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Interventional and intraoperative MRI at low field scanner – a review

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Abstract

Magnetic resonance imaging (MRI) is a cutting edge imaging modality in detecting diseases and pathologic tissue. The superior soft tissue contrast in MRI allows better definition of the pathology. MRI is increasingly used for guiding, monitoring and controlling percutaneous procedures and surgery.

The rapid development of interventional techniques in radiology has led to integration of imaging with computers, new therapy devices and operating room like conditions. This has projected as faster and more accurate imaging and hence more demanding procedures have been applied to the repertoire of the interventional radiologist. In combining features of various other imaging modalities and adding some more into them, interventional MRI (IMRI) has potential to take further the interventional radiology techniques, minimally invasive therapies and surgery. The term "Interventional MRI" consists in short all those procedures, which are performed under MRI guidance. These procedures can be either percutaneous or open surgical of nature.

One of the limiting factors in implementing MRI as guidance modality for interventional procedures has been the fact, that most widely used magnet design, a cylindrical magnet, is not ideal for guiding procedures as it does not allow direct access to the patient. Open, low field scanners usually operating around 0.2 T, offer this feature.

Clumsy hardware, bad patient access, slow image update frequency and strong magnetic fields have been other limiting factors for interventional MRI.

However, the advantages of MRI as an imaging modality have been so obvious that considerable development has taken place in the 20-year history of MRI.

The image quality has become better, ever faster software, new innovative sequences, better MRI hardware and increased computing power have accelerated imaging speed and image quality to a totally new level. Perhaps the most important feature in the recent development has been the introduction of open configuration low field MRI devices in the early 1990s; this enabled direct patient access and utilization of the MRI as an interventional device.

This article reviews the current status of interventional and intraoperative MRI with special emphasis in low field surrounding.

Keywords: Interventional; MRI; MR-guidance; Low field; Biopsy; Therapy

1. MRI as a guiding tool

Image guided interventions are an integral part of evidence based medicine. Information can be collected, e.g. as bacterial, cytological and histological specimens to clarify clinical diagnosis. Interventions can also be used for therapeutic purposes, much like surgery. The vital point in modern image guided procedures is minimal invasiveness, which leads to better patient compliance and often better treatment results. The development of ultrasound and CT boosted the use of interventional image guided procedures to a new level. It is possible to do biopsies, aspirations, drainages, palliative tumour therapies and procedures under imaging guidance [1–3].

Magnetic resonance imaging (MRI) was established as a promising diagnostic tool in the beginning of 1980s, it was soon recognized that MRI was a superior diagnostic imaging modality in diagnosing many pathological conditions and

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could be used for interventional procedures as a guidance method [4–8]. There are numerous applications that can be defined feasible to perform at low field MRI. One of the key issues in performing these procedures is the instrument guidance, which can also be performed in many ways.

First interventional procedures under MRI were done in the 1980s [9]. They were started as aspiration biopsies and biopsies [10]. In 1988 vanSonnenberg et al. [11] described a system for MR-guided biopsy and drainage. Experimental MR-guided therapies were reported in 1992 by Cline et al. [13] and Matsumoto et al. [12]. The applications and indications of MR-guided interventions have increased steadily.

2. MRI guidance: benefits and disadvantages

MRI, with superior soft tissue contrast, has a great potential for guiding the interventional procedures. The better visualization of the surrounding structures is a safety issue in many procedures. The soft tissue contrast of CT is good compared to X-rays, but not comparable to MRI. MRI also provides good visualization in the skull base area, where the "beam hardening" artefact limits visualization in CT. Another disadvantage of CT compared to MRI is its limited orientation, the gantry of the CT allows procedures to be performed in the axial or near axial planes, and limits the usage of long instruments. However, CT axial image data can be reformatted to sagittal or coronal views. When these reformatted images can be produced fast enough, CT will add interesting elements to the guidance of procedures in the future. The multi-slice detector technology has improved the imaging speed and the resolution of reformatted images.

There are many facts that support the use of MRI in interventions. The lack of ionizing radiation is considered an important advantage; this alone may lead to the increased use of MRI in interventions in future. But there are further advantages to the MRI and these are not easily, if at all, matched by any other imaging modality; firstly, MRI provides relatively good spatial and temporal resolution [14]. Secondly, high intrinsic contrast in tissue without or with the use of contrast medium [15]. Thirdly, multiplanar imaging capability with optional two- and three-dimensional view [16]. Furthermore, MRI has the ability to measure and quantify flow, diffusion and perfusion [17–20]. An important feature is also the temperature sensitivity of MRI, which allows the assessment of temperature changes [21].

The disadvantages of MRI guidance include the safety aspects of the MRI environment. The magnetic field must be taken into account in designing and building the facilities and choosing the patient monitoring equipment and instruments. Standard operating room equipment and surgical instruments cannot be used in the magnetic field. The development of MR-compatible instruments has been paralleled by the introduction of new MR-guided procedures. All the equipment and instruments in the MR field must be MR-safe, i.e. non-magnetic and not moving in the magnetic field. Additionally, all instruments and equipment used in the imaging area must be MR-compatible, i.e. not cause disturbing artefacts in the MR image. Today, readily available MRI compatible instruments exist.

When using instruments RF heating occurs at the tips of needles and guidewires must be taken into account to prevent tissue damage. Heating can occur also with MR-compatible instruments and it correlates to magnetic field strength and used imaging sequence being a bigger problem in high field MRI and sequences with high specific absorption rate (SAR) values. To date, no hazards using MR-compatible needles have been reported, but up to 76 °C temperatures have been reported at the tip of a nitinol guidewire at 1.5 T with maximum SAR values. [22–24]

The slow image update rate is another disadvantage of MRI. Despite the recent development, the visualization of lung parenchyma and thin bony structures is still limited in MRI compared to CT. Conventional closed-bore MR systems do not allow ideal access to perform interventional procedures. [4,6].

