Juho Kariniemi

MAGNETIC RESONANCE IMAGING-GUIDED PERCUTANEOUS ABDOMINAL INTERVENTIONS
Abstract

Magnetic resonance imaging (MRI) provides high contrast and spatial resolution images in arbitrarily chosen plane without ionizing radiation. These valuable features make it an attractive technique for guiding percutaneous interventional procedures. The purpose of this study was to develop percutaneous abdominal diagnostic and therapeutic procedures in MRI surroundings by evaluating the feasibility, safety and clinical results of specific interventional procedures.

The safety and accuracy of MRI-guided abdominal biopsy was evaluated by performing MRI-guided biopsy on 31 patients who were not amenable for an ultrasound-guided biopsy. The locations of the lesions were liver, pancreas, lymph node, retroperitoneal mass, adrenal gland, and spleen. Fine-needle aspiration (FNA) biopsy was performed on all 31 patients; 18 patients underwent both FNA biopsy and cutting needle core biopsy. The sensitivity, specificity and accuracy of FNA and core biopsies were 71, 100 and 81%, and 90, 100 and 94%, respectively. No immediate or late complications occurred.

The feasibility and safety of MRI-guided percutaneous drainage of pancreatic fluid collections was assessed by performing ten percutaneous drainages under MRI-guidance. Five of the patients had symptomatic pseudocysts and five had pancreatic abscesses. All procedures were performed with an MRI-compatible drainage kit using the Seldinger technique. All drainage catheters could be successfully placed into the pancreatic fluid collections under MRI-guidance with a mean procedure time of 44 minutes. No immediate complications occurred.

The feasibility and safety of MRI-guided percutaneous nephrostomy was evaluated by performing eight nephrostomies with MRI-guidance. The degree of the dilatation of the renal collecting system varied from minimal to severe. All procedures were performed solely under MRI guidance with MRI-compatible instruments. Seven out of eight nephrostomies were successfully performed under MRI guidance; nephrostomy catheter could not be placed in a nondilated system. The mean procedure time was 26 minutes. No major complications occurred during the procedures or follow-up.

The safety and effectiveness of MRI-guided percutaneous laser ablation for the treatment of small renal cell carcinoma (RCC) was assessed by treating eight patients with ten tumors with percutaneous MRI-guided laser ablation. All tumors were biopsy-proven RCCs. One to four laser fibers were used per tumor and the tumors were ablated under near real-time MRI control. All but one tumor were successfully ablated in one session. One complication, a myocardial infarction, occurred; all other patients tolerated the procedure well. No local recurrence was discovered during the follow-up with a mean time of 20 months.

Keywords: abdomen, ablation procedures, biopsy, drainage, laser, magnetic resonance imaging, percutaneous
Kariniemi, Juho, Vatsan magneettiohjatut perkutaaniset toimenpiteet.
Oulun yliopisto, Lääketieteellinen tiedekunta, Diagnostiikan laitos, Radiologia, Klinisen lääketieteen laitos, Kirurgia, PL 5000, 90014 Oulun yliopisto
Oulu

Tiivistelmä

Magneettiohjattujen vatsan neulanäytteiden turvallisuutta ja tarkkuutta arvioitiin 31 potilaalla, joille ei voitu tehdä ultraräntäohjattuja biopsiaa. Näytteitä otettiin maksasta, haimasta, imusolmukkeista, retroperitoneaalisista kasvaimista, lisämunuaisista ja pernasta. Kaikilta 31 potilaalta otettiin solunäyte, 18 potilaalta otettiin lisäksi kudonsäyte. Solunäytteiden sensitivisyys oli 71 %, spesifisyyys 100 % ja tarkkuus 90 %; kudonsäytteissä vastaavat luvut olivat 90 %, 100 % ja 94 %. Neulanäytteiden otosta ei aiheutunut yhtään komplikaatiota.

Magneettiohjauksen soveltuvuutta ja turvallisuutta haiman nestekevymien perkutaanisessa drenaauksessa arvioitiin kymmenellä potilaalla, joista puolet oli oireileva haiman pseudokysti ja puolet haiman abses. Kaikki kanavoinnit tehtiin Seldingerin tekniikalla käyttäen magneettiyhteensopivia toimenpidevälineitä. Kaikkien nestekevyyn drenaauksen magneettiohjattua toimenpide onnistui ilman välistöä komplikaatioja ja keskimäärin toimenpiteeseen kului aikaa 44 minuuttia.


Asiakansat: biopsia, drenaasi, laserpolto, magneettikuvauksesta, perkutaaninen, vatsa
To my family
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Oulu, October 2011

Juho Kariniemi
### Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>two-dimensional</td>
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<tr>
<td>3D</td>
<td>three-dimensional</td>
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<tr>
<td>b-FFE</td>
<td>balanced fast field echo</td>
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<tr>
<td>CEUS</td>
<td>contrast-enhanced ultrasound</td>
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<tr>
<td>CT</td>
<td>computed tomography</td>
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<td>F</td>
<td>French</td>
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<td>FA</td>
<td>flip angle</td>
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<tr>
<td>FIESTA</td>
<td>fast imaging employing steady-state acquisition</td>
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<td>FISP</td>
<td>fast imaging with steady-state precession</td>
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<td>FNA</td>
<td>fine needle aspiration</td>
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<td>FOV</td>
<td>field of view</td>
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<td>HIFU</td>
<td>high-intensity focused ultrasound</td>
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<tr>
<td>LED</td>
<td>light emitting diode</td>
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<td>MR</td>
<td>magnetic resonance</td>
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<td>MRI</td>
<td>magnetic resonance imaging</td>
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<tr>
<td>Nd:YAG</td>
<td>neodymium-doped yttrium aluminum garnet</td>
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<tr>
<td>PCN</td>
<td>percutaneous nephrostomy</td>
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<tr>
<td>PRF</td>
<td>proton resonance frequency</td>
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<tr>
<td>RF</td>
<td>radiofrequency</td>
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<td>RFA</td>
<td>radiofrequency ablation</td>
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<td>RCC</td>
<td>renal cell carcinoma</td>
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<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>SSFP</td>
<td>steady-state free precession</td>
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<td>T</td>
<td>Tesla</td>
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<td>T1</td>
<td>T1-weighted</td>
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<td>T2</td>
<td>T2-weighted</td>
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<tr>
<td>TA</td>
<td>acquisition time</td>
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<td>TE</td>
<td>echo time</td>
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<td>TR</td>
<td>repetition time</td>
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<tr>
<td>TSE</td>
<td>turbo spin-echo</td>
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<tr>
<td>US</td>
<td>ultrasonography, ultrasound</td>
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List of original publications

This thesis is based on the following articles, which are referred to in the text by their Roman numerals.


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1 Introduction

Interventional radiology is a therapeutic and diagnostic subspecialty that comprises a wide range of minimally invasive image-guided therapeutic procedures as well as invasive diagnostic imaging. The range of diseases and organs amenable to image-guided therapeutic procedures is extensive and constantly evolving; it includes diseases of the vascular, gastrointestinal, hepatobiliary, genitourinary, pulmonary, musculoskeletal, and central nervous system (Kaufman et al. 2010). The fundamental motivation in the development of percutaneous image-guided procedures is to improve patient care by reducing the invasiveness of the therapeutic procedure.

Image-guided percutaneous procedures are, by definition, heavily dependent on imaging, and the development of such procedures has been tightly coupled with the evolution of visualization techniques. As imaging has progressed from simple, static X-rays to modern computer-based imaging, the range of therapeutic applications has become more extensive. In contemporary interventional radiology practice, X-ray fluoroscopy, ultrasound (US) and computed tomography (CT) are the standard imaging methods used during percutaneous therapeutic procedures.

