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REVIEW ARTICLE

Interventional Magnetic Resonance: Realistic Prospect or Wishful Thinking?

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Interventional radiology started long after Roentgen's discovery of X-rays, the centennial of which was celebrated in 1995. Historically, invasive image-guided procedures started with percutaneous biopsies and angiography early this century, followed by computed tomography (CT)- and ultrasound-guided interventions in the 1970s and magnetic resonance (MR)-guided biopsy in the 1980s [1]. Interventional radiology has expanded substantially since then and imaging technology has become increasingly sophisticated.

X-ray fluoroscopy has provided something very important, i.e. real-time imaging, as has ultrasound, and it is hoped that CT and MR fluoroscopy will do so in the future. All the various diagnostic and therapeutic options currently offered by interventional radiology routinely are supervised and guided by either X-ray fluoroscopy, ultrasound, or CT. The complexity of interventional radiology has constantly increased, and it is possible to tackle even the most difficult interventions. This raises the questions whether MR will be of help for those complex procedures, and whether there is a real need for MR-guided interventions. In order to hint at the answers, which are not known yet, the potential advantages, limitations, and possible applications of interventional MR will be discussed.

Interventional Radiology: Potential Advantages of MRI

The most important consideration that motivates us to look for improvements is the radiation burden associated with X-ray examinations. If the interventions are time-consuming, the resulting radiation exposure may be unacceptably high, for both the patient and the physician. Curiosity regarding a technology that offers such a wide spectrum of imaging possibilities without ionizing irradiation makes MR imaging (MRI) attractive for interventions as well.

The lack of radiation alone might cause the following hypothesis to become a reality: In principle, every type of intervention may in the future be performed by MR guidance. But there are further potential advantages to the technique of MR that are not easily, if at all, matched by any other imaging modality:

—There is high intrinsic tissue contrast including possible visualization of vessel walls and their surroundings.
—Vessels and parenchymal organs may be visualized without application of contrast medium, although contrast medium may be advantageous.
—Multiplanar imaging provides transverse, longitudinal, and oblique orientations, facilitating interventions and anatomic-topographic orientation.
—Physiologic information can be obtained such as flow quantification, diffusion, and perfusion.
—Temperature sensitivity allows at least semiquantitative assessment of temperature changes.
—There is two- and three-dimensional imaging capability.

Thus, apart from imaging, characterization, and localization of lesions, there is also a potential for the guidance and monitoring of interventions.

Interventional Radiology: Current Limitations of MRI

Hardware and Patient Access

When considering the hardware of MR, current limitations of MR-guided interventions should be mentioned. MRI systems suitable for interventional purposes may be classified into [2]: dedicated open systems; open or closed standard imaging systems; high-, mid- or low-field systems; and hybrid units of MRI combined with X-ray fluoroscopy.

The double-doughnut GE system was the first dedicated interventional MR scanner [3]. It is a 0.5 Tesla (T) vertically open system and offers relatively free access to the patient and to the operational field. Standard open systems at 0.064 T (Toshiba), 0.2 T (Siemens), 0.3 T (Hitachi) and 0.35 T (Toshiba) (also superconducting cryogenless) are available currently. A 360 open mid-field system has been announced

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by FONAR. There is as yet no 1.5 T open magnet. Standard high-field systems have restricted access, but have all the advantages of rapid imaging and functional imaging. As a rule of thumb:

1. The lower the field strength, the longer the acquisition time required to achieve sufficient image quality.
2. Susceptibility artifacts, as created by biopsy needles, are less pronounced at low field strength.

Consequently, one has to weigh the free access of open systems against the higher temporal and spatial resolution provided by high-field scanners.

