

# Open Bore 1.5 Tesla MAGNETOM Espree: Guidance and Monitoring of Radiofrequency Ablation at Liver and Kidney

H. Rempp<sup>1</sup>; S. Clasen<sup>1</sup>; J. Roland<sup>2</sup>; C. Schraml<sup>1</sup>; A. Boss<sup>1</sup>; C. Maier<sup>2</sup>; C. Thomas<sup>1</sup>; P. Martirosian<sup>1</sup>; C.D. Claussen<sup>1</sup>; P.L. Pereira<sup>1</sup>

<sup>1</sup>University Hospital Tübingen, Department of Diagnostic Radiology, Tübingen, Germany

<sup>2</sup>Siemens Medical Solutions, Erlangen, Germany

## Introduction

Liver metastases are a frequent and – with regard to its treatment – complex issue. About 90 % of all hepatic malignancies are metastasis, most of them descending from gastrointestinal tumors, lung cancer and breast cancer [1]. The liver is the most frequent localization for metastases of the colon cancer. The fact that 20 % of patients dying from colon cancer do only have liver metastases shows its prognostic relevance [2-4]. Up to now, surgical resection has been the only curative therapy and is superior to chemotherapeutic treatment, even if chemotherapy is directly applied into the liver through catheters. However, surgical resections on the liver implicate a risk of further morbidity and a mortality rate up to 5 %. Most notably, only 25% of all liver metastases are treatable by surgery, as a predictable incomplete resectability and extrahepatic metastasis are contraindications for surgery. During the last decade, however, various minimally invasive alternative treatment options for non-resectable metastasis have emerged. These include, highly focused ultrasound, laser-induced thermotherapy, microwave, and radiofrequency (RF-) ablation using locally applied heat, aimed at destroying the tumor. Furthermore, these percutaneous thermal therapies may be performed in out-patient care, so patients

can often leave hospital one day after the intervention, so that the procedure is less cost-intensive.

## Radiofrequency ablation

Alternating electric current, moving with a frequency of 375–480 kHz between two electric poles at a tip of a needle, is the heat source for radiofrequency ablation. In the tissue, the heat is produced by the movement of ions under the influence of a focused electric field at the tip of the probe. RF-systems with one pole at the tip of the needle and the other electric pole at a larger grounding pad on the skin, so called monopolar systems, are distinguished from bipolar systems, where both poles are localized on the needle, only separated by a thin isolation zone. Electric conductivity of the tissue is only preserved, if overheating, drying and carbonization are effectively prevented. Most of the systems, therefore, use an internal water cooling circuit. Radiofrequency ablation produces spherically shaped zones of destroyed tissue which correspond histologically to coagulation necrosis. The necrotic zones remain in the liver, forming scarred tissue and contracting gradually. It must be the aim of a radiofrequency therapy not only including the tumor, but also generating a

security zone of necrotic healthy tissue around it. Different strategies have been developed to increase the volume of the ablation zone: Various parallel needles being fixed on a common hand grip, called cluster applicators, achieve larger zones. In addition, extendable needles forming an umbrella-shaped probe configuration have been developed. Another approach was the invention of open perfused systems, which were designed to decrease the tendency of the adjacent tissue to desiccate. In practice, tumors are often larger than the zone that can be produced by a single needle. In this case, various applications have to be performed with the probe being repositioned between the individual application steps. By applying this strategy, several overlapping zones may form a larger, continuous necrotic area including the former tumor and a safety margin at the periphery. It is therefore obvious that imaging has a key function in optimal planning, performing, monitoring and controlling percutaneous radiofrequency ablation.

## Imaging

Before an intervention for a cancer patient is planned, the patient should undergo the best imaging available. A precise clinical staging is necessary to choose an

optimally adapted treatment. If a limited number of organs are affected and the lesions are resectable, surgery may be the best option in numerous cases. In other cases irradiation therapy, systemic chemotherapy, a minimal invasive treatment option as the RF-ablation or a combination of these therapies may be optimal. Radiofrequency can be used to treat solid tumors in the lung, the liver and the kidneys or for symptomatic treatments in bone tumors. Best imaging for the ablation of lung and bone tumors allows computed tomography.

For percutaneous treatment of hepatic and renal tumors, different imaging methods are used in clinical practise.

**Ultrasound** is a cheap, easily available, flexible and fast imaging modality. It

allows the visualization of a high number of tumors and can be used as a real-time modality for the placement of a RF-applicator. However, not all tumors can be detected by ultrasound. Especially small lesions, overlaying bowel structures as well as obese patients give a limit to the visualization of hepatic lesions by ultrasound. Beyond that, small gas bubbles, emerging during radiofrequency ablation with vaporization of water, will impede a satisfactory monitoring.