Soon after magnetic resonance imaging (MRI) was introduced into diagnostic imaging in the early 1980s, its potential to guide percutaneous procedures was recognized. Research on the use of MRI to guide percutaneous interventional procedures has been driven by the plethora of MRI-technique-related valuable features including superb soft tissue contrast, multiplanar capabilities, lack of radiation, and functional imaging. MRI-guided interventions were started by performing simple needle navigations in the MRI environment. Since then, facilitated by advances in MRI hardware, visualization techniques, data postprocessing, instrumentation, and navigation, minimally invasive therapy under MRI guidance has grown to include a great number of therapeutic applications, such as endovascular procedures, thermal ablation, targeted drug delivery, stem cell therapy, and brachytherapy. (Kahn et al. 2008)

The purpose of this study was to develop MRI-guided percutaneous abdominal diagnostic and therapeutic procedures by evaluating the feasibility, safety and clinical results of specific interventional procedures.
2 Review of the literature

2.1 Percutaneous image-guided abdominal procedures

Percutaneous abdominal interventional procedures provide anatomic, bacteriologic or tissue diagnosis, physiological data, or a therapeutic alternative to conventional management. Most percutaneous image-guided procedures are based on the premise that a thin needle can be safely inserted into almost any organ of the human body without significant damage. This fundamental principle has spawned a multitude of applications in different abdominal organ systems and pathological conditions. All of these procedures share the common attributes of image guidance and minimally invasive approach, which has led to the broad adoption of needle or catheter-based procedures in the diagnosis and management of many common diseases.

2.1.1 Needle biopsy

Because many disease processes cannot be characterized definitively with diagnostic imaging alone, a tissue diagnosis is often necessary to guide subsequent management. Patients may present with clinical symptoms related to abdominal diseases, but the increasing use and sensitivity of radiological techniques has also led to the identification of incidental small lesions that require accurate tissue diagnosis. For these reasons biopsy has become one of the cornerstones of modern medicine. Although abdominal biopsies can be performed surgically, laparoscopically, or endoscopically, percutaneous image-guided techniques have virtually replaced more invasive procedures due to significant reduction in morbidity, mortality, time and cost. Hence, needle biopsy is today the most frequently performed interventional procedure in radiology practice (Gazelle & Haaga 1989, Mueller & vanSonnenberg 1990).

The most common indication for percutaneous abdominal biopsy is the diagnosis of malignancy, including primary neoplasms, metastatic disease, tumor staging, and recurrent disease after treatment. Biopsies are also used for diagnosis of inflammatory or infectious processes, abnormal fluid collections, and diffuse organ disease. Relative contraindications include uncorrectable coagulation abnormalities, lack of a safe pathway to the lesion, and an uncooperative patient (Charboneau et al. 1990). Virtually any location in the abdomen can be reached
with imaging-guided percutaneous biopsy, but the most common sites for biopsies are the solid organs, liver, adrenal gland, pancreas, and kidney. Peritoneal or retroperitoneal soft tissue masses and lymph nodes are also amenable to percutaneous biopsy techniques.

The choice of biopsy technique in terms of both instrument selection and imaging guidance depends on several factors. These include the size, location and vascularity of the lesion, the presence of intervening structures along the biopsy route, the amount of tissue required, and the preference and experience of the interventionist. A sample from a lesion can be obtained by either aspiration of pathologic material or by mechanical cutting of tissue. Fine-needle aspiration biopsy (FNAB) is a method whereby a very small quantity of tissue, fluid and cells is aspirated from a lesion with thin (20 to 25 gauge) needles. The aspirated material then undergoes cytologic or microbiologic evaluation, and if cell blocks are present, histologic analysis as well. Histologic sample, however, is more often obtained by using larger (14 to 19 gauge) cutting needles. Automated biopsy devices, which consistently provide high-quality tissue specimens, have improved the results of cutting needle biopsies (Elvin et al. 1990, Moulton & Moore 1993). In general, FNAB is sufficient for the diagnosis of malignancies and fluid samples, whereas for the diagnosis of lymphoma, rare tumors and benign disease, large-bore cutting needle biopsies are considered more accurate (Ha et al. 1991). On the other hand, combined use of FNAB and core needle biopsy has been shown to yield better biopsy results (Tikkakoski et al. 1993, Moulton & Moore 1993, Stewart et al. 2002).

The diagnostic accuracy of abdominal biopsy varies according to the anatomic site and the type of technique used, but typically accuracies ranging from 90% to 100% have been reported in the liver, kidney, and adrenal gland (Sundaram et al. 1982, Alspaugh et al. 1983, Martino et al. 1984, Nadel et al. 1986, Welch et al. 1994, Schmidbauer et al. 2008). Slightly lower accuracies in the range of 61–98% have been published for the biopsy of pancreatic and retroperitoneal lesions (Erwin et al. 1986, Welch et al. 1989, Hartwig et al. 2009). Image-guided percutaneous abdominal biopsy is a safe procedure, rarely causing significant complications. In a review of 11,700 patients who underwent percutaneous fine-needle abdominal biopsy the total complication rate was 0.55%, major complications occurred in 0.05% of the patients, and the mortality rate was 0.008% (Livraghi et al. 1983). Use of larger needles or cutting needles does not significantly increase the complication rates (Martino et al. 1984, Nyman et al. 1995). Another concern is the possible seeding of malignant tumor
cells along the needle tract. This, however, is extremely rare; in a study of 63,180 patients (Smith 1984), seeding was seen in 0.005%.

The choice of imaging used to guide biopsy rests on the ability of the modality to visualize both the lesion and the needle with adequate depiction of the surrounding anatomy. These criteria are well met by CT and ultrasound in all but the fewest cases, resulting in the current practice that the vast majority of abdominal biopsy procedures are performed using either one or the other of these modalities. In fact, these well-established techniques allow for biopsy with such a high success rate that there has been little room for MRI guidance in abdominal lesions. Nevertheless, there are a few circumstances where MRI guidance provides added value both in terms of safety and yield for abdominal biopsies. Firstly, MRI guidance is advantageous when the target lesion is not sufficiently visualized using the standard modalities, and the patient might otherwise be considered for more invasive procedures (Lewin et al. 1998, Rofsky et al. 1998, Schmidt et al. 1999, Lewin et al. 2000, Zangos et al. 2003a). Improved lesion conspicuity can be achieved with the inherent high soft tissue contrast of native MRI (Boll et al. 2004), or if needed, with contrast-enhanced MRI guidance (Konig et al. 2004). Secondly, with MRI it is possible to increase the biopsy yield by guiding the needle into viable tumor tissue instead of areas of necrosis (Deng et al. 2009). Finally, the multiplanar capabilities and high vascular conspicuity of MRI facilitate targeting lesions in complex anatomic locations, such as within the dome of the liver, in the subfrenic regions, in the adrenal glands, or in the retroperitoneum (Frahm et al. 1996b, Lu et al. 1997, Adam et al. 1999, Konig et al. 2003, Zangos et al. 2006).

### 2.1.2 Drainage of pancreatic fluid collections

Acute pancreatitis refers to inflammation of the pancreas with variable secondary involvement of adjacent tissues and remote organ systems (Bradley 1993). The incidence of acute pancreatitis in Finland is about 70 per 100,000 population, and it has been rising along with the increased consumption of alcohol (Jaakkola & Nordback 1993). The most common cause of pancreatitis in Finland is alcohol ingestion, which accounts for up to 70% of all cases, followed by gallstones, which are behind acute pancreatitis in 20% of patients (Kylanpaa et al. 2006). In 80% of cases, acute pancreatitis is mild and resolves without serious morbidity, but in up to 20%, acute pancreatitis is complicated by substantial morbidity and mortality (Lund et al. 2006). Complications may be systemic, local or both.
Systemic complications extend from mild complications to life-threatening multi-organ failure. Local manifestations, which include pancreatic necrosis and fluid collections, are also potentially lethal.

The fluid collections associated with pancreatitis can be divided into acute peripancreatic fluid collections, pseudocysts, and abscesses (Bradley 1993). Acute peripancreatic fluid collection represents a serous or exudative reaction to pancreatic injury, and the fluid composition is similar to that of plasma. They have a strong tendency to resolve spontaneously and do not need any treatment, unless they become infected, i.e. abscesses, or develop into pseudocysts. Pseudocysts form when there is direct leakage of pancreatic juice from the inflamed gland due to ductular disruption. The following inflammatory response induces the formation of a distinct cyst wall which in time organizes with connective tissue and fibrosis (Richter 1998). Pseudocysts can also resolve spontaneously and the indications for therapy are presence of symptoms, enlargement of cyst, and complications, such as infection, hemorrhage, rupture, and biliary or gastrointestinal obstruction (Pitchumoni & Agarwal 1999). Pancreatic abscess is a circumscribed collection of pus containing little or no necrosis, typically locating in the proximity of the pancreas. By definition, pancreatic abscesses also include late infected acute fluid collections and infected pseudocysts, as well as postoperative collections. Invasive treatment is always warranted, because pancreatic abscess is a highly lethal complication of acute pancreatitis (Katsohis et al. 1989).