Software and Imaging Speed

Simultaneous high spatial and temporal resolution is difficult to achieve. The consequence is that the pulse sequences must be tailored to the examination. If high image quality is needed, conventional spin-echo technique with image acquisition times in the range of minutes provides superior anatomic information. If high temporal resolution is required, usually gradient echo techniques are chosen, often at the cost of contrast and spatial resolution. With fast gradient echo techniques, acquisition time is in the range of a few seconds or, with echoplanar imaging, in the subsecond range. The development of pulse sequences is a growing field, leading closer to the final goal of high-resolution real-time imaging. As a result of these efforts subsecond high-resolution T2-weighted spin-echo images are achievable [4]. Complex techniques for MR fluoroscopy have been developed applying different strategies of *k*-space sampling [5–7], discussion of which is beyond the scope of this review. But in general, acquisition of high-quality MR images is time-consuming, while short acquisition times yield a poor image quality in terms of contrast as well as spatial resolution. The ideal combination of high temporal and high spatial resolution has yet to be achieved.

MR-Compatible Instruments and Artifacts

The interventionalist of today is accustomed to facts in imaging procedures and is repelled by artifacts. Metallic artifacts on CT may lead to considerable image distortion. This problem is even more crucial for MRI, and even if one uses non-ferromagnetic, so-called MR-compatible instruments, artifacts may still be present and may considerably impair the ability for precise localization of a lesion [8]. MR compatibility requires a completely new generation of devices that may be visualized actively or passively. Ferromagnetic instruments cannot be used because of severe image distortion and possible deflection of the device. Passive visualization of non-ferromagnetic devices takes advantage of signal void effects and susceptibility artifacts induced either by the instrument itself or by markers affixed to the device. The artifact created can be used for depiction and localization of the device. In contrast to other imaging modalities, however, even visualization of a needle may be difficult and complex [9]. It is possible for a 0.7-mm fine needle to display an artifact up to 8 mm in diameter, or for it to become invisible through changing the sequence or the angle to B_0 (static magnetic field) [10]. Needle artifacts are dependent on the material of the needle, the orientation of the needle relative to the magnetic field B_0, the pulse sequence and sequence parameters, the phase-encoding direction, and the magnetic field strength. Without going into all the details, some basics have to be known by any radiologist who wants to perform interventions under MR guidance. Susceptibility artifacts of any metallic object are larger at high field strength [11]. Gradient echo techniques produce larger susceptibility artifacts than spin-echo or turbo-spin-echo sequences [10]. The longer the echo time (TE) the larger the artifact. Orientation of the needle along B_0 will yield the smallest artifact and might even cause the device to be undetectable.

The more sophisticated active tracking technique exploits the positional information gathered from a miniature coil in the tip of the device [12]. This position is projected onto the MR image enabling real-time control of the instrument. Optical-based external referencing systems have also been described to localize and project the position of a needle tip onto the MR image [13]. Both methods require additional hardware and software components.

Projectional Versus Cross-Sectional Imaging

Cross-sectional imaging is not necessarily an ideal technique for interventions. Conventional radiography and X-ray fluoroscopy as projection techniques permit an overview of a complete anatomic region at a glance, even though obscured by overlying structures. They also allow instantaneous visualization of complete instruments at the same time. In contrast, cross-sectional modalities offer a stack of multiple slices, which require several glances before the situation can be completely understood. Currently, MRI does not provide a coherent and complete survey showing instruments and the rest of the body. MR fluoroscopy together with real-time image reconstruction will certainly help to eliminate that problem in the future, but there is still a long way to go before it will reach clinical reality.

Economic Implications

In today's cost-conscious environment it is imperative to determine the efficacy and efficiency of a method. No other diagnostic technique offers more promise in providing both morphologic and functional parameters than MR. However, it is certainly premature to speculate on the effectiveness of interventional MR. We are still studying the feasibility of this technique in a clinical and experimental setting. The cost of the imaging system is still greater than that of a sonographic or CT scanner. The actual cost of an MRI study in Germany usually exceeds euro 500. The cost for low- and mid-field units is less than euro 750,000; high-field systems are more expensive (approx. euro 1.5m). Other fixed and variable costs are beyond the scope of this paper but have to be taken into account when cost-effectiveness is debated [14].