3. Open low field MRI systems

MRI interventions are performed on both high field and low field devices [25,26]. High field devices are usually closed bore magnets due to the fact that the stronger magnetic fields (1–3 T) require more robust shielding and gradient structure to maintain field homogeneity. The advantage of higher magnetic field is reflected in better spatial and temporal resolution. Low field scanners are less resolute upon structural configuration of the magnet, thus it has been possible to construct open configuration MRI scanners on which one side is usually open for patient access. Scanners of this type are obviously more suited to a bed-side type interventional procedures than closed systems [27,28]. The open magnet's field strength varies from 0.2 to 1.0 T. There is trade-off in image quality towards less resolution due to open structure of these systems. The image quality of low field scanners is however sufficient for interventional use [6,29].

4. Imaging sequences and image quality

Imaging sequences in interventional MRI (IMRI) are somewhat different to the ones used in diagnostic MRI. This is because fast imaging speed is related to good spatial and temporal resolution. It is difficult to achieve all these simultaneously; there is a trade-off between image speed, signal to noise ratio, and resolution [30]. This is why many imaging sequences used in IMRI are custom-made and originate from fast imaging sequences. Most often they are various gradient echo techniques generally with short TR; also different strategies for k-space sampling have been developed in order to speed up the imaging. These include LoLo, keyhole, segmented k-space, and wavelet encoded data acquisition techniques [31–34]. New parallel imaging techniques like SMASH and SENSE are likely to set the standard for image quality in coming years [35,36].

5. Scanners for interventional MRI

Conventional superconducting magnets have better homogeneity of the magnetic field and a more optimal signal-to-noise ratio than open low field MRI systems. Imaging at 1.5 T allows better image quality, functional imaging and spectroscopy. Despite the restricted patient access, some procedures, such as breast and brain biopsies and vascular interventions, have been performed with this design.

Most of the published research on MR-guided interventions has been performed in a ‘double-doughnut’ magnet (Signa SPTM, General Electric (GE) Medical Systems, Milwaukee, WI, USA). In this scanner the central segment of a conventional high field system has been taken out, allowing access to the patient from the sides and the top. Access to the patient is much better in this case compared to a closed bore magnet, and it is currently the only system available that allows complete vertical and side access to the patient at the imaging isocentre. A large number of surgical procedures and interventions [5,37–40] have been performed with this system. However, this magnet is also superconducting and cannot be turned on and off during the operation.

Most biplanar horizontal magnets are resistive or permanent, their field strengths ranging from 0.064 to 0.7 T. Several manufacturers produce biplanar systems with two or four supporting pillars, resulting in more restricted access to the patient. A C-shaped magnet with one supporting pillar allows wide access from the pillars contra lateral side and the head and foot ends of the magnet (Magnetom OpenTM, Siemens Medical Systems, Erlangen, Germany and Panorama 0.23 T Philips Medical Systems MR-Technologies Finland, Vantaa, Finland). A superconducting 0.6 T model of this design has also been introduced (Panorama 0.6 T Philips Medical Systems MR-Technologies Finland, Vantaa, Finland). Vertical approach is very limited with this design. The biplanar concept has the advantage of a fairly homogeneous static magnetic field, but it is limited to lower field strength than the cylindrical designs. The vertical magnetic fields of these systems require different coil designs than the horizontal field scanners, for instance, closed-bore scanners.

The features of different scanner types are presented in Table 1.

6. Instrument tracking and safety in interventional procedures in MRI

Instrument tracking in MRI is based upon the creative use of scanner hardware, software, sequences and tracking options [24,41,42]. MRI interventions can be performed in a straightforward diagnostic MRI unit with standard software, but it is much more feasible and also safer to perform them using user interface designed for MRI interventions [43–45]. This type of software allows planning, imaging and performing the interventional procedure in a predetermined way using default settings for imaging and image windowing. This allows categorizing the interventions and providing custom-made imaging features for each of them. The software usually comes with hardware that enables monitoring the procedure from the imaging room and user interface hardware that can be used in MRI environment.

Table 1
Examples of magnet designs for MR-guided interventions and surgery

Magnet design	Magnetic field (T)	Advantages	Disadvantages	Manufacturers
Cylindrical		Image quality	Cost	
Long-bore	1–3		No access	All
Short-bore	1–1.5		Poor access	Philips, Siemens, GE
Double doughnut	0.5	Vertical access positioning	Limited access of support staff cost	GE
Biplanar, horizontal	0.02–0.7		Low SNR	
C-shaped		Access cost		Philips*, Siemens
Two- or four-pillar magnets			Restricted access	Hitachi Toshiba, GE
Prototypes				
Movable, in ceiling	1.5	Image quality	Cost staged imaging	
Large biplanar		Most open		Fonar
Vertical biplanar		Vertical access	Limited access of support staff	
Small C-shaped	0.12	Small size	Small FOV	Odin
Hybrid systems				
Short-bore	1.5–3	Image quality	Cost	Philips, GE
X-ray + CT		Speed of X-ray SNR signal-to-noise ratio	Staged imaging	

Philips Medical Systems, Eindhoven, The Netherlands, GE General Electric Medical Systems, Milwaukee, WI, USA, Philips* Philips Medical Systems, Vantaa, Finland, Siemens Medical Systems, Erlangen, Germany, Hitachi Medical Corporation, Japan, Toshiba Medical Systems, Japan, Fonar Corporation Melville, NY, USA, Odin Medical Technologies, Haifa, Israel.

Instrument tracking gives the possibility to obtain images in the instrument plane simultaneously during the procedure. This leads to multiplanar interactive scanning environment, where the ability to interactively localize, plan and monitor the procedure is an essential feature. This setting requires active instrument tracking. Active instrument tracking can be achieved in at least two ways; the instrument can be tracked with infrared camera when an appropriate number of mirrors with known locale is provided [42–45]. Another method to achieve active tracking is to use a built-in receiver or active coils in the instrument to achieve exact positional information of the device [44,46]. Locally induced field inhomogeneities can also be used to pinpoint the instrument position [47]. In this method a current is applied through a wire built in the wall of the instrument causing field inhomogeneity and thus signal void. There are also other potential methods for active instrument tracking, such as using electron spin resonance (ESR) [48] or inducing a signal from the instrument tip from an external source [24].