Currently, the major modes of therapy for pancreatic fluid collections are image-guided percutaneous drainage, endoscopic drainage, surgical intervention and a combination of these. Needle aspiration alone as therapy, even if performed multiple times, is usually not adequate as a cure because of recurrence of the collection (vanSonnenberg et al. 1989b). The choice of procedure depends on several factors concerning both the patient and the fluid collection, but institute preference also plays a major role in the decision (Lee et al. 1992, Banks 1997, Lee et al. 1998b). While many percutaneous drainage procedures are curative, some are performed to stabilize the critically ill patient prior to definitive surgery (vanSonnenberg et al. 1984, Balthazar et al. 1994). Conversely, partially successful surgical therapy is often followed by percutaneous drainage (vanSonnenberg et al. 1989a, vanSonnenberg et al. 2001). The results of percutaneous drainage are significantly influenced by the clinical scenario. In optimal circumstances the cure rates for pancreatic pseudocysts are usually in the 90% range (vanSonnenberg et al. 1989a, Adams et al. 1990, Wittich &

The best access route for percutaneous fluid collection drainage is the shortest and safest tract. The trocar technique as well as the Seldinger technique may be used in the placement of the catheter. The preferred approach is to avoid traversal of vital structures, such as the pleura, bowel and major vessels (Picus & Marx 1991). However, if a direct route is not available, solid abdominal organs, and even the stomach or small bowel may be traversed in order to provide optimal drainage (Wittich et al. 1995). A transgastric route can also be deliberately chosen, especially in drainage of pancreatic pseudocysts (Sacks & Robinson 1988). The advantage of this approach is the diminished risk of pancreaticocutaneous fistula. Another option in pseudocysts is cystogastrostomy, which is usually inserted with endoscopic techniques, but can also be placed percutaneously (Davies et al. 1996).

The standard imaging modalities used for guiding percutaneous drainage of pancreatic fluid collections are CT and ultrasound, the latter sometimes combined with x-ray fluoroscopy (vanSonnenberg et al. 1982, Clark & Towbin 1983, vanSonnenberg et al. 1989b, Palmeri et al. 1997, Zerem et al. 2002). At present, scientific literature on percutaneous MRI-guided drainage in general is scarce. Three preliminary reports in a small number of patients with heterogeneous fluid collections, including one pancreatic pseudocyst, have demonstrated the initial feasibility of MRI-guidance alone (vanSonnenberg et al. 1988, Gehl et al. 1996) or in conjunction with fluoroscopy (Buecker et al. 2001) in percutaneous drainages.

2.1.3 Nephrostomy

Since its initial description over 50 years ago (Goodwin et al. 1955), the placement of a catheter into the renal collecting system, i.e. percutaneous nephrostomy (PCN), has become the foundation of interventional uroradiology used in a wide range of clinical settings. The most common indication for PCN is the relief of urinary tract obstruction, which can be caused by extrinsic pelvic malignancy, prostate or urothelial carcinoma, ureteral or anastomotic stricture, pyonephrosis or stone. PCN can also be used as a urinary diversion in urinary tract fistula or hemorrhagic cystitis. Another important indication for PCN is to gain access for a subsequent interventional urologic procedure, such as ureteral
stent placement, nephrolithotomy, dilatation of ureteral stricture, endopyelotomy, biopsy, or foreign body removal. In some situations, PCN acts as a temporizing measure prior to corrective surgery or endoscopic treatment, but in certain cases, e.g. in malignant diseases or ureteral fistula, it alone may be the definitive treatment. The relative contraindications to PCN are uncorrectable severe coagulopathy and terminal illness with imminent death.

Technical success rates for PCN vary depending on the clinical scenario, particularly on the degree of hydronephrosis. In patients with obstructed, dilated collecting systems, a PCN can be placed in 98–99% of patients (Stables et al. 1978, Lee et al. 1994, Farrell & Hicks 1997). The success rate is lower (85%) in patients with nondilated collecting systems (Ramchandani et al. 2003). When all complications related to PCN are considered together, they occur in approximately 10% of patients. However, major complications, such as sepsis, bleeding requiring transfusion, and puncture of adjacent organs, are uncommon, occurring in 1–4% of the procedures (Kaskarelis et al. 2001, Ramchandani et al. 2003).

The technique of PCN, including the imaging used for guidance, varies according to institute and operator preference, as well as according to the degree of dilatation of the collecting system. The most frequently used method is combined sonographic and fluoroscopic guidance, in which the initial puncture of the dilated collecting system is done with use of ultrasound, and all the subsequent steps of the procedure, guide wire advancement, tract dilatation and catheter placement, are done under fluoroscopic guidance (Zegel et al. 1981, Farrell & Hicks 1997, Wah et al. 2004, Cormio et al. 2007). After opacifying the collecting system with contrast media, the procedure can be performed under fluoroscopic guidance alone (Hunter et al. 1984, Zagoria & Dyer 1999, Dyer et al. 2002, Rana et al. 2007). Other variations of the technique include the exclusive use of ultrasound (van Sonnenberg et al. 1992, von der Recke et al. 1994, Gupta et al. 1997) or CT (Thanos et al. 2006, Egilmez et al. 2007) in guidance, and combined CT- and fluoroscopic guidance (Barbaric et al. 1997).

Experience with MRI-guided PCN is very limited. The first case report of an MRI-guided PCN in a single patient with an obstructed kidney was published over a decade ago (Hagspiel et al. 1998). Since then, only two experimental studies in nondilated porcine urinary tract have emerged (Merkle et al. 1999, Nolte-Ernsting et al. 1999).
2.1.4 Ablation of renal cell carcinoma

Kidney cancers account for about 3% of all cancer cases in Finland, with 738 new diagnoses and 346 deaths in 2007 (Finnish Cancer Registry 2009). The term kidney cancer includes all malignant tumors originating from a primary site in the kidney. Renal cell carcinoma (RCC) is by far the most common kidney cancer, comprising 85% to 90% of these malignant tumors. The incidence of RCC has been increasing worldwide, largely due to the widespread use of new and improved, noninvasive abdominal imaging modalities. More than 60% of RCCs are now detected incidentally in asymptomatic patients (Volpe et al. 2004). Typically, these serendipitously discovered RCCs present at an early stage, are small (≤ 4 cm) and generally slow growing, and occur in elderly patients with comorbid conditions (Jayson & Sanders 1998, Hafez et al. 1999, Hollingsworth et al. 2006).

Radical nephrectomy has long been the standard of care for the treatment of RCC. However, the shift in diagnosis of RCC toward small asymptomatic tumors has prompted the evolution of management of small RCC to nephron-sparing surgery, open or laparoscopic partial nephrectomy, which have been shown to produce oncologic outcomes equivalent to that of radical nephrectomy for patients with small renal tumors (Fergany et al. 2000, Uzzo & Novick 2001). Because local tumor resection without removal of the kidney has proven effective, there has been interest to develop even less invasive techniques for tumor eradication. Percutaneous thermal ablative therapies represent a treatment strategy that enables management of RCC as a minimally invasive procedure. Compared to surgical extirpation, potential benefits of thermal ablation include diminished perioperative morbidity, shorter hospital stay, quicker recovery, preservation of renal function, and the possibility to treat surgically unfit patients (Aron & Gill 2005, Lehman & Landman 2008). Furthermore, percutaneous thermal ablation is less expensive than surgery in the treatment of RCC (Lotan & Cadeddu 2005, Pandharipande et al. 2008).