**Computed tomography** is the standard imaging modality for detailed lung examinations and has become even faster and less radiation intensive with new technologies such as multislice imaging. Nevertheless, the restricted soft tissue contrast may impede a sufficient visualization of

the lesion to be treated. For these reasons, the use of magnetic resonance imaging guidance with low field open-architecture scanners was taken up [5, 6]. For interventions at liver and kidney, **MR imaging offers the major advantages** of multiplanar capabilities, high soft tissue contrast, no requirement of iodinated contrast media, and those without ionizing radiation [8]. Moreover, the effects of thermoablative therapies can be monitored and controlled by using T2 and T1-weighted imaging or at high field scanners by directly applying thermosensitive sequences such as the proton resonance frequency method [7], which allows the display of temperature evolution during the therapy.

**Table 1: MR advantages**

	Ultrasound	Computed Tomography	Magnetic Resonance Imaging
<b>Availability</b>	easily available, cheap	easily available	cost-intensive
<b>Time factor</b>	fast	fast	
<b>Contrast media</b>	not required	iodatet	optional
<b>Visualization of tumor tissue</b>	limited	may be limited to a time window after administration of a contrast agent	<b>high soft-tissue contrast</b>
<b>Limits</b>	<ul style="list-style-type: none"> <li>■ obese patients</li> <li>■ steam bubbles during ablation</li> <li>■ deep localisation of tumor</li> </ul>	allergy to contrast agent	<ul style="list-style-type: none"> <li>■ pacemaker</li> <li>■ metallic implants</li> </ul>
<b>Thermal effects</b>	not visible	not visible	<ul style="list-style-type: none"> <li>■ sensitivity to thermal effects</li> <li>■ monitoring of induced coagulation directly after ablation</li> <li>■ precise overlapping of coagulation zones</li> <li>■ control of end point of coagulation</li> <li>■ prevention of tissue damage</li> </ul>
<b>Additional capabilities mapping</b>			<b>Temperature/Perfusion/Diffusion</b>
<b>Multiplanar capabilities</b>	online imaging available in one plane	online imaging available in one plane	<ul style="list-style-type: none"> <li>■ MR-fluoroscopy</li> <li>■ <b>precise targeting in 3 planes</b></li> <li>■ 3D visualization of tumor and ablation zone</li> </ul>
<b>X-ray exposure</b>	none	<b>X-ray exposure</b>	none

## Different MR systems

The C-shaped configuration of open low-field MR systems, operating typically at a magnetic field strength in the order of 0.2T, offers easier patient access and surveillance for interventional treatment than classic closed-bore high-field MR systems at 1.5T. Applicator positioning can be monitored by almost real-time fast gradient echo sequences [5]. At low field strength,  $T2^*$  decay is lower and susceptibility related artefacts are reduced compared to higher field strength, allowing for a better visualization of the tissue adjacent to the metallic applicator. However, low field MR scanners suffer

from a low signal yield: As the signal-to-noise ratio (SNR) scales with the magnetic field strength, the signal-to-noise ratio at a 0.2T is less than the seventh part of the SNR at 1.5T. In practise, this effect is less pronounced as changes in the T1 and T2 relaxation time partially compensate for the signal loss. Nevertheless, longer acquisition times and more averages must be planned, without reaching the signal yield of 1.5T imaging. For coronal abdominal imaging which must be performed under breathhold condition to decrease breathing artefacts, reaching a satisfactory image quality is especially challenging. Another problem of low field systems is

the decreased T1 relaxation time. For gadolinium based contrast enhanced imaging, the lower T1 contrast must be compensated with a higher dose of the injected gadolinium. Furthermore, at 0.2T, the difference between the resonance frequencies of water and fat is only 30 Hz, preventing the use of spectral fat saturation.

Another disadvantage of C-shaped low-field scanners is the relative temporal and spatial inhomogeneity of the magnetic field which may be a hindrance for the application of thermosensitive sequences. In case of the proton resonance frequency method, a high stability of the magnetic



**1** Siemens MAGNETOM Espree during radiofrequency ablation of a liver metastasis.

field is required to detect small changes of the proton resonance frequency. Therefore, during abdominal interventions reliable temperature measurement is not feasible due to the combination of a low magnetic field strength, high inhomogeneity of the magnetic field and the presence of metallic applicators.

## Interventions at the Open Bore MAGNETOM Espree

With its large bore of 70 cm, the 1.5T magnetic resonance tomograph MAGNETOM Espree facilitates patient access during interventions, performing at the same time faster imaging with a higher signal yield than low field scanners could offer. Instrument placement – e.g. RF-applicator, microwave or cryotherapy probe – and position control can be done fast and almost online by balanced gradient echo sequences (TrueFISP), while the patient can be surveyed during energy application outside or even inside the scanner. Magnetic field stability allows the application of thermosensitive sequences in order to monitor thermoablative intervention.