Ideally IMRI procedures would be performed in a real time imaging setting and thus simple passive instrument tracking would be sufficient; this is also an option when immediate image update is not necessary due to the nature of the procedure. Passive instrument tracking is based on the inherent susceptibility artifact caused by the instrument in the image data also this can be enhanced with modified catheter structure [49]. At the moment passive tracking methods are in frequent clinical use, namely instrument artifacts follow-up [50,51]. Of active tracking methods, optical tracking is clinically in use [6,45,52,53].

Intraoperative real-time imaging with MRI is often limited by the achievable signal-to-noise ratio and tissue contrast. Therefore, a modality-independent method for localizing the instrument in real time is beneficial on less frequently updated images: an optical tracking system augments this localization by providing instantaneous feedback [27,39], while intraoperative MRI is used for generating updated roadmaps along the needle path. Compared to passive tracking, where the needle artifact alone is used for deducing the instrument's position and orientation, optical tracking offers distinct advantages [54]. The initial needle orientation at the puncture site can be determined with the aid of graphic tools and/or needle-guided scout images, whereas passive tracking requires more elaborate slice positioning and MR-visible markers. Determination of the puncture is possible with optical tracking overlays in one or two MRI sets, and no skin markers are needed [55] (Fig. 1).

Difficulties in pinpointing the exact orientation of the needle from its artifact have adverse effects on the overall accuracy of needle alignment, and the acquisition of affirmative images accrues a time penalty. Other active guidance systems, such as ultrasound probes and mechanical arms could also be used instead of optical systems, but they lack the flexibility of wireless instrument tracking [56,57].

The first-generation IMRI systems by the leading manufacturers (Philips, GE, Siemens) use optical navigator devices

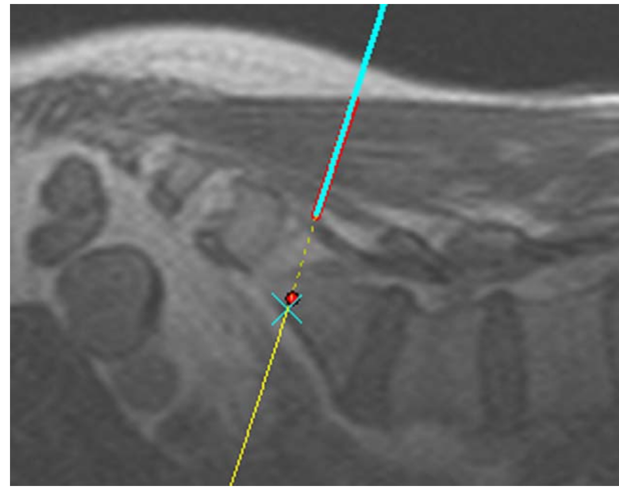

Fig. 1. Optical tracking in use at large screen display: the estimation of the path (thin line) of the needle (thick line) crosses the first sacral root in True-FISP sagittal image.

for tracking the position and orientation of the instrument. Signa SPTM (GE Medical Systems, Milwaukee, WI, USA) has an instrument holder with 2–3 LEDs connected by a cable to a computer. A hand-held pointing device with LEDs is used in Magnetom OpenTM (Siemens Medical Systems, Erlangen, Germany). IMRI system. This probe can be used to select imaging planes, but instruments cannot be fixed to it [58].

In addition, some open configuration MRI devices are equipped with sophisticated instrument localization and user interface tools to facilitate almost all interventional procedures to be performed with real-time control [42] (Fig. 2).

By using the technique published by Lufkin et al. [7], it is possible to see the whole instrument with three standard

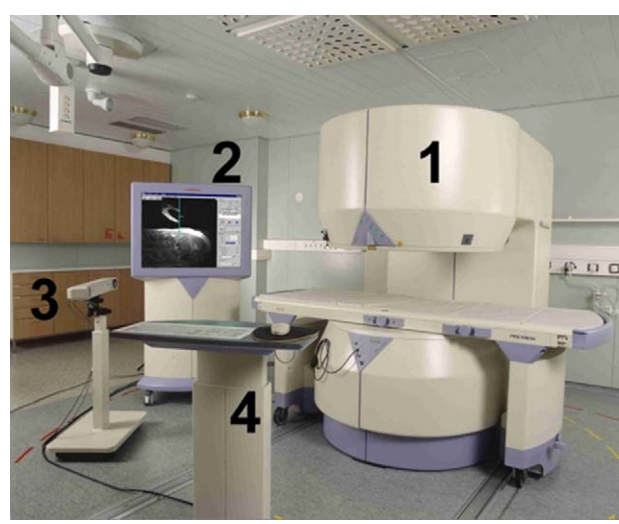

Fig. 2. Typical set up for low field IMRI facility: (1) the MR scanner, (2) the projector, (3) optical tracker camera, (4) user interface console (Panorama 0.23 TTM Philips Medical Systems MR-Technologies Finland, Vantaa, Finland).

image sets used in diagnostic MRI. This image update rate is, however, too slow for interventional purposes. Various instrument tracking methods have been developed for MR-guided procedures [56,59,60]. Optical tracking, which is the most common method for instrument tracking, locates the instrument with a stereovision camera [27,39]. The advantages of optical tracking are real-time operation, reduction of the need for imaging during the procedure and a consequent reduction of procedure time, the disadvantages being the need for line of sight and insensitivity to needle bending. The bending of the needle makes confirmatory imaging more important in fine-needle biopsies and injections than in procedures done with a stiff instrument, such as a bone biopsy drill.

Acquired image presentation in a quick and efficient manner is a key component in MRI guided procedures and an innovative user interface is the motor to achieve this. Most manufacturers have included user interface for interventional use for their scanners designated for this purpose. Three-dimensional volumetric models and software for data presentation and modulation have also been presented [61–63]. These tools enhance the end users possibilities to use acquired data.