Several different thermal ablation modalities have been used to eradicate RCC. Most methods of thermal ablation destroy the tumor by using heat to kill the malignant cells. When tissue temperature is increased over 60°C, near instantaneous irreversible cellular damage occurs (Goldberg & Gazelle 2001). In radiofrequency ablation (RFA) and microwave ablation (Yoshimura et al. 2001, Carrafiello et al. 2010), electromagnetic energy provides the heat necessary to induce tissue necrosis. In laser ablation, the destruction of tissue is induced by
conversion of absorbed light into heat, whereas in high-intensity focused ultrasound (HIFU) heat is produced by sound energy. In cryoablation, on the other hand, cellular death is accomplished by rapid freezing of the target tissue to at least −40°C, followed by a thawing phase. This freeze-thaw cycle is then usually repeated, resulting in cell death by two mechanisms: a direct cytotoxic effect from intracellular ice crystallization during freezing and vascular injury with resultant ischemia during thawing (Hoffmann & Bischof 2002, Baust & Gage 2005).

For nearly all methods of thermal ablation, energy is delivered with needle-shaped applicators, which are placed in the tumor either percutaneously or laparoscopically. The only exception to this is HIFU ablation, which can be performed noninvasively from extracorporeal US energy source (Wu et al. 2003, Marberger et al. 2005, Hacker et al. 2006). Of these various ablation techniques, the most widely clinically applied ones in renal tumor ablation are RFA (Farrell et al. 2003, Merkle et al. 2005, Gervais et al. 2005b, Park et al. 2006, Hegarty et al. 2006, Zagoria et al. 2007, Raman et al. 2008, Levinson et al. 2008) and cryoablation (Silverman et al. 2000, Cestari et al. 2004, Gupta et al. 2006, Hegarty et al. 2006, Bandi et al. 2007, Atwell et al. 2008, Tsivian et al. 2010).

Laser ablation has been extensively used, with excellent results, to treat malignant hepatic tumors, with the largest published series of any percutaneous ablative technique (Vogl et al. 2002). Although laser is likely just as effective ablating RCC as hepatic malignancy, experience in renal ablation is very limited. Outside of an experimental study (Lotfi et al. 1994), only one clinical report with a small number of patients has emerged; however, no complete ablations of the tumors were achieved in that study (Dick et al. 2002).

2.2 Guiding methods for percutaneous abdominal procedures

Reliable image guidance is a basic prerequisite for all percutaneous interventional procedures. The term “image guidance” refers to ways in which different imaging techniques are used before, during, and after the intervention. In every percutaneous abdominal procedure, imaging is used at least in planning and targeting. Before the procedure, when an intervention is planned, the images are reviewed to determine whether a patient is a suitable candidate for the procedure at hand, what the best route for the intervention is, and what critical structures should be avoided. Targeting during the procedure involves accurate visualization of the target organ or lesion, surrounding anatomy, and the devices used in the intervention. Furthermore, in therapeutic procedures, imaging has to be able to
monitor and control the procedure during the intervention. Monitoring a procedure describes the process in which changes in imaging findings that occur due to the intervention are viewed. These changes are then utilized to control the procedure by the operator. Finally, after the procedure, imaging is used to assess treatment response. X-ray fluoroscopy, US, CT, and more recently MRI are the imaging techniques available for these purposes.

2.2.1 X-ray fluoroscopy

X-ray fluoroscopy has been the standard imaging modality for percutaneous interventional procedures since their invention, and despite the advent of new modalities, it still has an essential role in interventional radiology. X-ray fluoroscopy has several strengths as a guiding tool: it provides high spatial and temporal (30 frames per second) resolution imaging and excellent contrast for the devices used in percutaneous interventions. These features would make circumstances imaging-wise almost ideal for a percutaneous procedure; real-time control and superior visualization of the instruments during the intervention. However, especially in abdominal procedures, fluoroscopy is hampered by virtually non-existent soft tissue contrast. This means that the operator would have to rely upon secondary anatomical landmarks when targeting soft tissue lesions. Therefore, contrast material is needed to opacify otherwise invisible abdominal targets, such as urinary tract structures. Despite the development of contrast materials over the past decades, there is still a potential risk of adverse effects with these agents (Namasivayam et al. 2006). An alternative means to circumvent the poor soft tissue contrast of fluoroscopy is to combine it with cross-sectional imaging, such as US, to be able to utilize the strengths of each imaging technique. This technique is routinely employed for instance in the placement of a percutaneous nephrostomy catheter (Farrell & Hicks 1997).

Another disadvantage of fluoroscopy is the radiation exposure to the patient and the personnel. The radiation dose depends on a number of factors; however, particularly in abdominal procedures, the operator’s close proximity to the radiation field, large size of the object, and lengthy operation times are prone to increase the dose to the staff (Stratakis et al. 2006). Recent developments in x-ray technology, such as flat-panel detectors, have not been inherently able to reduce the radiation dose (Chida et al. 2009). Although the risks of ionizing radiation are generally considered to be outweighed by the benefits to the patient, a radiation-free technique, if feasible, is preferable. This issue has also been addressed in
European and national legislation regarding the use of radiation in medical procedures (European Union 1997).

X-ray fluoroscopy produces a two-dimensional projection image of a three-dimensional object. This single-plane character of fluoroscopy inherently limits the acquired information, rendering it difficult to localize a device’s true position in relation to the target. A recently introduced clinical development, a system in which a cone-beam x-ray tube and a flat-panel detector are integrated with a C-arm gantry, has the ability to expand X-ray fluoroscopy beyond a single plane. The key advantage of this concept is that in addition to an advanced fluoroscopic capability, it allows image acquisition and rotation around an isocenter to occur simultaneously, making three-dimensional and cross-sectional image reconstruction possible (Siewerdsen et al. 2005, Hirota et al. 2006). An application of this technology for percutaneous needle interventions utilizes dedicated needle path planning software merged with cone beam CT enabling real-time three-dimensional fluoroscopy (Racadio et al. 2007, Braak et al. 2010).

2.2.2 Ultrasound

The development of US-guided percutaneous interventions coincided with the evolution of diagnostic US in the 1970s. (Holm et al. 1972, Gronvall et al. 1977) Today, US is a well-established guidance tool for the majority of abdominal procedures, such as needle biopsy, aspiration, and drainage of fluid collections. In many institutions, ultrasound is the modality of choice for these percutaneous interventions because of the several advantages it offers. Ultrasound units are widely available, small and mobile, capable of traveling to a patient’s bedside, if needed. This also makes it easy to combine US with other imaging modalities, such as X-ray fluoroscopy. Compared with other cross-sectional imaging, US equipment is relatively inexpensive. Adding to the cost-effectiveness, compared to CT, US-guided procedures require less time to perform (Kliewer et al. 1999). Images are created from sound waves, which makes US safe for the patient, interventionist and support staff. US allows visualization of the anatomy in any desired plane, making it easy to use angled approaches whenever needed. With the application of color flow Doppler imaging the vascular structures can be identified and avoided, helping to prevent complications. The most beneficial aspect of US is its real-time capability, which enables the operator to see the target, devices and intervening structures at all times during the procedure. These
features enable the interventionist to plan and target precisely, which is expressed as increased accuracy (Sheafor et al. 1998, Dameron et al. 1999).

A recent development in US technology, contrast-enhanced ultrasound (CEUS), is further expanding the possibilities of US as a guidance method. With contrast specific imaging techniques, after intravenous administration of microbubble contrast agent, CEUS allows imaging of blood flow at the tissue perfusion level, analogous to that shown on contrast-enhanced CT and MRI. This technique has numerous applications in diagnostic imaging in different anatomical locations (Furlow 2009). In percutaneous abdominal procedures, CEUS has been introduced to help in guiding liver biopsy (Yoon et al. 2010), percutaneous transhepatic cholangiography (Ignee et al. 2009), and RFA of hepatic tumors (Minami et al. 2007), as well as to assess treatment response after RFA of hepatic (Dill-Macky et al. 2006) and renal tumors (Hoeffel et al. 2010). Compared to other contrast agents used in imaging, US contrast agents are safe, with a low incidence of side effects, they are neither nephrotoxic nor cardiotoxic and do not require renal function tests before their administration (Jakobsen et al. 2005).

US is optimal for targets located superficially or at moderate depth in thin to average-sized patients. The major disadvantage of US is the inability of sound waves to penetrate through surgical dressings or wounds in patients’ skin, overlying bowel gas or bone, or thick soft tissue in obese patients. In these circumstances US image quality may be sufficiently degraded to make safe execution of a procedure impossible (Atwell et al. 2005). Furthermore, guide wires and catheters are not readily seen with ultrasound, which makes it difficult to perform procedures requiring advanced manipulation of these devices under ultrasound guidance alone.