## Planning

Before the decision for a radiofrequency ablation therapy is made, the patient undergoes a thorough staging examination, which not only provides a basis for a multidisciplinary oncological treatment decision but also for the evaluation of the technical feasibility. This includes parameters like the number of lesions to treat, the tumor size and shape, its vascularisation, the vicinity of delicate structures such as bowel, adrenal gland or gallbladder, as well as the planning for the access of the applicator. Multimodal strategies may be appropriate for large lesions, which may be down-sized by neoadjuvant chemotherapy or in the case of hepatocellular carcinoma, where a pre-interventional transcatheter arterial chemoembolisation offers synergistic effects. Size and shape of the tumor have influence on the RF-device chosen. Although there-

fore in most cases precise pre-interventional abdominal imaging already has been performed, every intervention starts with an integrated standardized planning examination. The selection of an eligible needle track for the applicator is assisted by a grid on the patient's abdomen. After labeling of the puncture site, placement of the biopsy loop coil, disinfection and sterile covering the patient can be placed back into the scanner.

## Peri-interventional imaging

Imaging during an intervention has three main functions: targeting, monitoring and controlling. Targeting corresponds to the placement of the RF applicator into the tumor tissue. Monitoring describes the observation of therapy effects during the thermal ablation therapy. Controlling comprises the intraprocedural tools used to regulate the treatment.

The Siemens MAGNETOM Espree facilitates the interactive placement of the RF applicator into the target tissue. Due to the large bore, the placement of the RF probe can be directly performed under MR imaging. A direct viewing of images and a control of the MR scanner is enabled by MR compatible equipment such as a magnetically shielded liquid crystal monitor, an MR compatible mouse, and foot paddles, which can be placed beside the operator.

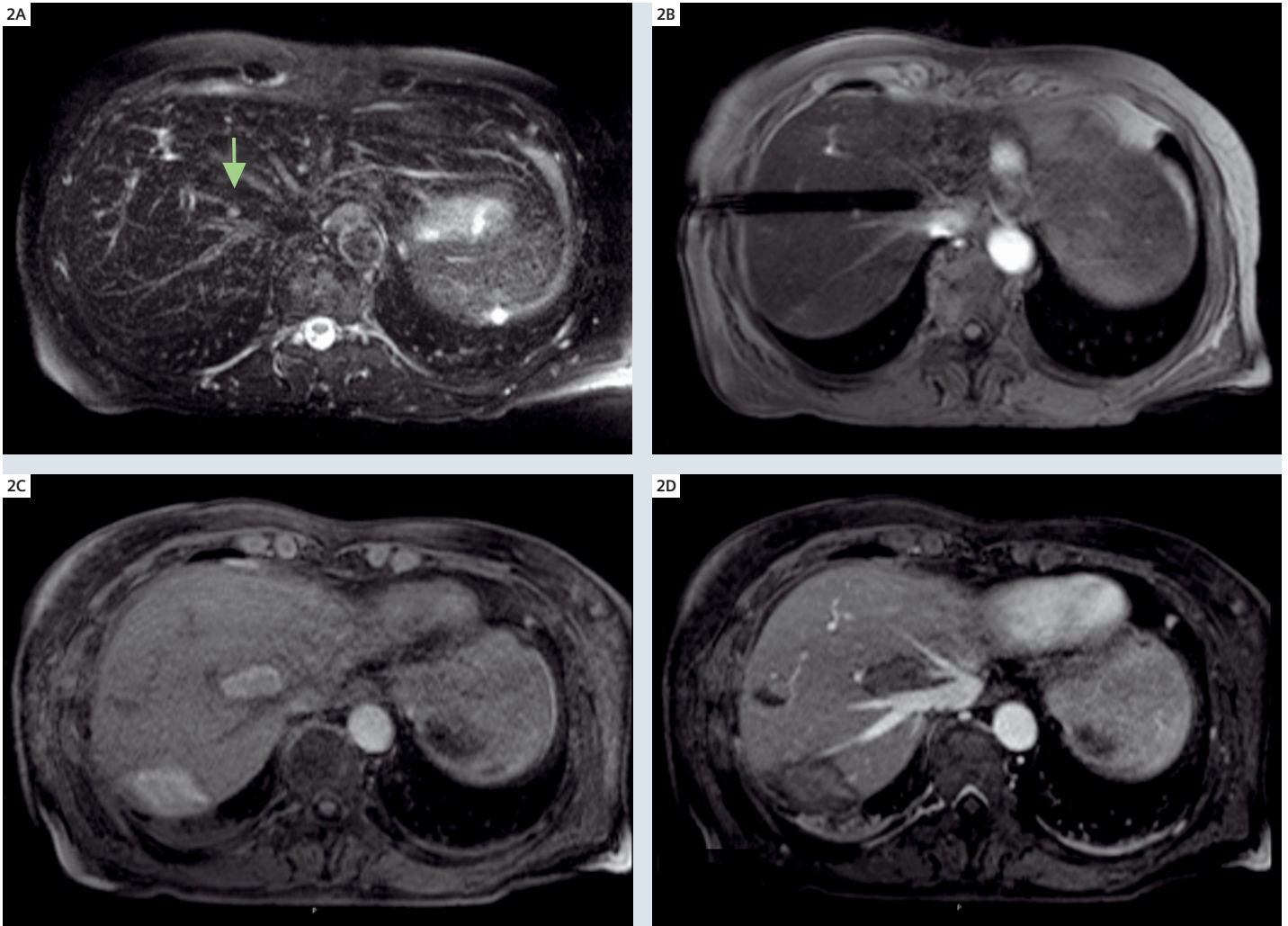
## Targeting

A good visualization of the target tissue, the adjacent anatomic structures and needle tip are preconditions for a safe and effective therapy. MR imaging is capable of delineating delicate structures and tumor tissue without the application of contrast media due to its high soft-tissue contrast. This allows the needle placement without dependence on a short time window after the application of a contrast agent. During the positioning of the probe, two imaging strategies can be used: the position of not moving probes can be controlled by T1-weighted FLASH or T2-weighted HASTE-sequences under