Several concepts for IMRI scanners and facilities have been developed to improve neurosurgical operations [64–67] and radiological interventions [68]. Most of the revised MRI facilities have been designed for use either as radiological intervention suites or as operating rooms. A ‘twin operating room’ (OR) concept, where the MRI scanner is placed beside the OR, has been used in at least two institutions for open neurosurgery [66,67]. Few studies have been published where surgery is carried out in the magnetic fringe fields of low field scanners [45,69,70].

7. Clinical applications

7.1. MRI guided biopsy

Correct assessment of information obtainable from lesions of infectious, malignant or benign origin is necessary for the selection of treatment options. Percutaneous or surgical biopsy is the method of choice for diagnosing lesions of unknown origin. The most common presentation of a lesion is that of metastatic lesion, and in a patient with a neoplastic history the diagnosis is straightforward. However, if there is no neoplastic history or such history dates back several years, a biopsy is certainly needed. Even if the lesion is presumably metastatic, it is sometimes useful to obtain a biopsy, particularly if there is no previous history of metastatic disease.

Lee et al. reported good results in 33 MR-guided procedures at a variety of locations with a C-arm open-configuration system [71]. Furthermore, Lewin et al. concluded from 106 biopsies and aspirations that a modified clinical C-arm system is feasible, with relatively rapid needle placement [6]. Parkkola et al. and Blanco-Sequeiros et al. pointed a 0.23 T open scanner to be a feasible guiding method for soft tissue and bone biopsies [52,72].

MR-guided brain biopsy has been proved to be a safer and faster procedure than frame-based stereotaxy. Schulz et al. reported that, in biopsies of the petroclival region, MRI guidance provides maximum patient safety and a level of diagnostic accuracy not attainable with other guiding systems [73,74]. In another study, diagnostic tissue specimens were obtained in all of the 40 brain biopsies with a short-bore 1.5 T magnet with a skull-mounted trajectory guide [75].

Good results have been published from biopsies performed in a conventional closed-bore scanner without any special IMRI instrumentation. The contrast and visibility of the needle permitted more than 400 uncomplicated punctures and interventions. The mean duration of a biopsy was 19 min [51].

Due to its good sensitivity, MRI is able to detect bone lesions not seen at all in other modalities. Particularly, lesions with oedema, often seen only in MRI as a bright involvement of bone marrow in heavily T2-weighted sequences and STIR sequences can be reliably visualized and readily biopsied [50,76–78]. There are also results suggesting that the use of contrast medium may contribute to the accuracy of bone lesion detection in MRI. This is the case especially in recurrent malignancies and in certain types of cartilaginous lesion [79]. Contrast media have been used effectively in MRI guided biopsies. In taking biopsy from primary bone malignancies it is advisable to use contrast medium, as it is likely to increase the accuracy of biopsy by pointing out the enhancing dimensions of tumour [80]. It is also important to know the exact anatomic proportions of the tumour. In primary bone tumours, choosing the proper biopsy route is of utmost importance since removal of the biopsy channel is mandatory during surgery.

The spatial resolution capability of MRI in bone remains a controversial issue, at least in the low field scanners. Unless fast sequences with relatively good resolution, such as CBASS/true-FISP, are used, the procedures targeted to the areas containing fine bony structures should be done under CT-guidance. In the vertebral region the pedicles and cervical area must be considered as such structures.

In a recent series of MRI guided bone biopsies the success rates are comparable to the results obtained in CT studies published on this topic [40,52,78].

MR-guided percutaneous biopsy is in essence safe, accurate and feasible to perform. Combined fine needle biopsy is advantageous when malignant disease is suspected [52]. MRI can be used as the sole modality or with optical tracking guidance in biopsies or as a backup modality in performing procedures not possible otherwise [40,52].

8. Periradicular therapy

In selective nerve root therapy a mixture of therapeutic agents, usually a combination of corticosteroid and anes-

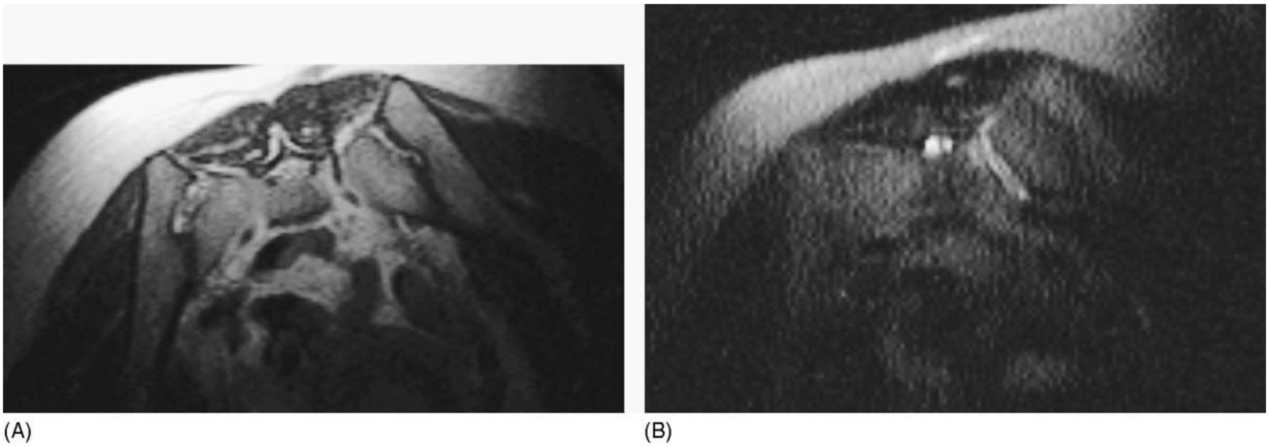

Fig. 3. (A) MRI image of a needle positioned adjacent to the lumbar nerve V. (B) Corresponding SSFSE image from the same level after the saline injection, the nerve root is readily outlined and position of the needle verified.

thetic, is injected into the periradicular nerve root channel. This is called periradicular nerve root infiltration or epidural infiltration.