### 2.2.3 Computed tomography

Soon after CT was developed for diagnostic imaging in the 1970s, its value as a guidance tool for percutaneous interventions was discovered (Haaga & Alfidi 1976). Since then, owing to the many advantages of CT-guidance, these procedures have become widely disseminated throughout the world. The main assets of CT are its superior contrast and spatial resolution and ability to image areas not well demonstrated by US, such as the lung, retroperitoneum, and bone. It is also superior to US in the large patient and when targets are obscured by bowel gas (Welch et al. 1989, Charboneau et al. 1990). CT’s ability to accurately
image a wide range of densities provides the flexibility to use standard equipment in percutaneous interventions, which is an important advantage over MRI (Lewin et al. 1996).

The principal disadvantage of CT is the inherent radiation exposure to the operator and patient (Teeuwisse et al. 2001). Another drawback of CT is the limited orientation of the gantry, which, without significant post-processing, not only makes CT a single-plane technology, but allows only axial or near-axial planes to be used in interventions. The physical properties of the gantry also limit access to the patient and the usage of long instruments. Traditionally, compared with US and fluoroscopy, CT has also been limited by its lack of continuous imaging capability. Therefore, CT has been associated with longer procedure times owing to the incremental scanning. The development of CT fluoroscopy, however, made near real-time image reconstruction and displaying possible (Katada et al. 1996). Since its inception, CT fluoroscopy has been used to guide a variety of percutaneous interventions, including abdominal procedures (Froelich et al. 1998, Daly et al. 1999, Zech et al. 2002, Lagana et al. 2008).

CT fluoroscopy has the potential for increased procedure efficiency by reducing the time needed for an intervention. Theoretically, shorter operation time also reduces the radiation dose; however, if used improperly with high current and prolonged CT fluoroscopy time, there is a potential for considerable radiation exposure to the patient and personnel (Silverman et al. 1999). Compared to X-ray fluoroscopy, for a given fluoroscopy time period, the patient dose in CT fluoroscopy is twenty-fold (Nawfel et al. 2000). Therefore, in addition to other measures to lower the radiation dose, it is recommendable to use an intermittent CT fluoroscopy operational mode (Carlson et al. 2001, Paulson et al. 2001). This, on the other hand, prevents the full capitalization of the real-time capability of CT fluoroscopy.

### 2.2.4 Magnetic resonance imaging

Investigators begun to explore the possibilities of using MRI as a guiding method for percutaneous procedures soon after MRI was introduced into diagnostic imaging in the early 1980s (Mueller et al. 1986, Lufkin et al. 1988, Duckwiler et al. 1989). The goal of this ongoing research is to utilize MRI for guidance of minimally invasive procedures in a manner analogous to conventional guidance methods, taking advantage of features that are inherent, and for the most part, unique to MRI technique.
Benefits and limitations of MRI-guidance

The ability to perform procedures without ionizing radiation is a major advantage of MRI as the risks associated with increased radiation doses in interventional radiology have become more recognized (Miller et al. 2003). This is of particular importance to personnel performing these procedures on a daily basis, but also imperative to certain patient groups, such as children and pregnant women. MRI provides incomparable soft tissue contrast and superior spatial resolution, allowing both identification of lesions that cannot be seen on other cross-sectional imaging and visualizing the anatomy surrounding the target accurately (Lewin et al. 2000). MRI also enables the visualization of blood vessels during a procedure without using intravenous contrast media. These features help to avoid serious vascular complications, but also aid in preventing damage to fine structures which might not be seen with other imaging modalities (Lewin 1999). MRI has the unique ability to bring out different tissue characteristics during an intervention by using different pulse sequences. This includes basic switching between T1 and T2 weighting, but also more sophisticated functional data, such as flow, perfusion, and diffusion, can be acquired (Iacconi 2010). This information can be used to direct interventions toward the most appropriate part of the target by helping to separate anatomy from pathology. The multiplanar imaging capabilities of MRI allow for tracking of interventional devices in any conceivable plane, which facilitates targeting lesions in difficult locations. Finally, the high sensitivity of MRI for temperature change and tissue damage provides an unequivocal advantage over other imaging modalities for monitoring thermal tumor ablative therapies (Germain et al. 2001a).

It is generally acknowledged that exposure to static magnetic fields and RF radiation associated with the clinical use of MRI systems produces no substantial harmful biologic effects in humans (Shellock 2000, Schenck 2000). However, it leads to a restricted indication of MRI for the expanding group of patients carrying ferromagnetic active implants, such as cardiac pacemakers and various neuroprostheses (Shellock & Spinazzi 2008). Besides these general contraindications to MRI, specific challenges have to be met in interventional MRI, since safety demands in the MRI environment limit the use of standard interventional equipment. All devices used in MRI-guided procedures have to be MR-compatible. Recently, however, the terminology pertaining to these devices has been revised to correspond with standardized tests (Shellock et al. 2009). MR safe indicates that an item poses no known hazards in all MRI environments. A
device that has been demonstrated to pose no known hazards in a specified MRI environment with specified conditions of use is called MR conditional, whereas MR unsafe is an item that is known to pose hazards in all MRI environments.

A particular concern in interventional MRI is that RF fields applied during imaging may induce tissue damaging heating in guide wires, because they are made of conductive materials. The increase in temperature depends on several factors, including the strength of the magnetic field, length, diameter, position and shape of the device. The phenomenon is complex, but there is evidence to suggest that substantial temperature elevation may occur in high-field magnets (Nitz et al. 2001, Buecker 2006), whereas in low-field magnets the temperature rise seems to be not significant (Liu et al. 2000).

Technical developments in magnet systems and pulse sequences have led to a substantial improvement in the speed of imaging. With currently available technology, temporal resolution of up to 20 frames per second is achievable (Beer et al. 2010). However, in interventional use, significantly lower speed of imaging is available; in percutaneous MRI-guided abdominal procedures frame rates of 1–2 images per second are reported with the latest MRI systems (Statius et al. 2008, Fischbach et al. 2010). This is a limitation of MRI-guidance compared to the established interventional imaging modalities, which all offer real-time imaging capability.

**MRI systems and system interfaces**

Many different MRI system configurations have been used to guide percutaneous procedures. Each of these concepts has strengths and weaknesses for interventional imaging, with a constant trade-off between patient access and image quality. The signal-to-noise ratio (SNR) of MRI is directly proportional to the field strength, homogeneity, and stability. These factors can better be optimized the more closed the magnet design is, employing high field strengths to generate high spatial and temporal resolution imaging. This design, however, results in poor freedom of interventional approach. The environment best suited to interventional procedures is one with maximum access to the patient, i.e., open magnet design, with the accompanying penalty in the quality of imaging due to lower field strength. The interventional use of MRI requires finding a feasible balance between the opposing forces of openness and best image quality.

Conventional superconducting cylindrical high field magnets, typically operating at 1.5 T or above, offer superior image quality at the cost of limited
access to the patient due to long, narrow magnet bores. This leads to time consuming “in-and-out” technique, where the patient is withdrawn from the magnet to reposition the device between scans. Nevertheless, these systems have successfully been used to perform various percutaneous procedures (Vogl et al. 1995a, Salomonowitz 2001). Recently, the development of open bore, high field systems with shorter and wider bore have substantially improved the access enabling interventional procedures to be performed in the same manner as in CT (Stattaus et al. 2008).

The first system specifically designed for MRI-guided procedures was the 0.5 T vertical gap, “double donut” design (Schenck et al. 1995). Two superconducting magnets were separated by a 58-cm gap, allowing physicians to stand between the magnets with their hands on the patient’s anatomy at isocenter providing unprecedented patient access. Several published series of biopsies and aspirations have been done with this design (Silverman et al. 1995, Kettenbach et al. 2000, Genant et al. 2002); however, manufacturing of this system has since been discontinued. Another approach that is well suited for interventional use in terms of patient access is the biplanar magnet design, in which the patient is positioned between two flat magnetic poles allowing access from a side, analogous to that of C-arm fluoroscopy. Although these systems suffer from lower field strengths, typically ranging from 0.064 T to 0.3 T, they have been widely utilized in percutaneous interventions (Lewin et al. 1998, Ojala et al. 2000, Blanco Sequeiros et al. 2002). An evolution of this model with field strength of 1 T providing advanced imaging features has recently been introduced into clinical use (Fischbach et al. 2010, Streitparth et al. 2010).