Siting is also quite costly. The interventional MR suite should fulfill the same requirements as other interventional rooms, with free access to the patient from all sides and with adequate space around the patient. The magnet with the most convenient access—the double-doughnut system—is also the most expensive, in addition to the cost of installation and environment. Full access to anesthesia, life-support, and monitoring should be feasible. All equipment should be MR-compatible. One limitation is distortion of the electrocardiogram, which precludes application in patients with ischemic heart disease. In financial terms it appears that the acquisition of an MRI unit exclusively for radiologic interventions cannot be justified in most instances. Most MR systems, therefore, will have to be used for both routine imaging and interventions. And even under these circumstances the question will have to be answered of whether the benefit of the procedure justifies the expense [15].

Interventional MR: Applications

Free access, real-time imaging and facts instead of artifacts are what is needed in terms of the prerequisites for interventional MR. None of these requirements is perfectly met. On the other hand, every interventional radiologist is at this time broadly satisfied with his accomplishments based on standard equipment: hardly anyone wants to go back to the early days of interventional radiology. This is why currently clinical applications of MR are limited to nonvascular interventions including biopsy, preoperative marking, drainages, interstitial therapy, neurolysis, and neurosurgical interventions.

Percutaneous Biopsies

Percutaneous biopsy is usually easy with most imaging modalities if the lesion is clearly visible and readily accessible. Due to the high tissue contrast of MR there are a small number of lesions that are not detectable with other imaging modalities, the female breast being the prime example. As shown by the large number of papers already published on this topic, MRI guidance for breast biopsies and preoperative marking of female breast lesions that are occult on modalities other than MRI, is rapidly becoming an important clinical tool (Fig. 1) [16–20]. The results of successful localization as reported in the literature are very satisfying. In general, the indications for MR-guided biopsies encompass low lesion conspicuity on other imaging modalities (Fig. 1), complex topographic anatomy, and difficult needle trajectory (Fig. 2). Besides the female breast there are several sites where MR-guided biopsy has been performed: liver [21, 22], bone [23] and soft tissue [21, 24], adrenal glands [25], and head and neck [26].

Therapeutic Nonvascular Interventions

The first drainage of abdominal abscess procedures have been performed in patients [27, 28]. Furthermore the feasibility of percutaneous cholecystostomy [29] and nephrostomy [30] has been demonstrated experimentally in vivo. Visualization of the drainage catheter has been described as the most challenging part of these procedures [27]. This problem can be overcome by the marking of catheters, for example with dysprosium rings. Like gadolinium, dysprosium is a lanthanide, which creates a limited susceptibility artifact when the catheter is doped in confined areas.

Interstitial thermotherapy monitored by different imaging modalities was initiated for the treatment of primary and secondary liver tumors as well as for head and neck tumors. The techniques used for that purpose include laser ablation, radiofrequency ablation, cryoablation, ethanol injection, and focused ultrasound ablation. Lesions that have been treated so far are those in the brain, female breast, head and neck, liver, and prostate. Liver metastases—particularly from colorectal cancer—are a preferred target for interstitial thermotherapy. Laser [31] and radiofrequency ablation [32] are the most frequently applied techniques. For obvious technical reasons radiofrequency ablation is not suitable for real-time MR monitoring. There are some limitations to MR guidance of interstitial thermotherapy: precision of tumor destruction requires improved visualization of temperature changes. Thermosensitive pulse sequences based on fast T1-weighted protocols are useful for monitoring thermal changes in tissue [33]. There is a characteristic loss of signal intensity during laser therapy reflecting the extent of coagulation necrosis. But the contrast can be relatively poor between the lesion and the signal drop due to temperature elevation. Semiquantitative methods exploiting diffusion [34] or proton resonance frequency shift [35] are more sensitive to temperature changes but are prone to movement artifacts. While the latter method holds promise for the brain [36], in areas subject to respiration the evaluation of the spread of heat may be considerably impaired. In addition, the exact predictability of the extent of the resulting necrosis is difficult. Within the range 37–50°C, the relaxation time T1 varies approximately linearly with temperature changes at a rate of 1% per 1°C. However, when tissue is heated above 50°C, the T1 dependence on temperature varies in different tissue types and deviates from linear behavior due to physiological structural and metabolic changes in the tissue during thermal therapy [37, 38]. In our experience, real-time MR is not yet accurate enough for monitoring of interstitial thermotherapy of the abdomen. Furthermore, the size of the tumor is critical. In tumors larger than 2 cm in diameter it is difficult to induce 100% necrosis with a single probe. The extent of necrosis can be enhanced with multiple probes, including lesions up to 5 cm in diameter. In addition, more