breathhold conditions. For sedated patients, these sequences can be applied with respiration triggering. Moving probes can be monitored by fast steady-state free precession gradient echo sequences (TrueFISP) allowing almost real-time imaging of the needle progress onto the target tissue. Due to the free choice of gradient fields, the plane of MR imaging can always be optimized containing the target tissue and the applicator simultaneously. The Interactive Front End (IFE) software integrates the visualization of three selectable planes onto a single screen [11]. It provides both 2D and 3D display and manipulation of images. The images are sequentially updated within 1–3 seconds with an interactive real time sequence. IFE also enables the operator to dislocate and angulate the selected plane interactively as well as to interactively switch between TrueFISP and FLASH sequences. Additionally acquired images can be recorded and used to recover their scan parameters for future scans. By offering almost real-time spatial information in a condensed way, IFE helps make targeting more smooth and secure, as a time-consuming switching of the image planes is not necessary any more. While intersecting two TrueFISP imaging planes might create artifacts caused by the interferences on the magnetic steady state in areas located in the planes' intersection line, these artifacts can be reduced by an appropriate choice of the image planes and by selecting a repeated imaging of the same plane.

## Monitoring

Depending on the size of the tumor to be treated and the number of applicators, targeting aims to place the applicator centrally into the lesion or, if two or more probes are used, beside it in order to inclose it. The challenge of the ablation therapy is to ensure that the entire tumor and a sufficient safety margin on its edges are thermally destroyed. For larger lesions, a strategy to achieve a complete ablation is to perform overlapping ablation zones



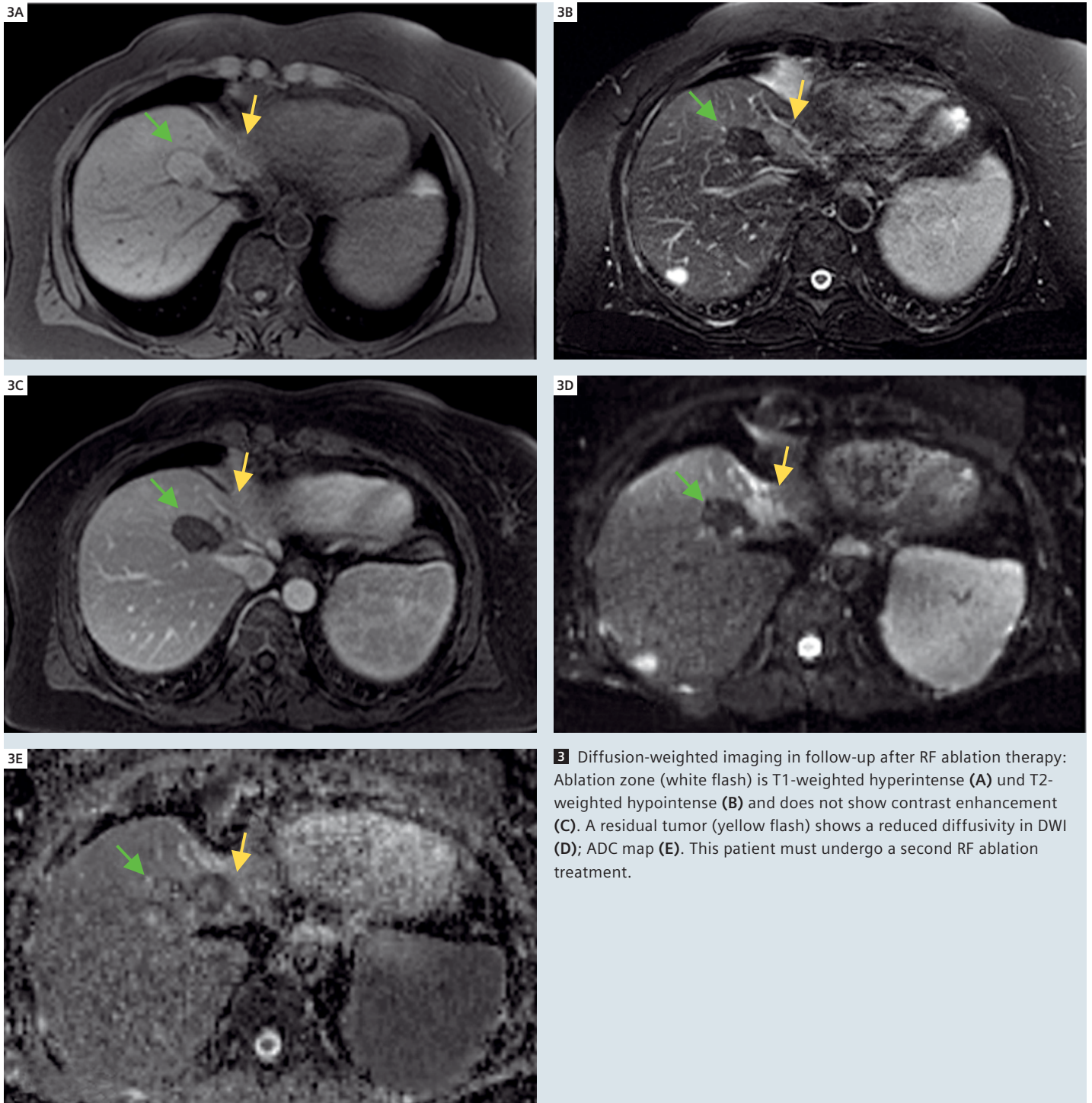
**2** (A): T2-weighted hyperintense liver metastasis of a colon cancer. (B): Placement of the RF applicator (C): Post-interventional T1 hyperintense coagulation zone. Another ablation zone is visible below. (D): Coagulation zone is not perfused with contrast enhanced imaging.