A different concept is a hybrid interventional MRI unit, which combines MRI and X-ray equipment in order to exploit the strengths of each imaging modality in interventional use. These systems allow for switching back and forth between the two modalities with a sliding table top while maintaining the sterile operating field (Buecker et al. 2001, Ganguly et al. 2005, Kee et al. 2005). Furthermore, with image coregistration, it is possible to use 3D MR images as a roadmap for X-ray fluoroscopic procedures (Rhode et al. 2005).

Because of the complex nature of MRI, the interventionist needs to control a large amount of imaging parameters while manipulating interventional devices and watching MR images as they are being acquired during an MRI-guided percutaneous intervention. To enable this, system interfaces with fast communications between MR scanner, workstation, and display have been developed. Implementations of these interfaces vary among vendors, but
regardless of the solution, they offer the possibility for the operator to dynamically adjust different imaging and interventional parameters while performing the procedure next to the patient (Yutzy & Duerk 2008).

Instrument navigation

Virtually every percutaneous abdominal procedure starts with a needle puncture; therefore, visualizing the needle accurately is of paramount importance. Unlike in conventional imaging, there are several user-defined parameters that affect the visibility of the needle in MRI surroundings. During the intervention, the needle is seen in the MR image by using its susceptibility artifact, which is larger at higher field strengths, and when the needle is perpendicular to the static magnetic field and to the frequency encoding direction. Pulse sequence also alters the visibility of the needle; gradient echo sequences are associated with larger needle artifacts than spin echo sequences. Additionally, the composition of the needle influences the artifact width, which is enlarged with increased amount of ferromagnetic material in the needle. (Lewin et al. 1996, Frahm et al. 1996a).

During planning and targeting, these different factors may be adapted to get optimum guidance to a procedure. Sometimes it is advantageous to enhance the artifact of an otherwise poorly visible device in low field surroundings by adjusting the parameters to obtain larger artifact. Usually, however, a large needle artifact is disadvantageous since it leads to localization inaccuracy, which may be unacceptable when targeting small lesions near critical structures (Lewin 1999).

Besides using the instrument-generated susceptibility artifact, several methods are available to guide needle navigation toward the target under MRI. The choice of technique is partly dictated by the magnet design, since some techniques are better suited for open than closed magnet systems, and vice versa. Another factor determining the choice of navigation technique is the nature of the procedure at hand. Some techniques, such as frame-based stereotaxy (Lehman et al. 2005), add-on stereotactic reference solutions (Busse et al. 2010), and augmented reality (Wacker et al. 2006), require static targets, making them unsuitable for abdominal procedures where respiratory motion occurs. Other techniques are specifically developed to be used in certain applications, e.g. active tracking with a resonant RF micro-coil attached to the tip of the instrument, which is used in intravascular interventions (Bock & Wacker 2008).

The simplest and most commonly used navigation method for MRI guidance is the freehand technique. It essentially employs similar methods as are used in
percutaneous procedures using ultrasound or CT guidance. In open systems, the skin entry point may be located using a fingertip, and the needle is then advanced into the targeted pathology under MR “fluoroscopic” guidance, using fast imaging sequences. Deviation of the needle from the intended trajectory can be detected by using multiple slices, or by acquiring image sets in two orthogonal scan planes oriented along the shaft of the needle (Sakarya et al. 2003, Zangos et al. 2003b, van den Bosch et al. 2006). In closed systems, the technique is basically the same except that the entry point is located with a fiducial marker and the instrument is guided with subsequent cycles of fast control imaging inside and needle repositioning outside the bore (Rofsky et al. 1998, Adam et al. 1999, Meeuwis et al. 2007, Das et al. 2010).

An interactive image guidance system based on active optical tracking of the instrument is available for open bore MR systems. An infrared camera monitors the reflected light from small balls attached to a hand-held probe holding the needle. These data are fed through a 3D digitizer, which continuously relates this spatial information to the software of the scanner, allowing automatic scan plane orientation along the position of the needle, as well as graphic overlay information of the needle trajectory. These features enable rapid interactive planning and targeting in an arbitrary plane during a percutaneous interventional procedure (Silverman et al. 1995, Lewin et al. 1998, Sequeiros et al. 2002, Ojala et al. 2002).

**Pulse sequences**

As there is no single pulse sequence that meets all needs for interventional MRI, choosing the right sequence for a planned intervention is crucial for a successful procedure. The selection of the pulse sequence depends on a number of factors, including the hardware used, the navigation technique, and the type of procedure at hand. In general, however, rapid image acquisition with sufficient contrast between normal and pathologic tissue and adequate visualization of the interventional device is essential (Boll et al. 2004). These have been achieved with improvements in fast gradient-echo pulse sequences, modification in k-space sampling, and the development of parallel imaging techniques (Nitz 2002).

Today, there are a myriad of specific pulse sequences available for interventional MRI. An example of these is the balanced steady-state free precession (SSFP) sequence, for which different vendors have defined their own acronyms, including TrueFISP, FIESTA, and balanced FFE. This sequence meets
well the requirements of interventional use, providing the combination of fast imaging with exceptionally high SNR (Scheffler & Lehnhardt 2003). Balanced SSFP sequences offer mixed T1/T2 contrast with excellent ability to distinguish blood vessels from surrounding tissue. Typically, with modern MR equipment, an image speed of up to two frames per second is possible with these sequences (Moche et al. 2008).

Special interventional techniques, such as thermal tumor ablation, may require other optimized pulse sequences for monitoring the therapy. In MR thermometry, several methods using different temperature-sensitive MR parameters have been investigated; however, to date, only two techniques have been widely implemented in in vivo monitoring during thermal therapy, namely the T1 method and the proton resonance frequency (PRF) shift method (Rieke & Butts 2008). Of these, the most commonly used is the PRF shift method, which provides quantitative temperature information based on the change in the phase of spins at different temperatures in a gradient echo image. The advantage of this technique is its tissue-independency, which is important when temperature has to be monitored in tumors and healthy tissues, in coagulated and living tissues. On the downside, the sensitivity of the PRF method is poor in low field environment, and it cannot be used in tissues containing fat (Germain et al. 2001a).

The temperature-dependence of the T1 time was the first parameter used to monitor temperature (Parker et al. 1983). The spin-lattice relaxation time T1 increases with an increase in temperature, which is subsequently shown as a decrease in signal intensity in T1-weighted MR image. The T1 method is easy to implement since a qualitative temperature measurement can be achieved with any T1 weighted sequence. Moreover, T1 temperature sensitivity is good at low field magnets, and unlike the PRF method, the T1 method can be used to monitor temperature of fatty tissues such as breast. Disadvantages of the T1 method include the non-linearity and tissue-dependence of T1 temperature sensitivity (Germain et al. 2001b).
3 Purpose of the study

The purpose of this study was to develop percutaneous abdominal diagnostic and therapeutic procedures in MRI surroundings by evaluating the feasibility, safety and clinical results of the named interventional procedures. The hypothesis was that these procedures can be performed safely and successfully under MRI-guidance. The specific aims were to assess

1. the safety and accuracy of MRI-guided abdominal biopsies when an US-guided biopsy is not feasible
2. the feasibility and safety of MRI-guided percutaneous drainage of pancreatic fluid collections
3. the feasibility and safety of MRI-guided percutaneous nephrostomy
4. the safety and effectiveness of MRI-guided percutaneous laser ablation for the treatment of small RCC
4 Material and methods

4.1 Study population

The present study was conducted in Oulu University Hospital between the years 2000 and 2009. The total number of patients included in the study was 57. Informed consent was obtained from all patients, and any contraindications to magnetic imaging were excluded before the procedures. Coagulation parameters were obtained from every patient to rule out any bleeding abnormalities.