Selective periradicular therapy with local corticosteroids and anesthetics has been used for preoperative evaluation of lumbosacral pain and sciatica patients in order to determine the not always clear correlation between the clinical symptoms and imaging findings [81–84]. Periradicular therapy has also a significant therapeutic effect in discogenic radicular lumbosacral and sciatic pain [29,85–87].

It has been shown that MR-guided nerve root infiltration is safe and accurate [29,88]. However, fluoroscopy or CT-guided procedure is usually the method of choice for nerve root infiltration therapy in the lumbosacral area. Although fluoroscopy is cheap and easy to apply, it does have disadvantages of use in guiding interventions. Firstly, the procedural steering must be done according to bony anatomical landmarks and any variation or change in the soft tissue morphology due to anatomical variation or pathology is not detected. The use of contrast media does little to overcome this dilemma, since when contrast is injected only the edges of adjacent structures to the needle are readily visualized. Secondly, there is radiation burden to the operator and to the patient both on CT and fluoroscopy.

As an adjunct to optical tracking and direct visualization of the needle, saline solution can be used as contrast agent in MRI to visualize the nerve root sheath injected. This proved to be a very effective means of confirming the right placement of the needle [29,88] (Fig. 3). Gadolinium compounds with T1-weighted sequences have also been used for this purpose [89]. However, to this date these compounds have not been accepted for intrathecal use and using saline as contrast agent makes it possible to avoid the possible side effects of intrathecal or epidural gadolinium infiltration.

Low back disorders are extremely prevalent in all societies, and the rate of caused disability, as well as the costs, have increased – independently of disease prevalence – over recent decades [90]. It is obvious that we cannot solve this dilemma with increasing surgical interventions. Minimally invasive interventional procedures are an option to relieve pain and minimize the risk of disability.

Previous reports concerning the effect of nerve root infiltration therapy on radicular pain have been promising. It has been reported that the patients with irritation after failed back surgery had an excellent outcome from nerve root infiltration therapy, with almost 80% of initial pain free result [88]. It has also been reported that 75.4% of patients with radicular leg pain had a successful long-term outcome after lumbar transforaminal epidural steroid injection [86].

On the basis of the literature, MR-guided needle introduction is an accurate procedure and may be used to substitute conventional techniques for nerve root infiltration. This would be especially useful in cases where there are substantial anatomical or structural changes due to variation or pathology. It is concluded that MR-guided nerve root infiltration therapy is safe, accurate and feasible to perform. Nerve root infiltration therapy is effective treatment form to control radicular pain and can be used to substitute more invasive procedures in a selected patient group.

9. MRI-guided breast biopsy

A proportion of breast lesions are seen in MRI and only in MRI [91–95]. This fact leads to the need of breast biopsy procedure performed under MRI control as part of an accepted diagnostic chain of breast disease. Unless MRI guided histological sample is available it would clearly effect the survival of affected individuals with malignant breast lesion seen only on MRI. Histologic sample is of critical importance since only histological sample enables specific classification of the lesion and thus determines the line of action in the treatment of possible malignant lesion detected.

MRI control can be used to mark the lesion for the surgeon to perform open surgical biopsy; this can be done with wire marking. Another approach is to perform percutaneous, less invasive biopsy to extract sample material from the lesion. The latter method is of obvious advantage, since it is less traumatic and can be easily performed on an outpatient basis. This is also the standard method of how breast lesions seen in other imaging modalities are handled.

There are few developmental MRI guided breast biopsy devices in use but none of these are applied on low field scanners [96]. There are no imaging protocols or guidelines for low field MRI breast imaging or biopsy.

Modern low field MRI scanners with good gradients and computer software have better diagnostic capability to detect breast lesions. Low field MRI scanners are easier to construct open structured than are high field scanners. Open configuration has many advantages, one of which is greater patient compliance due to their structure; invasive procedures are much easier to perform in an open MRI unit since they allow easy access to the patient and direct control of procedure (Fig. 4). It is also noted that low field scanners are much cheaper than high field scanners.

It is important to notice, that when indicated, MRI guidance must enable as accurate and straightforward a biopsy procedure as in mammography guided biopsy when performing biopsy on lesions of size 1 centimeter and larger.

As diagnostic imaging has developed and malignant breast lesions not seen in any other modality are detected in MRI, it is necessary to evolve the latter part of diagnostic chain in malignant breast disease. This indicates the development of solo MRI guided breast biopsy methods, also in low field surroundings. Since clinical diagnostic breast MRI imaging is current practice in most diagnostic centers it is necessary to broaden the diagnostic capabilities to obtain better results in treating breast cancer. MRI guided breast biopsies are per-