by relocating the applicator after energy deposition. Tissues resistance to heat considerably varies; furthermore, adjacent vessels may lead to an unwanted cooling of the target volume. The unpredictable reaction of the tissue and the sometimes complex geometrical situation between the different applicator positions make a monitoring of the therapy effects indispensable.

Due to its sensitivity to thermal effects, high field MR is superior to other imaging modalities concerning the display of therapy effects during radiofrequency ablation. Necrotic tissue shows reduced water content and can be identified due to its

well-delineated hypointense appearance on T2-weighted images [9]. On T2-weighted images, the ablation zone is characterized by a zonal structure. The former needle track is filled with a proteinaceous, extracellular fluid which appears as a centrally located thin hyperintense line on the T2-weighted images. The T2-weighted hypointense ablation zone is limited at its outer rim by a hyperintense margin which histologically corresponds to a zone of transition between the necrotic area and normal parenchyma. It is characterized by a reactive hemorrhagic reaction, the presence of red blood cells, liver cells in process of degeneration and

an interstitial edema [10]. T2-weighted images are suitable to estimate the size of the necrotic area, as a possible overestimation of the induced coagulation has been shown to be less than 2 mm [10]. STIR and T1-weighted images tend to underestimate the induced coagulation, which appear as a hyperintense zone on them, whereas T1-weighted contrast enhanced images, which show a non-enhancement, lead to a slight overestimation (up to 4 mm) [12]. Gadolinium enhanced images, however, cannot be repeated randomly as the contrast media has to be cleared from organism first. The contrast between the tumor and the