In study I, the medical records of 31 consecutive patients who underwent percutaneous MRI-guided abdominal biopsy were retrospectively reviewed. The patients ranged in age from 12 to 81 years (mean, 54 years); 12 were male and 19 were female. Fine-needle aspiration (FNA) biopsy was performed on 13 patients and both FNA biopsy and cutting needle core biopsy were carried out on 18 patients. The indication for biopsy was a primary tumor in six cases, suspected metastasis or recurrence of malignancy in 14 patients and a lesion of unknown origin in 11 cases. The locations of the targets were liver (n=14), pancreas (n=6), lymph node (n=4), retroperitoneal mass (n=3), adrenal gland (n=3) and spleen (n=1). The average size of the lesion was 2.2 cm (range 1–4 cm) in maximum diameter. The reason for using MRI as a guiding method for biopsy was that the lesion in question was not visible on US (n=18), neither on US nor on precontrast CT (n=9), or US-guided biopsy was considered to be unsafe owing to intervening or adjacent structures (n=4).

In study II, ten consecutive patients with symptomatic peripancreatic fluid collections complicating pancreatitis were prospectively enrolled in a feasibility study. In addition to the need of percutaneous drainage of the fluid collection, according to the judgment of the surgeon, the inclusion criterion for the study was the ineligibility for an ultrasound-guided procedure due to overlying bowel gas, which was assessed by the interventional radiologist. The patients were aged 23–72 years (mean 47.7 years). Nine patients were male, one was female. The underlying causes of pancreatitis were alcohol in seven patients, gallstones in two patients, and unknown in one patient. Five of the fluid collections were symptomatic pseudocysts (four infected, one painful), five were pancreatic abscesses. Computed tomography was performed in all patients before the drainage.
In study III, eight patients were prospectively enrolled in a feasibility study. The patients were randomly selected among the patients who were referred to our department for a PCN by a urologist. The patients were selected for the MRI-guided procedure if the MRI suite was available at the time of the referral. Mean patient age was 62 years (range, 51–84 years); six patients were men, two were women. The indication for percutaneous nephrostomy was ureteral obstruction in all cases. This was due to a malignancy in six patients, stone in one patient, and in one patient the cause of obstruction was unknown at the time of the procedure. In five patients, the PCN was performed on the right side and in three patients on the left side. Preprocedural evaluation included an ultrasound examination of the kidney for grading the degree of the dilatation of the renal collection system on a four-step scale (Kamholtz et al. 1989). Of the eight kidneys, one was grade 1, five were grade 2, and two were grade 3 hydronephrotic.

In study IV, the medical records and imaging studies of eight consecutive patients (5 females, 3 males; age range, 43–83 years; mean age, 69 years) with ten tumors who underwent laser ablation for treatment of RCC were retrospectively reviewed. All patients were referred for the treatment by a urologist. Tumor size ranged from 1.5 to 3.8 cm (mean, 2.7 cm). According to a previously described classification (Farrell et al. 2003), five tumors were exophytic, three were parenchymal, and two were central type. All patients had a primary RCC. Six patients had needle biopsy-proven RCC before the procedure. Two patients had highly suspicious findings for malignancy on preprocedural imaging, and an MRI-guided percutaneous biopsy was performed during the treatment session, just prior to ablation. They were later confirmed to have RCC. The indications for laser ablation were comorbid diseases rendering surgery highly risky (n=6), or need for nephron-sparing treatment (n=2). Of the two patients who needed a nephron-sparing procedure, one had a solitary kidney and one had renal insufficiency.

4.2 Interventional MRI system

The MRI scanner used in all procedures was a resistive 0.23 T open configuration C-shaped electromagnet (Panorama, Philips Medical Systems, Vantaa, Finland). If necessary, this type of magnet can be turned off and on with a ramp-up time of six minutes; however, this feature was not needed in this study. The magnet’s design with one supporting pillar allows wide access to the patient from three sides through a horizontal gap with a diameter of 44 cm. In addition to the scanner, the
interventional system included an MRI-compatible console, a 36-inch video projector screen, ring-shaped surface coil, as well as optical tracking hardware and software with dedicated sequences and protocols. The display was large enough for showing four images with excellent resolution from 2–4 meters of viewing distance, enabling displaying three orthogonal MR images simultaneously on the screen. The MR suite was equipped with an MRI-compatible patient monitoring system (AS/3 CM; Datex-Ohmeda Division, Instrumentarium Corporation, Helsinki, Finland) and an MRI-compatible respirator (Servo 900C; Siemens Corporation, Munich, Germany).

The optical tracking system is based on a camera, which sends and detects infrared light reflecting from spheres in the instrument holder and in the scanner. The instrument holder, which is made of sterilizable biocompatible plastic, is capable of accommodating needles with different lengths and widths. After calibration, the software calculates the position of the instrument in 3D space. The common interface between the optical tracking system and the MRI scanner enables instrument-guided scanning where the plane and the orientation of the acquired image follow the position and orientation of the instrument. The trajectory of the instrument is shown in real time as a graphic overlay in the image, which facilitates targeting. The target can also be marked as a graphic overlay point on the image, and the software provides spatial feedback from the position of the instrument in relation to the determined target point. The spatial accuracy of the optical tracking is 2 mm at the magnet isocenter and 8 mm at the edge of the imaging area.

4.3 Needle biopsy (I)

The needle biopsies were done by three interventional radiologists; ten were performed under local anesthesia and 21 under general anesthesia. The patients remained in hospital at least 24 h for observation after the procedures. All biopsies were done solely under MRI-guidance with a ring-shaped surface coil providing access to the puncture site. The position of the patient was chosen on the basis of previous cross-sectional imaging. Before the biopsy, a survey scan in multiple directions was performed in the estimated location of the lesion using T1-weighted turbo spin-echo (TSE) sequences (five slices, echo time (TE) 400 ms, repetition time (TR) 16 ms, slice thickness/interval 7.0 mm/8.0 mm, field of view (FOV) 380×380, matrix 324×324, acquisition time (TA) 23 s), 3D balanced fast field echo (b-FFE) sequences (eight slices, TE 4.2 ms, TR 8.4 ms, slice...
thickness/interval 5.0 mm/5.0 mm, flip angle (FA) 45°, FOV 380×380, matrix 256×256, TA 24 s) and T2-weighted TSE images (nine slices, TE 3500 ms, TR 150 ms, slice thickness/interval 7.0 mm/8.0 mm, FOV 380×380, matrix 192×192, TA 35 s) to localize the target and to determine the protocol for best lesion contrast. The puncture site and the route were determined by using optical tracking (Figure 1). During the biopsy, the needle was guided with graphic overlay information provided by optical tracking, as well as instrument-generated susceptibility. For controlling the needle in its course during the biopsy either T1-weighted FFE (five slices, TE 11 ms, TR 130 ms, slice thickness/interval 10.0 mm/10.0 mm, FA 60, FOV 380×380, matrix 256×256, TA 18 s; three slices, TE 7 ms, TR 95 ms, slice thickness/interval 7.0 mm/7.0 mm, FOV 380×380, matrix 300×300, TA 12 s), 3D b-FFE or 2D b-FFE (one slice, TE 4.5 ms TR 9.1 ms, slice thickness/interval 10.0 mm/10.0 mm, FA 45°, FOV 380×380, matrix 256×256, TA 1.5 s) sequences were applied with the breath-holding technique. Additional contrast-enhanced imaging with gadopentetate dimeglumine (Magnevist, Schering, Berlin, Germany) and T1-weighted TSE (five slices, TE 400 ms, TR 16 ms, slice thickness/interval 7.0 mm/8.0 mm, FOV 380×380, matrix 324×324, TA 23 s) sequences was used in two patients.

In each case, a coaxial needle technique was used. All needles used in the biopsies were magnetic-resonance-compatible, except for local anesthetic needles. A 16-gauge coaxial needle (MRI Devices Daum, Schwerin, Germany) was advanced into the vicinity of the target, and an 18-gauge biopsy set (Somatex, Berlin, Germany; or MRI Devices Daum) was introduced through the coaxial needle and advanced into the lesion to collect a core biopsy (Figure 2). A FNA biopsy was obtained in a similar manner through the 16-gauge needle with a 20-gauge Chiba needle (Cook, Bloomington, IN, USA). One to three samples were collected from each biopsy, depending upon the discretion of the interventional radiologist performing the biopsy. The core biopsy samples were fixed in 10% formalin and the fine-needle aspirates in 50% alcohol for later processing.
Fig. 1. Targeting with the optical tracking system. The thin extension line of the needle (thick line) is crossing a small liver lesion in an oblique axial 3D b-FFE image.