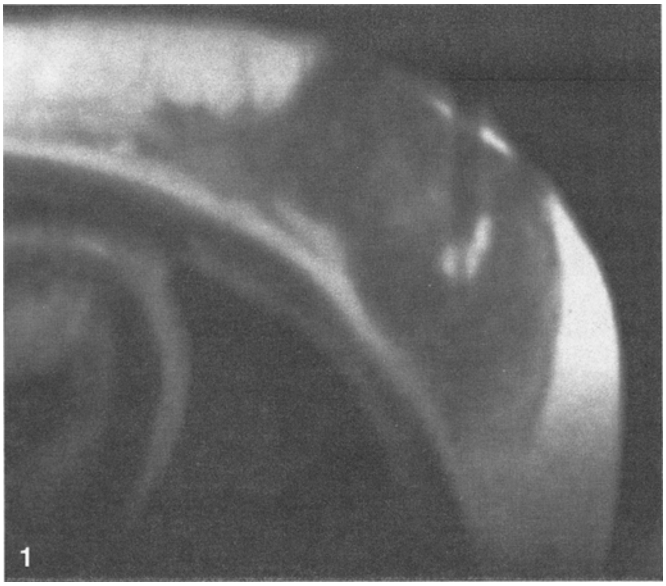


Fig. 1. T2-weighted MR image acquired in 600 msec applying the LoLo technique. A breast lesion with a significant increase in signal intensity after gadolinium administration was marked with an MR-compatible hook wire. Successful surgical removal of the lesion, which turned out to be a fibroadenoma, was performed. The fibroadenoma was neither palpable nor visible on X-ray mammography or sonography.