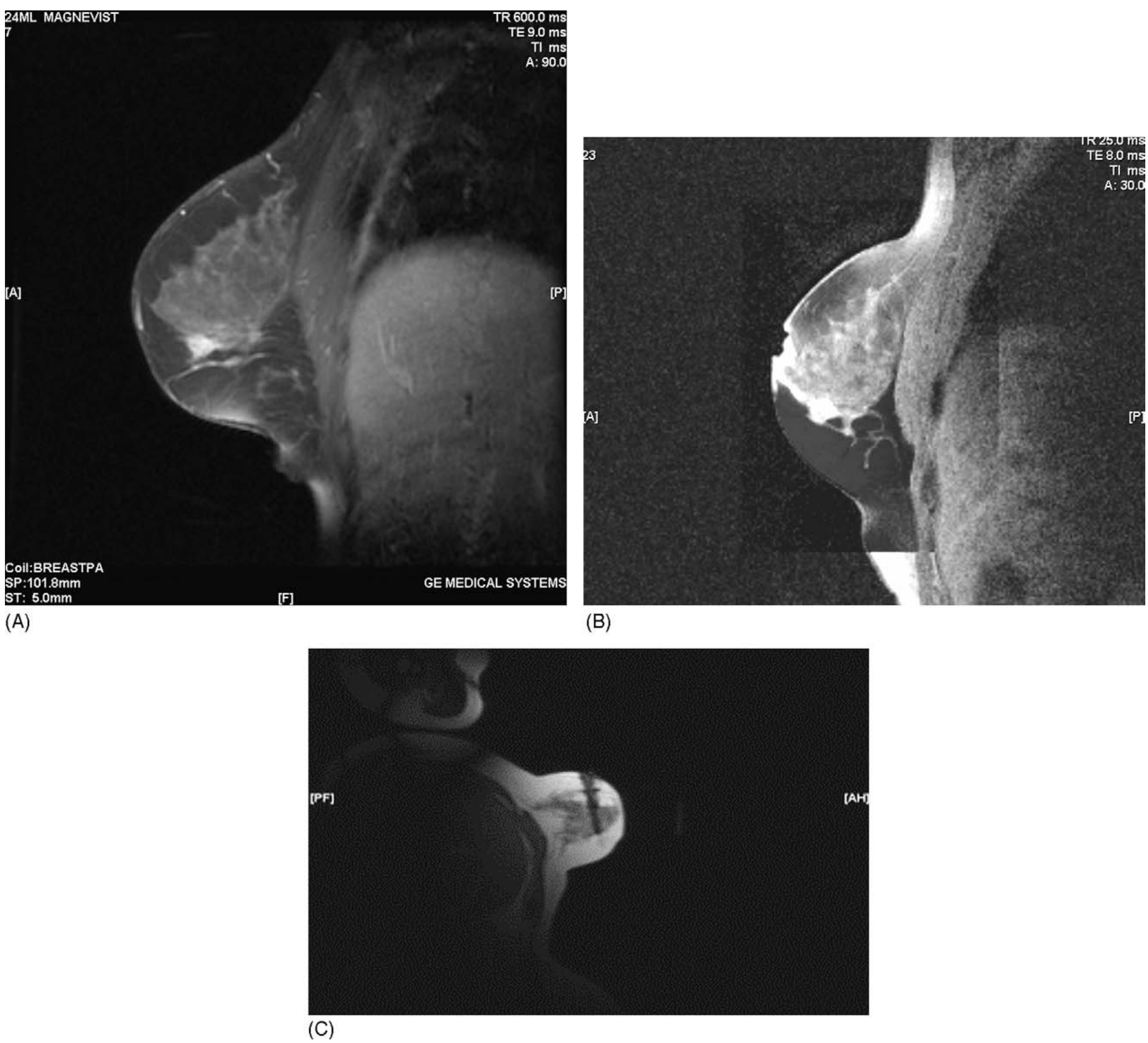

Fig. 4. (A) High field MRI image (1.5 T) of an breast lesion. (B) Corresponding low field image (0.23 T). (C) Biopsy of the lesion seen in images (A) and (B), optical tracking was used.

formed in future in all bigger hospitals in which breast cancer is treated.

10. Drainages, vascular interventions

X-ray fluoroscopy, US and CT are the standard guiding modalities for drainage and intravascular therapies. Positioning capability of fluoroscopy is superior to MRI for intravascular therapies, where exact position of various instruments and coils or stents must be seen simultaneously. During the recent years, MR-compatible catheters and guiding wires have been developed and intense research has been done to visualize these instruments in MRI.

MRI guidance has been proved to be useful in drainage, where two imaging modalities, US and X-ray fluoroscopy, are usually needed. The first case report of MR-guided nephrostomy was published in 1998 by Hagspiel et al. [97]. Recently, good results have been published about draining abdominal fluid collections with a hybrid IMRI system consisting on short-bore high field MR scanner with C-arm fluoroscopy. The multiplanar imaging capabilities of MRI were particularly helpful for draining subphrenic fluid collections [98]. An example of such a condition is pancreatic pseudocysts (Fig. 5).

11. Ablative therapies in MRI

MRI is frequently used for therapy monitoring and guidance. Interstitial tumour therapy can be achieved via radiation and chemical or thermal coagulation of tissue. Brachytherapy is widely in use [26]. Alcohol and other cytotoxic substances are frequently used [2] for chemical cell destruction. Thermal coagulation in tissue can be achieved by heating the tissue with laser [99,100] radiofrequency energy [101], microwaves [102], Cryotherapy [103], and focused ultrasound (FUS) [104,105]. Depending on the indication and therapy modality used the results vary from good to excellent when compared to surgery [106–109].

Laser energy has been successfully used under MRI control for thermal tumour ablation. Typically the ablation is monitored under MRI by recognizing the temperature changes in tissue. There are several ways to achieve this, of which the method based on water proton resonance frequency is the most coveted, other options include T1 relaxation time of water protons, molecular diffusion constant of water, water proton resonance frequency, proton spectroscopic imaging, temperature sensitive contrast agents, and theoretically even spin density or magnetization transfer can namely be used for MRI thermometry [21]. An example of laser ablation procedure in MRI is illustrated in Fig. 6. Vogl et al. demonstrated a series where hepatic tumours were treated with laser tumour ablation [110]. RF-energy can also be used for tumour therapy [111], although special equipment is needed with MRI [112,113].

Microwaves affect the tissue much in the same way as RF-energy by coagulating tissue. The affected area is smaller than in laser or RF-therapy. Cryotherapy destroys the tissue by a freezing effect and it can be done under MR-guidance [114]. The effect of the therapy is distributed via shattering the cell structure. The affected tissue area in cryotherapy is of the same size as in laser and RF-energy. FUS is a unique method amongst all these methods since it is truly non-invasive since it needs no skin penetration is needed. The feasibility of FUS in breast tumour therapy has been investigated [104,105].