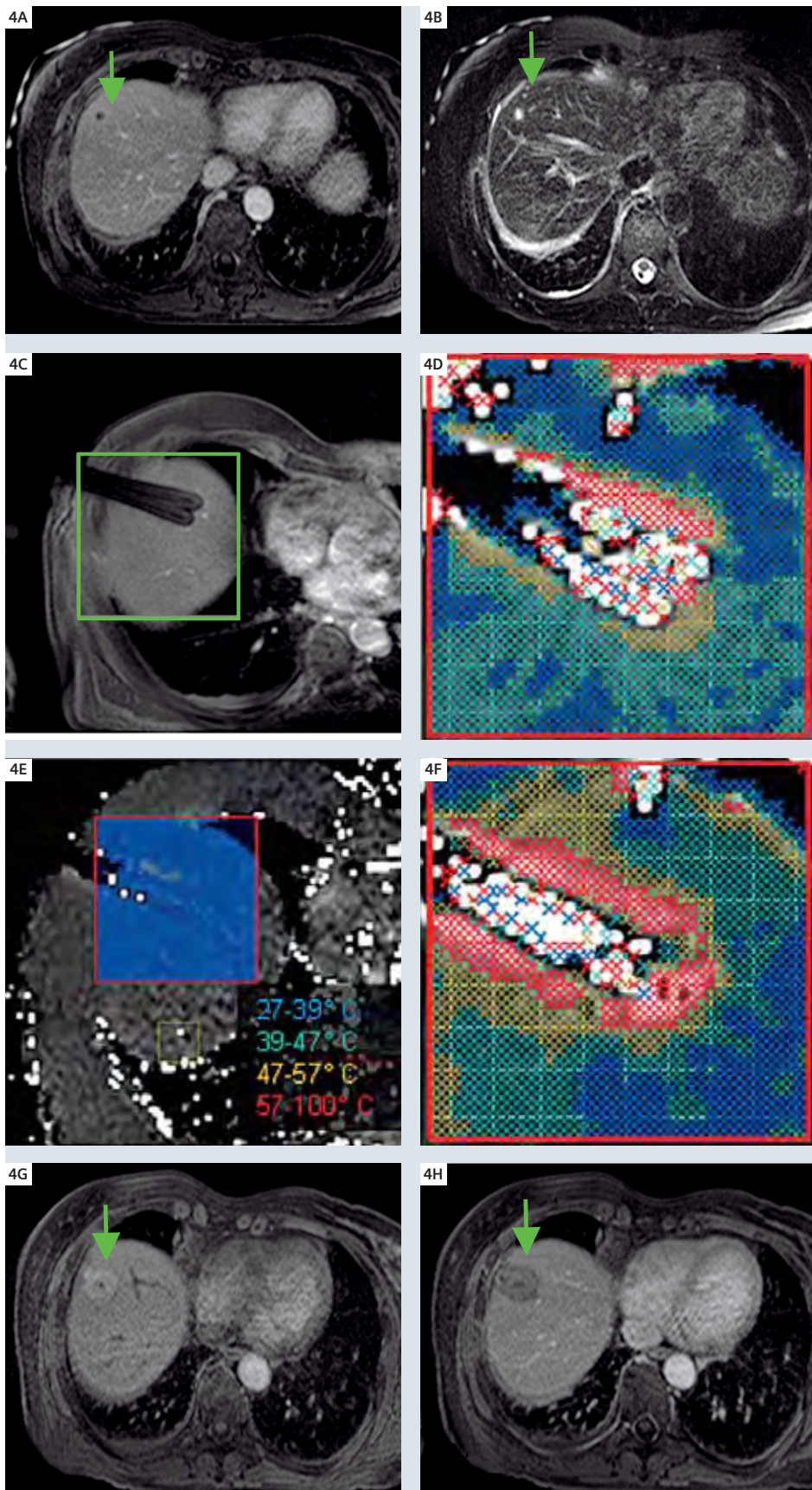


coagulated area is optimal in T2-weighted and STIR images, which are therefore useful to detect residual tumor areas after RF ablation. In conclusion, T2-weighted images are most useful for characterizing the necrotic area and for detecting possibly remaining tumor areas (Fig. 2).

### Controlling

Beside the different T1 or T2-weighted images, other options to control energy application do exist. The generators used for the energy deposition may offer the possibility to check temperature and impedance. Temperature is typically mea-

sured by a thermometer placed at the tip of the needle. An estimation of the induced coagulation can be established based on the information about temperature persisting over a certain period of time at the centre of the zone. Impedance measurements rely on the fact that



the water content in the target tissue decreases in the course of radiofrequency ablation. Lower water content scales with higher electric resistance. The impedance information given by commercially available RF systems can thus be used to evaluate the progress in coagulation [13]. However, monitoring size and shape of the coagulated zone is only feasible by imaging.

Magnetic resonance imaging offers more than the mere spatial information about the coagulated zone. With high field scanners, thermometric and functional imaging become feasible and clinically applicable. In delicate situations, these sequences may allow the use of radiofrequency ablation without taking risks.

### Diffusion-weighted imaging

Due to recent technical developments, diffusion-weighted imaging (DWI) of the abdomen has become possible in clinical routine. In DWI, image contrast is determined by the thermally induced motion of water molecules, called Brownian motion. This random motion in applied field gradients leads to incoherent phase shifts resulting in signal attenuation [14]. Thus, DWI allows for characterization of biological tissue on the basis of its water diffusion properties determined by the microstructural organization, cell density and viability of the studied tissue [15]. Therefore, DWI may be useful in the detection of thermally-induced tissue necrosis and offer valuable diagnostic possibilities both in controlling and in the follow-up imaging of RF ablation (Fig. 3).

**4A-4C** Metastasis in upper part of the liver with T1-weighted hypointense and T2-weighted hyperintense signal (white flash).

**4D-4F** Multipolar applicator placement and thermometry reference image with proton resonance frequency shift method. Enlarged: Temperature development during RF ablation.

**4G, 4H** Coagulation zone after treatment (white flash).

## MR-temperature mapping

MR temperature monitoring with modern MR scanners benefits from the opportunity of combining online anatomical and temperature information in one image, thus allowing for the protection of tissue nearby the heated area which is in danger of heat necrosis, such as the heart or the intestine. Several physical properties that can be measured by MR can be used to perform a temperature measurement by applying different techniques. 2D or 3D temperature maps can be derived from measuring the thermal diffusivity, performing single voxel spectroscopy, using temperature sensitive contrast agents, and measuring the spin-lattice relaxation time T1 or the proton resonance frequency shift (PRF). The PRF method is currently the most commonly used temperature sensitive MR technique [16]. It has been demonstrated to be tissue independent [17] for all water protons. The method is based on a change of proton's Larmor frequency which scales with a temperature change. This variance is attributed to a changing shielding of the electrons in water molecules due to the changes in the strength and length of the hydrogen oxygen bond. Temperature changes can be calculated by subtracting phase images acquired before and after a temperature change. Temperature mapping is susceptible to artifacts due to the low order of the temperature coefficient (10–8/°C) and interfering factors such as body movement, respiration, and metallic applicators. Fast sequences – using parallel imaging or EPI-techniques – and trigger schemes have been established to overcome the motion artefacts (Fig. 4).