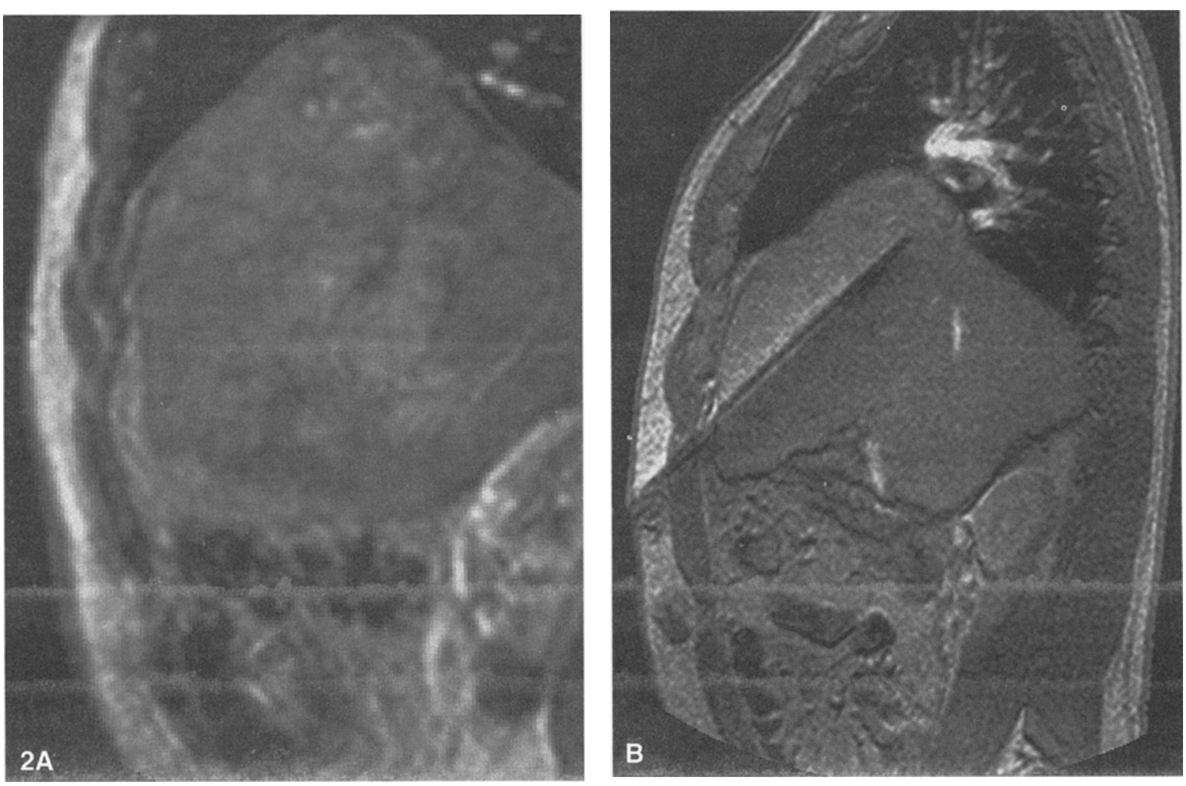


Fig. 2. Patient with liver cirrhosis and a suspicious lesion in segment VIII directly under the dome of the diaphragm. On sagittal spoiled gradient echo images (EPI technique) (**A**) the lesion could be differentiated in the early phase after gadolinium administration. The biopsy was performed with a 14 G Trucut needle and controlled in the sagittal (**B**) as well as the paracoronal plane (not shown).

than five liver lesions should not be treated. LITT (Laser-induced Interstitial ThermoTherapy) of the liver is regarded as a palliative procedure and may be applied preferably to colorectal metastases, since it has been shown that at least 20% of patients with this disease have exclusively liver metastases. Criticism regarding interstitial thermotherapy of liver metastases is not directed toward the feasibility of this technique—regardless of whether MR or ultrasound is used for monitoring—but toward the assumption that destruction of the greatest possible quantity of neoplastic tissue should prolong survival. There are no reliable data regarding long-term effectiveness. A mean survival time of 35 months following interstitial thermotherapy of liver metastases (most from colorectal cancer) in 135 patients was reported in the literature [39]. However, those results must be compared with the results of hepatic resection and chemotherapeutic protocols. Results from other areas (head and neck) are scarce in the literature [40].

Apart from radiologic procedures, MRI also provides a means for stereotactic surgical intervention in the brain. This applies to biopsy and interstitial therapy [36]. Performing a neurosurgical operation in or at the magnet allows for instantaneous control of the effectiveness of surgical tumor removal.

Intraoperative cryotherapy is a well-established technique for the treatment of liver metastases. MR is highly accurate in demonstrating the extent of the frozen tissue [41, 42], but it is difficult to obtain MR-compatible probes for clinical use. In addition, the size of the MR probe should not exceed a diameter of 9 Fr in order to allow a percutaneous approach. On the other hand, this small-caliber probe may lack the effectiveness to create lesions of a large enough frozen area; a small ice-ball is not enough to treat larger lesions. Regarding the precision with which the damage can be visualized, cryotherapy is superior to coagulation therapy. Possible fields of application of this technique include lesions of the liver, brain, breast, and prostate.

Ethanol injection for interstitial therapy of hepatocellular carcinomas using ultrasound guidance has been shown to be effective in small tumors. Metastases have also been treated in this way. MRI does not offer any advantage over ultrasound or CT guidance in this situation. There is no doubt that the spread of ethanol is less predictable than evolving heat or cold, but it is a very inexpensive technique.

Focused ultrasound is in an early stage of development and evaluation [43–45] and has been shown to lead to coagulation necrosis due to a thermal effect [46]. Although this is a very interesting technique, ultrasound is limited by overlying bones and air. Hence, there is also a limitation to free access to lesions in the body itself. One may conclude that breast lesions are an ideal target for focused ultrasound therapy. However, it remains debatable whether this is reasonable from a medical point of view. An open magnet is not a prerequisite for that procedure.