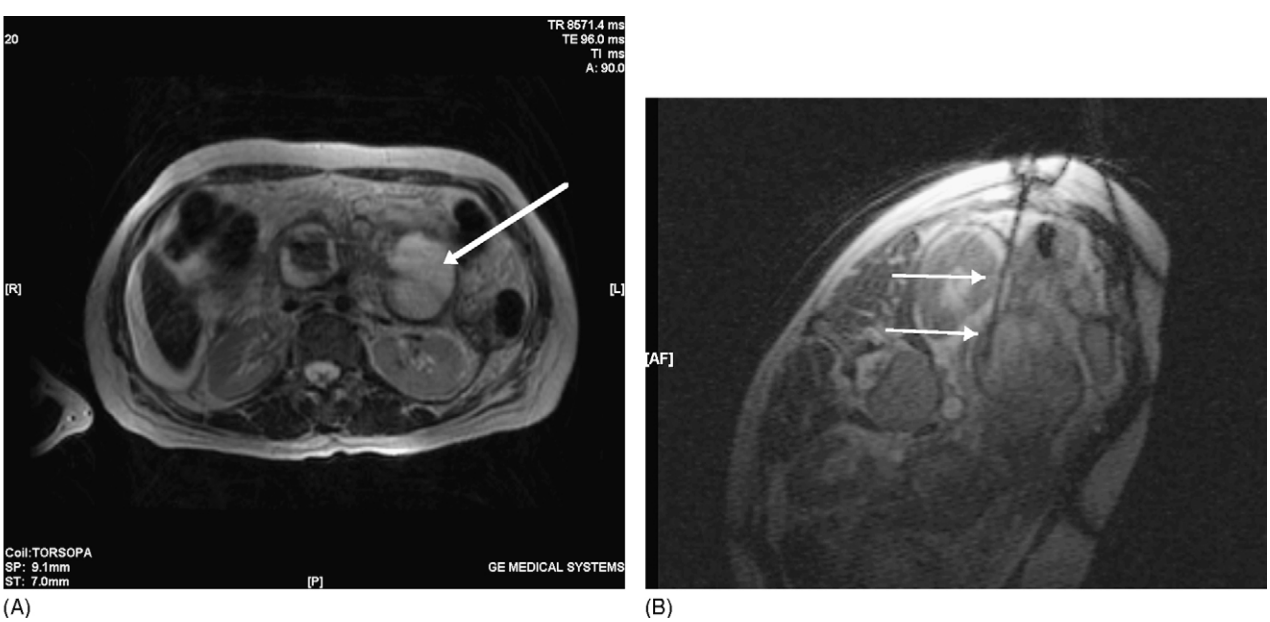

Fig. 5. (A) Pancreatic pseudocyst (arrow). High field pre-procedural image (T2). (B) Needle in pseudocyst (arrows), same patient and sequence as in (A) (image direction flipped).