## Arterial Spin Labeling (ASL) for renal perfusion study

RF ablation is also a convenient therapy option in case of malignancies of the kidneys, such as renal cell carcinomas. The MR-guided intervention may for instance be useful in the case of older patients with comorbidities not allowing for a surgical treatment. As the kidneys are highly per-

fused and the differentiation between residual tumor and liquid deposits or a minor hemorrhage after ablation is difficult, additional monitoring and controlling may be useful. As contrast-enhanced T1-weighted perfusion imaging may be performed only once during treatment because the contrast-medium requires several hours for clearance from the blood stream, spin-labeling perfusion imaging may be an alternative for perfusion assessment of the tumor and the coagulation necrosis. In the spin labeling technique, blood water is used as an endogenous tracer allowing for arbitrary repetitions of perfusion assessment. Spin labeling perfusion imaging is performed using a FAIR-TrueFISP technique [18, 19]. This technique works with magnitude images recorded after slice selective or global inversion, respectively. An adiabatic inversion RF FOCI (frequency offset corrected inversion) pulse is used for slice-selective inversion. Perfusion images are generated by subtraction of the images with selective and global inversion.

One of the greatest advantages of RF ablation compared to surgical resection is that it can be performed in several ablation cycles until completeness of tumor coagulation is achieved, which can be visualized by a non-perfused zone. Therefore, the spin labeling technique seems most favorable as monitoring modality. In addition to spin-labeling perfusion imaging, 3D spoiled gradient echo sequences in good image quality may be acquired during one breathhold allowing for the implementation of a MR urography protocol for depiction of the ureter. In RF ablation of renal cell carcinoma, the ureter is especially in danger in case of treatment of a lesion at the lower pole of the kidney, which typically has a close anatomical relationship to the ureter.

## Post-interventional imaging

The response of the ablation therapy must be assessed by post-interventional imaging and is a compulsory part of the oncological aftercare, which normally

also comprises regular extrahepatic imaging, clinical examinations and laboratory tests, depending on the primary tumor. Both, excellent contrast between possible residual tumor areas and the coagulated zone and the best comparability to the prior interventional images make MR a good choice in oncological aftercare imaging. Residual tumors and new metastasis appearing in a formerly healthy part of the liver can be assessed by a second radiofrequency ablation therapy, if a multi-disciplinary team indicates the therapy.

## Clinical results

Reports in literature about the clinical application of percutaneous RF-ablation under MR-guidance are much fewer in number than reports about the treatment under ultrasound or CT-guidance. The feasibility of RF-ablations under MR-guidance have been demonstrated and can be performed by low-field open-architecture MR-systems as well as with closed-bore MR systems operating at 1.5T [21]. The low number of publications and the still limited follow-up period make a comparison of different image modalities guiding the RF therapy difficult. Furthermore, it has to be considered that patient selection will not be consistent as the repartition of imaging capacities and patient's complexity will differ with the size of the performing medical centre. The clinical experience in the application of MR-guided RF-ablation is summarized in Table 1.

Table 1: Clinical experience

Author	Year	Patients (n)	Sessions (n)	Magnetic field strength	Tumors (n) (HCC/Met.)	Tumor size (cm)	Follow-up (months)	Major complications	Complete coagulation
Lewin	1998	NA	NA	0.2T	6 (0/6)	NA	NA	0	NA
Kelekis	2003	4	6	0.23T	8 (3/5)	2.0 (1.2-2.4)	4.4 (1-9)	0	7/8 (88 %)
Huppert	2000	11	22	0.2T	16 (2/14)	2.3 (1.3-3.0)	11.8 (3-18)	0	14/16 (87 %)
Kettenbach	2003	26	33	0.2T	48 (15/33)	2.9 (0.6-8.6)	NA (1-2)	4/26 (15 %)	18/35 (51%)
Aschoff	2000	8	NA	0.2T	19 (0/19)	NA	NA	NA	NA
Mahnken	2004	10	10	1.5T	14 (1/13)	3.3 (2.0-4.7)	12.2 (1-18)	NA	13/14 (93 %)
Gaffke	2006	8	9	1.5T	12 (0/12)	2.4 (1.0-3.2)	7 (4-9)	0	12/12(100 %)

## Conclusion

MR-guided radiofrequency ablation is a safe and effective minimally invasive therapy in the treatment of primary and secondary malignancies of the liver as well as renal cell carcinoma. Multiplanar imaging, a high soft-tissue contrast and the possibility of fluoroscopy facilitate targeting and monitoring. Open-bored high field scanners like the 1.5T Siemens MAGNETOM Espree combine the advantages of interventional low field scanners such as good patient access with fast and high-contrast imaging available only at high field scanners. Interactive capabilities and special software and hardware equipment like a shielded monitor and condensed image representation with the IFE tool help the operator. Therapy controlling may be simplified with special imaging sequences allowing for instance real-time temperature measurement. Consequently, larger tumors necessitating precise repositioning of the applicator and controlling of overlapping ablation zones can be approached, while faster and due to the better imaging safer treatments may increase clinical results and therefore interdisciplinary acceptance.