Therapeutic Vascular Interventions

Instruments in interventional radiology used to be rather simple: puncture needle, catheter, and guidewire. Historically, the development of suitable catheters—among other things—proved to be the key to success of angiographic interventions. This should be kept in mind, especially when MRI-guided angiographic interventions are being considered. Once steerable catheters were manufactured, superselective vascular catheterization became possible and laid the ground work for vascular therapeutic procedures. Without superselective catheterization, embolization or angioplasty would have been unthinkable! But today there are even more sophisticated devices such as laser, rotational devices, or hydrodynamic catheters, and other instrumental innovations. MR-guided vascular interventions represent a great challenge to MRI guidance. One has to start again from the very beginning regarding imaging, guidance, and instruments. The only practical techniques for vascular intervention are X-ray fluoroscopy and catheter angiography. Nonetheless, possible vascular applications already done experimentally under MRI guidance include: embolization, PTA (Fig. 3) [47, 48], stenting (Fig. 4) [49], TIPS [50], and cava filter placement [51].

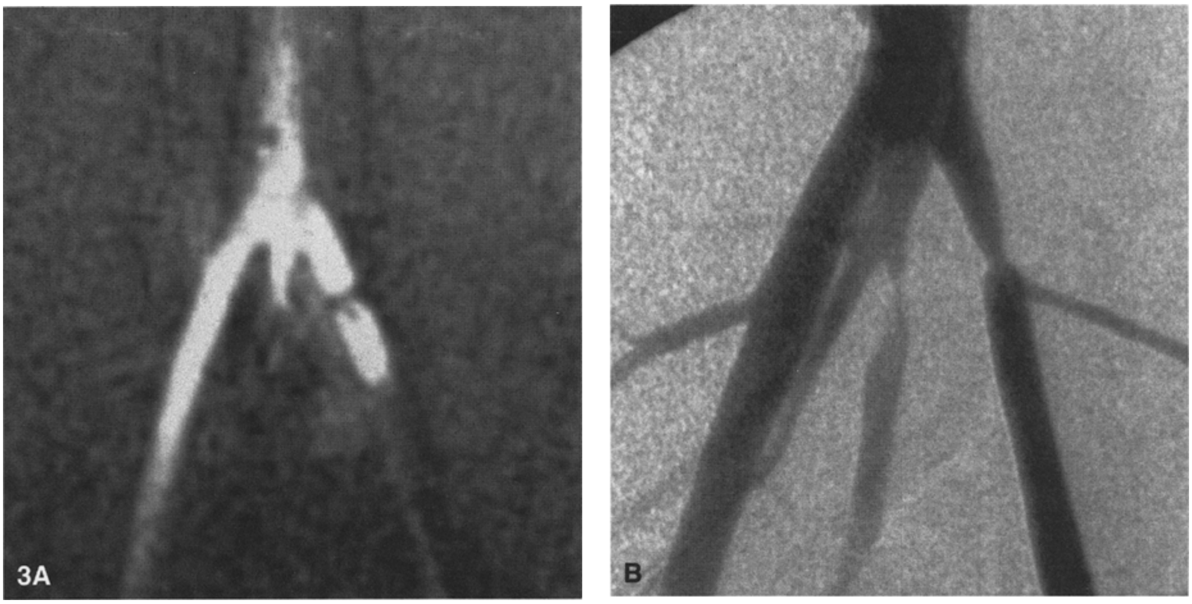
Catheter Visualization

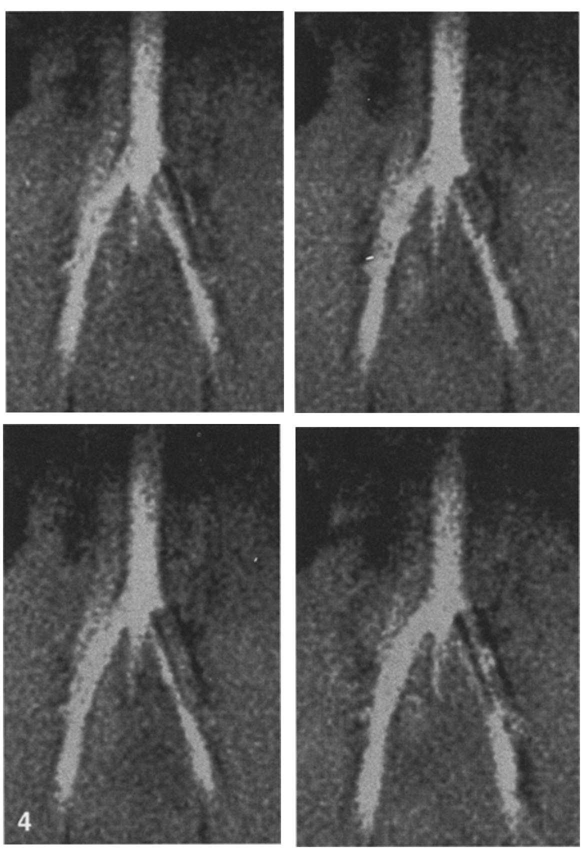
Since vascular interventions may be very complex, requiring real-time imaging and very high spatial resolution, visualization of even small vessels is a prerequisite. Catheters and devices can be visualized actively and/or passively. Active tip-tracking catheters are provided with a miniature radiofrequency coil incorporated in the tip of the catheter (Fig. 5) [12, 52, 53]. This allows active identification of the spatial position of the tip and guidance of the scan plane. However, the catheter is usually not visualized along its whole length, otherwise the high temporal resolution of catheter tracking is reduced [54]. If the position of the catheter tip is projected onto a maximum intensity projection image, which does not necessarily show the actual anatomy, complications such as dissections or perforations can not be detected directly. A combination of active tip tracking with real-time imaging can circumvent this problem [55].