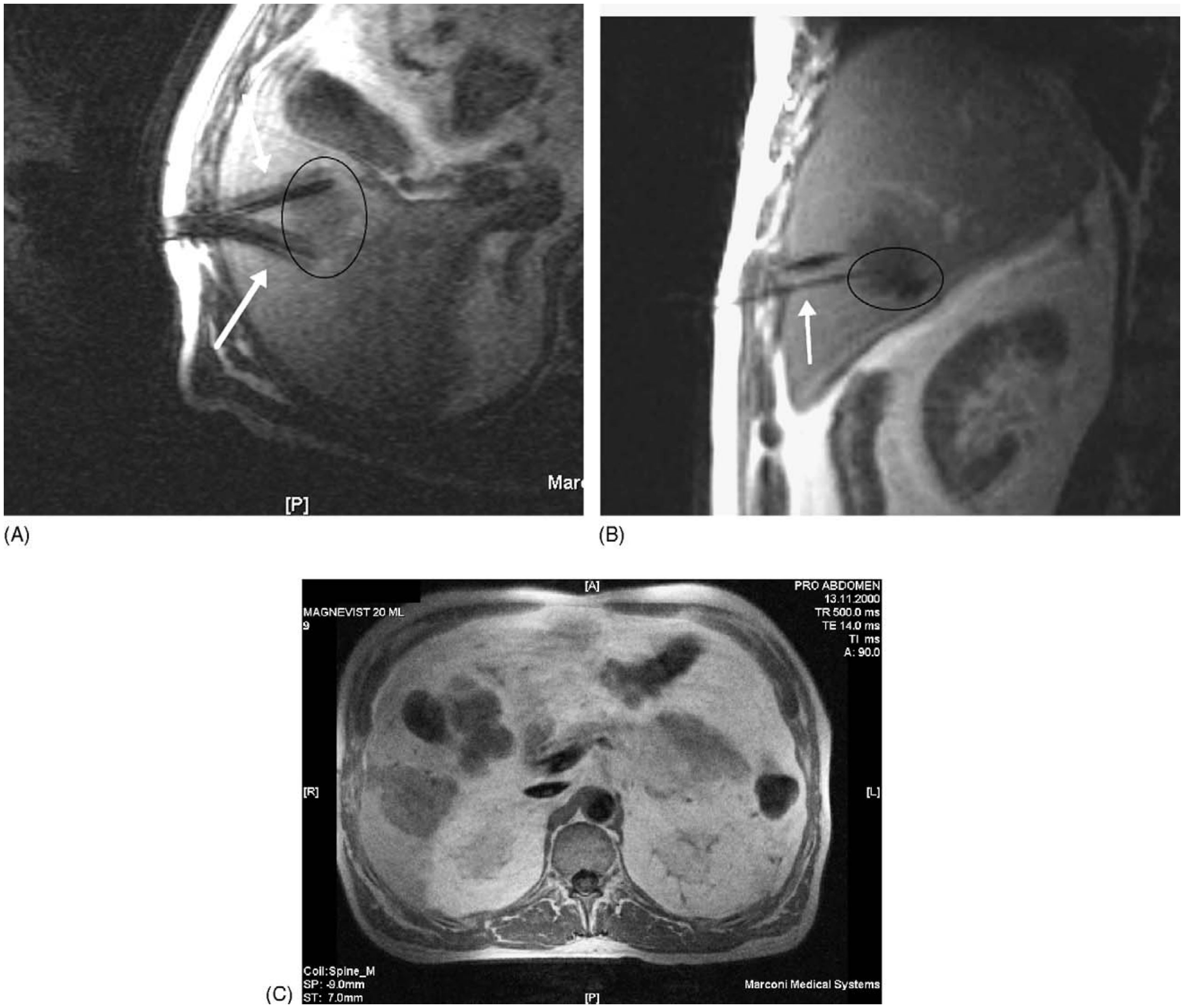

Fig. 6. (A) Liver tumour (oval) identified in interventional MRI sequence (True-FISP) image at low field device (0.23 T), laser catheters (arrows) placed into the tumour. (B) Thermal effect seen as a subtle decrease (oval) of signal around the laser probe (arrow) in MRI image, which was acquired in vivo using modified True-FISP sequence with 0.23 T scanner. (C) Post-operative MRI image of the therapy area (T1 contrast).

The uniting factor in percutaneous tumour therapies is the low morbidity and low mortality associated with these procedures [100,106]. Thermal therapy is not confined to soft tissue tumours, also bone tumours can be treated [115,116]. Primary success rate of over 90% has been reached without initial complications and with minimal invasiveness [115]. Due to low B0 in low field devices, capability to quantitatively measure temperature is limited in these devices. T1 signal decrease due to the temperature change is however readily distinguishable [117,118].

12. Intraoperative MRI

Image-guided neurosurgery has emerged as an alternative to frame-based stereotaxy and conventional neurosurgery. Intraoperative MRI is a promising method for image guidance in minimally invasive neurosurgery. In a study where neurosurgeons thought they had removed 90% of the tumour on the first attempt, post-operative MRI showed, that only 50% of the tumour, on an average, had been removed [119]. In IMRI, depending on the parameters used and the tumour type, total resection could be performed in 50–86% of brain tumours [120,121].

Most of the studies concerning this topic have been done with Signa SPTM (GE Medical Systems, Milwaukee, WI, USA), which is so far the only one to allow open direct vertical access to the operating area. The third alternative to intraoperative MR guidance is the short-bore 1.5 T scanner, which allows neurosurgery to be performed by moving the patient’s head 40 cm out of the magnet bore.

Open low field scanners have also been successfully used in neurosurgery. Open surgery is performed in a staged fashion, i.e. the patient is transported from the operative area to the

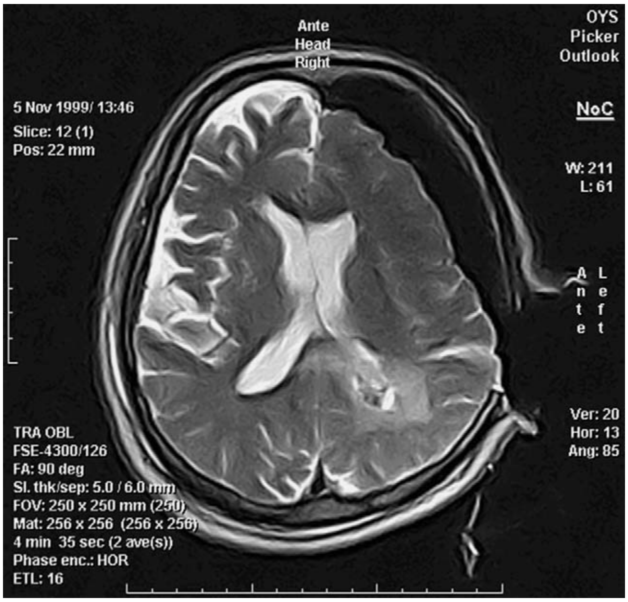

Fig. 7. An intraoperative T2-weighted image during brain tumour resection.

scanner whenever intraoperative images are needed (Fig. 7). Steinmeier et al. reported a retrospective series of 55 patients with cerebral lesions, all of whom were surgically treated in low field MRI guidance [66].

Intraoperative MRI is an imaging tool that can be used effectively for navigation with attached instrument tracking device. A low field scanners can be turned off during surgery and this can be particularly appropriate for neurosurgery if ferromagnetic, non-MRI-compatible instrumentation or equipment needs to be used [45].

13. Conclusion and future directions

When MR-guided interventions and operation are considered as a whole, it can be stated that the lack of information upon commercially available MR-guided localization and biopsy systems has obstructed the transfer of MRI as guidance modality from research sites to clinical practices. For instance, the sensitivity of MRI for visualization of the invasive breast cancer has approached 100%. Although prototypical biopsy systems have been developed, considerable progress is still required before MRI is used as 'standard' imaging modality for breast biopsy [94,122].

In neurosurgery, intraoperative MRI guidance eliminates some of the problems caused by the use of preoperative imaging in frame-based or frameless neuro-navigation systems. Intraoperative MRI allows detection of all anatomic changes that occur during the operation (e.g. brain shifts) and adjustments can be made during the procedure. The formal studies comparing success rates of conventional and MR-guided surgery is still needed.

Interventional procedures are in effect minimally invasive procedures of surgical nature. These procedures have been performed under a group of radiological imaging modalities, of which most recent is MRI. There are various MRI systems in use in which MRIs feasibility as a potential platform for interventional procedures has been demonstrated. Low field MRI scanner and open configuration high field scanners seem to be very suitable for interventional procedures, but there is still lack of clinical studies demonstrating the clinical feasibility of MR-guidance in more complicated interventional procedures. Also, extended assessment of clinical data is essential to establish cost effectiveness of IMRI procedures, although there are preliminary reports upon this [123]. Despite the inherent potential of MRI guided interventions and operations it is more probable that in the future MRI and operating room will be functionally integrated with other imaging modalities to become a multifunctional unit. This type of installation will allow the separate use of modalities and combination of them when needed. Cross-modality image integration, spatial and temporal information of the anatomy, pathology and therapy devices will be provided to the users of these systems. This will reflect in the best achievable control of the treatment where multiple control mechanisms can be used simultaneously.

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