## References

- Abrams HL, Spiro R, Goldstein N: Metastases in carcinoma. *Cancer* 3 (1950) 74–85.
- Jaffe BM, Donegan WL, Watson F et al.: Factors influencing survival in patients with untreated hepatic metastases. *Surg Gynecol Obstet* 127 (1968) 1–11.
- Goslin R, Steele G, Zamcheck N et al.: Factors influencing survival in patients with hepatic metastases from adenocarcinoma of the colon and rectum. *Dis Colon Rectum* 25 (1982) 749–754.
- Stelle G, Ravikumar TS: Resection of hepatic metastases from colorectal cancer: biologic perspective. *Ann surg* 210 (1989) 127–138.
- Lewin JS, Connell CF, Duerk JL, et al. Interactive MRI-guided radiofrequency interstitial thermal ablation of abdominal tumors : clinical trial for evaluation of safety and feasibility. *J Magn Reson Imaging* 1998;8(1): 40–7.
- Kettenbach J, Kostler W, Rucklinger E, et al. Percutaneous saline-enhanced radiofrequency ablation of unresectable hepatic tumors: initial experience in 26 patients. *AJR Am J Roentgenol* 2003;180(6): 1537–45.
- Ishihara Y, Calderon A, Watanabe H, A precise and fast temperature mapping using water proton chemical shift. *Magn Reson Med*. 1995 Dec; 34(6):814-23.
- Mahnken AH, Bueker A, Spuentrup E, et al. MR-guided radiofrequency ablation of hepatic malignancies at 1.5 T: initial results. *J Magn Reson Imaging* 2004; 19(3): 342–8.
- Graham SJ, Bronskill MJ, Henkelman RM. Time and temperature dependence of MR parameters during thermal coagulation of ex vivo rabbit muscle. *Magn Reson Med* 1998;39(2):198–203.
- Lazebnik RS, Breen MS, Lewin JS, Wilson DL. Automatic model-based evaluation of magnetic resonance-guided radio frequency ablation lesions with histological correlation. *J Magn Reson Imaging* 2004; 19(2):245–54.
- Lorenz CH et al. Proc. ISMRM w.
- Merkle EM, Boll DT, Boaz T, et al. MRI-guided radiofrequency thermal ablation of implanted VX2 liver tumors in a rabbit model: demonstration of feasibility at 0.2 T. *Magn Reson Med* 1999; 42(1): 141–9.
- Pereira PL, Trübenbach J, Schenk M, et al. Radiofrequency ablation: in vivo comparison of four commercially available devices in pig livers. *Radiology* 2004; 232(2): 482–90.
- Colagrande S, Carbone SF, Carusi LM, Cova M, Villari N. Magnetic resonance diffusion-weighted imaging: extraneurological applications. *Radiol Med (Torino)* 2006; 111:392–419.
- Naganawa S, Kawai H, Fukatsu H, et al. Diffusion-weighted imaging of the liver: technical challenges and prospects for the future. *Magn Reson Med Sci* 2005; 4:175–186.
- Hindman JC. Proton resonance shift of water in the gas and liquid state. *J Chem Phys* 1966; 44:4582–4592.
- Cline HE, Hynynen K, Schneider E, et al. Simultaneous magnetic resonance phase and magnitude temperature maps in muscle. *Magn Reson Med*. 1996 Mar;35(3):309–15.
- Quesson B, de Zwart JA, Moonen CT. Magnetic resonance temperature imaging for guidance of thermotherapy. *J Magn Reson Imaging*. 2000 Oct;12(4):525–33.
- Martirosian P, Klose U, Mader I, Schick F. FAIR True-FISP perfusion imaging of the kidneys. *Magn Reson Med*. 2004;51:353–361.
- Boss A, Martirosian P, Schraml C, Clasen S, Fenchel M, Anastasiadis A, Claussen CD, Pereira PL, Schick F. Morphological, contrast-enhanced and spin labeling perfusion imaging for monitoring of relapse after RF ablation of renal cell carcinomas. *Eur Radiol*. 2006; 27:1–11.
- Clasen S. et al. *Eur J Radiology*. Magnetic resonance imaging for hepatic radiofrequency ablation. 2006; 140–148.
- Clasen S, Boss A, Schmidt D, Schraml C, Fritz J, Schick F, Claussen CD, Pereira PL. MR-guided radiofrequency ablation in a 0.2-T open MR system: Technical success and technique effectiveness in 100 liver tumors. *J Magn Reson Imaging*. 2007 Sep 25;26(4):1043–1052.