The field inhomogeneity catheter is a passive visualization technique, because the catheter is depicted directly with the MR image [56, 57]. A loop of insulated copper wire is incorporated into the catheter wall (Fig. 5), and by applying a minimal direct current of up to 150 mA a local magnetic field is produced around the whole length of the catheter. When placed in the scanner this small additional magnetic field locally destroys the homogeneity of the main magnetic field and causes signal loss. The strength of the local magnetic field around the catheter can be varied and even switched off by the strength of current applied through the wire. This allows the visibility of the catheter to be changed independent of the sequence and its parameters [58, 59].

Susceptibility-based catheters are marked with paramagnetic substances (dysprosium or nitinol markers) (Fig. 5), which lead to local signal loss due to the susceptibility difference between the marker and the surroundings [60]. The dependence of the susceptibility effects on the orientation to the main magnetic field is overcome by marking the catheter spherically. This technique of passive catheter visualization is the least expensive, but the size of the catheter still depends on the sequence and its parameters. Knowing the difficulty of achieving high-resolution real-time imaging this is not the ideal situation, but there are initial reports of fast imaging techniques allowing control of angiographic interventions with passively marked catheters [61].

The most important advantages of active tracking over passive tracking are the high temporal resolution together with the option to use the three-dimensional coordinates to steer the scan plane. In view of the instruments illustrated in Figure 5, it will be realized that the challenge for the future involves not only the development of the equipment, but also development of the simplest instruments such as needles, guidewires, and catheters.





