high spatial resolution in combination with an optimized real-time imaging [*5*, *18*].

The combination of the high-field MR unit with a fully equipped DSA unit offers an optimal platform for interventional procedures requiring high spatial resolution as well as instant patient access. This setting improves interventional accuracy with maximum safety for the patient. With the design of the presented hybrid system in separate rooms, the systems can be used both as stand-alone units and in the hybrid interventional mode. In the interventional mode both units are connected with a newly developed table, thus allowing a fast patient transfer from one unit to the other.

Special indications are complex interventional maneuvers, where both modalities are almost simultaneously applied. For the performance of MR-guided laser-induced thermotherapy (LITT), temperature-sensitive gradient-echo sequences are used to monitor heat-induced changes in malignant tumors and adjacent normal tissue structures [*8*]. Using vascular occlusion of feeding arteries, the amount of laser-induced necrosis can be further increased [*9*]; thus, the hybrid system is used for the angiographic balloon or drug vascular occlusion followed by MR-guided LITT, with the backup of a fully equipped angiographic suite in case of complications.

In contrast to one-room solutions, such as the combined CT and angiography suite with a pivoting table, which was presented by Capasso et al. [*1*], there are much lower maintenance costs for our system due to the possibility of operating both the MR and angiography units as stand-alone facilities; however, technicians and nursing staff must be trained to perform both examinations, as well as the hybrid procedure [*5*, *10*, *11*, *12*, *13*, *14*].

Our preliminary experience proves that the hybrid system is valuable for complex transarterial chemoembolization maneuvers in patients with hypervascularized liver tumors, such as liver metastases, in order to demonstrate adequate perfusion of the tumor itself and the surrounding liver parenchyma before embolization. The possibility to access the appropriate catheter position during intervention through real-time and dynamic MR imaging eases the procedure and increases the therapeutic accuracy of TACE. The need for catheter repositioning in 30% of the cases in our population demonstrates the need for multiplanar, soft tissue imaging during liver intervention. In combining high-field MR system and a fully equipped interventional vascular angiographic unit as a backup, this hybrid system improves the therapeutic capabilities of interventional vascular procedures in the liver. The possibility to perform image fusion eases the identification of tumor feeding vessels and target vessels.

Further indications for employment of the hybrid system are embolization or local chemotherapy in other organ systems, MR-guided tumor ablation [*15*, *16*, *17*], or peripheral vascular interventions under MRI guidance such as percutaneous transluminal angioplasty (PTA) of the pelvic and thigh arteries as well as stent or stent graft implantation [*18*, *19*]. In these settings the DSA unit serves as a backup modality.

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