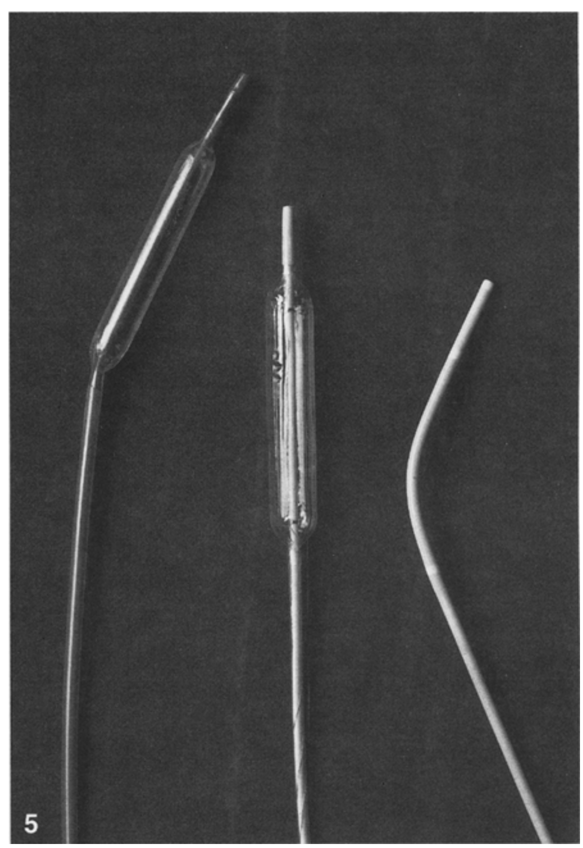


Fig. 3. Percutaneous transluminal angioplasty. Combining active tip-tracking and radial scanning allows simultaneous real-time visualization of the anatomic background together with the catheter tip, which is projected into the image and marked by a flickering cross (not visible on the stored images). (**A**) A balloon catheter filled with an aqueous gadolinium solution (1:200). The surgically created stenosis is well depicted during the dilatation. A corresponding digital subtraction angiogram (**B**) verifies the correct localization of the stenosis by real-time MRI.

Fig. 4. MR-guided placement of a stent in the iliac artery of a living pig [49]. Radial filling of *k*-space [6] together with the sliding window reconstruction technique [5] is exploited to achieve a frame rate of 20 images per second.

Fig. 5. Examples of specially designed MR catheters for angiographic interventions. On the left is a balloon catheter shown for active visualization with a microcoil at its tip. The balloon catheter in the middle is a field inhomogeneity catheter equipped with a copper wire. By applying a current, local artifacts of variable size can be produced. The catheter on the right is marked with dysprosium rings, which produce an artifact independent of the orientation of the catheter to B_o.

Safety Issues

The safety of interventional devices is a most important issue. Tip-tracking catheters can behave like antennas. Thus, radiofrequency excitation used during the MR examination may lead to heating of the catheter and the surrounding tissue. In vitro experiments at 0.5 T have demonstrated that for the worst case scenario the heat does not lead to damage of the surrounding tissue [48]. But significant temperature elevations have been noted at 1.5 T, although for sequences usually not used for angiographic interventions [48]. As the image quality of 0.5 T scanners is inferior to that of high-field systems, this point will have to be thoroughly examined in the future. It has to be stressed that this applies to all catheters or devices with incorporated conductive material, but not to susceptibility-based catheters.

Without going into the technical details of real-time MR imaging, which will have changed even since this paper was written, a few examples of MR-guided angiographic interventions are included to give an impression of the up-to-date (real-time) image quality that can be achieved (Figs. 3, 4).

Interventional MRI: The Future?

The most interesting question in connection with MR-guided interventions is whether MRI will replace X-ray fluoroscopy for image-guided interventions. Experts in interventional radiology might regard MR-guided interventions as frustrating and time-consuming, at least for the time being. Of the potential applications of interventional MRI, percutaneous biopsy and interstitial therapy seem to be realistic applications, although to what extent and for precisely which indications remains rather speculative and awaits further studies for clarification, since there are also several other modalities available for that purpose. Lesions seen only on MRI are certainly a good indication for the technique.

MR-guided vascular interventions have proved to be rather complex, requiring high temporal as well as high spatial resolution. For safety and practical reasons, catheters and guidewires must be visualized adequately and in real-time throughout their full extent, which is not yet satisfactorily possible. Therefore, vascular intervention in MRI is not yet ready for clinical use. It represents a great challenge, not only with respect to improvement of sequences and scanners, but also because it demands almost complete re-engineering of even the simplest instruments such as needles, guidewires, and catheters.

What seemed to be a utopian dream yesterday has often become today's accepted reality. This has been clearly demonstrated throughout the history of technical development in general and in our own field of radiology in particular, which has witnessed the birth of the entire discipline of interventional radiology in the last 50 years. For the early interventionalist, rapid imaging was also a problem, even though fluoroscopy was available from very early on. For the next generation of MR interventionalists, the task of achieving real-time imaging with high temporal and spatial resolution will be of the utmost importance to further progress in the field.

From an economic point of view, it seems reasonable to test the practicality of MRI-guided interventions with currently available MR units, and most of the new projects can be attempted in this environment. We are still at the very beginning of a long journey for which we have taken only the first few faltering steps. The prospects that await us, however, are interesting and promising enough to warrant intensive efforts to explore and expand the techniques as far as possible in the next few years.

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