Fig. 2. Biopsy of a small liver lesion of unknown origin in a 66-year-old woman, same patient as in Figure 1. (A) Oblique axial 3D b-FFE image showing a 16-gauge needle (arrowhead) adjacent to a 1-cm lesion (arrow) in the right lobe of the liver. (B) An 18-gauge biopsy needle (open arrow) going through the lesion in the oblique sagittal 3D b-FFE image. Pathologic diagnosis was hemangioma.
4.4 Drainage of pancreatic fluid collections and nephrostomy (II–III)

All procedures were carried out entirely under MRI-guidance in local anesthesia (lidocaine 1%); intravenous analgesics (alfentanil) were administered if needed. All patients with pancreatic fluid collections were treated with parenteral antibiotics, routine prophylactic antibiotics for the nephrostomy patients were not used; however, half of the patients were already on antibiotics for other indications at the time of the procedure. All procedures were performed on an inpatient basis. The nephrostomy patients were placed in a supine oblique position, the position of the patients with pancreatic fluid collections was chosen on the basis of previous cross-sectional imaging. Before the initial puncture, the target was first visualized with survey scans in multiple projections using 3D b-FFE sequences. The calyx chosen for entry (II) or the fluid collection (III) was marked as a target point on two orthogonal MR images. Optical tracking allowed choosing the puncture route arbitrarily in any given plane. During the puncture, in addition to optical tracking, instrument-generated susceptibility artifact was used for needle guidance with either 3D or 2D b-FFE sequences.

In each case, an MRI compatible drainage kit (Somatex, Berlin, Germany) was used. The kit includes an 18-gauge needle, 0.035-inch stiff guide wire, 6-French (F) and 8-F dilators, 8-F pigtail drainage catheter, and 1.5-litre secretion bag. The dilators and drainage catheters consist of polyurethane impregnated with iron oxide to accentuate the signal loss on MR images. The drainage kit was used with a standard Seldinger technique. After access to the renal collecting system or fluid collection was gained, all the subsequent steps of the procedure, the guide wire advancement, the tract dilatation, and the catheter placement were monitored using 3D b-FFE sequences (Figure 3). Imaging was repeated whenever the position of a device was changed. The approach was direct in all cases; no neighboring organs were traversed. In every nephrostomy, the targeted calyx was located in the middle third of the kidney. The most common access route for pancreatic fluid collection drainage was through left anterior pararenal space (n=7), followed by left anterior paracolic space (n=2), and gastroplenic route (n=1).
Fig. 3. MRI-guided percutaneous drainage of a pancreatic pseudocyst with the Seldinger technique. (A) Axial 3D b-FFE image showing an 18 G needle (arrow) inserted into a large pseudocyst (P) in the tail of the pancreas. (B) 0.035-inch guide wire (arrow) in the pseudocyst. (C) The shaft (arrow) and the tip (arrowhead) of 8-F dilator in the pseudocyst. (D) The shaft (arrow) of the 8-F drainage catheter extending into the pseudocyst in oblique sagittal 3D b-FFE image.

4.5 Laser ablation of RCC (IV)

In each case, the goal of the treatment was to eradicate all viable tumor tissue. All ten tumors underwent laser ablation during a single session. Procedures were performed during general anesthesia of the patient. All patients received a single
dose of intravenous prophylactic antibiotic treatment (cefuroxime 1.5 g) before the procedure. Preprocedural CT and/or MRI were utilized for the treatment planning. An MRI-compatible irrigated laser catheter kit (Somatex, Teltow, Germany) was used with the Seldinger technique. For the targeting, both US and MRI were used. To shorten the procedure, US (Power Vision 7000, Toshiba Corporation, Tokyo, Japan) was used to guide an 18-gauge needle into the tumor, a 0.035-inch guide wire was introduced through the needle, and a 9-F sheath was advanced into the lesion over the wire. After removing the wire, a laser irrigation catheter with an MRI-compatible marker was pushed into the tumor through the sheath. The position of the system was then confirmed, and adjusted with MRI, if needed. Subsequently, the marker was replaced with a laser fiber and the ablation treatment was initiated. Additional fibers were placed in the same manner, if needed. Depending on the size of the mass, 1–4 (mean 2.6) fibers were used per tumor. The number of fibers was based on the assumption that each fiber produces coagulative necrosis with a diameter of 3 cm. In two cases where the colon was adjacent to the tumor, sterile saline was injected perirenally prior to ablation to separate the bowel from the tumor. The subsequent steps of the treatment, monitoring, controlling, as well as post-procedural imaging were done with MRI. In two cases where the tumor was not visualized with US, the procedure was performed entirely under MRI-guidance. In these cases, tracking software-produced graphic overlay and instrument-generated susceptibility in MRI image sets (3D b-FFE) were used to place the sheath into the target.

A Nd:YAG laser device with maximum power of 100 watts (W) was used for all treatments (Medilas Fibertom, Dornier MedTech, Garmingen, Germany). Infrared laser light at a wavelength of 1064 μm was delivered via a water-cooled 400 μm flexible diffusor fiber with a 2- to 4-cm active tip, determined by the size and morphology of the tumor. When several fibers were used simultaneously, a laser beam splitter was applied to facilitate synchronous energy delivery for multiple fibers. The laser ablation was conducted using a constant energy flow and a power of 10 W per cm of active length of the fiber. The total duration of energy application and the total amount of energy applied per tumor are given in Table 1. The treatment was monitored using 3D b-FFE sequences (8 slices, TE 7.7 ms, TR 3.8 ms, 8 slices, slice thickness/ interval 6.0 mm/ 6.0 mm, FOV 380x380 mm, matrix 160x160, FA 63°, acquisition time 24 seconds) observing the decrease in signal intensity, caused by the temperature rise in the heated tissue (Germain et al. 2001b). Imaging sequence was repeated at 1 minute 30 second intervals. If needed, the position of the fiber was adjusted during the ablation to
cover the whole tumor. When the signal void spread beyond the tumor edge by a 0.5 cm margin the treatment was considered complete (Figure 4). The laser fiber and the laser application system were then removed. Fibrin glue (Tisseel duo, Baxter AG, Vienna, Austria) was injected into the treatment channel while retracting the introducer sheath. Post operatively the patients were monitored for 6 hours in the recovery room. All treatments were conducted on inpatient basis; the patients were discharged from the hospital after an average of five days (range, 3–12 days).

Fig. 4. Percutaneous MRI-guided biopsy and laser ablation of a 2.2-cm renal cell carcinoma after contralateral nephrectomy in a 54-year-old woman. (A) Biopsy needle approaching the tumor (arrow) in an oblique axial 3D b-FFE image. Two of the three laser fibers (arrows) placed into the tumor in oblique axial (B) and oblique coronal (C) 3D b-FFE image. (D) Laser-induced signal void (arrow) in and around the tumor.
4.6 Evaluation of the procedures

4.6.1 Needle biopsy (I)

The data concerning the room time, which included the time for patient preparation and possible anesthesia procedures, and immediate or delayed complications were collected from the medical records. The needle time was calculated from the time stamps on the MR images, defined as the time between the first and the last MR image with a needle. The biopsy specimen was determined to be either representative or nonrepresentative, and the amount of biopsy material was graded as either sufficient or insufficient for diagnostic use by a pathologist.

For evaluation of success, the histopathological diagnosis from the core-needle biopsies and the cytological diagnosis from the FNA biopsies were compared with the current or final diagnosis made from clinical and imaging follow-up, or results from open surgery, if available. Cytology results were divided into five diagnostic categories that included insufficient, normal, benign atypia, possibly malignant, highly suspicious for malignancy, and malignant. A designation of malignancy as well as the possibility and suspicion of malignancy was considered a positive result. Negative results were considered true-negative if no malignancy was discovered on subsequent surgery or if the findings during the follow-up were consistent with a benign disease. Insufficient or nonrepresentative samples were considered false-negative findings together with cases in which subsequent operation or biopsy showed malignancy. Diagnostic sensitivity, specificity and accuracy were calculated separately for core needle and FNA biopsies.

4.6.2 Drainage of pancreatic fluid collections and nephrostomy (II–III)

The assessment of feasibility included the technical success of the procedures, as well as a qualitative evaluation of the visibility and performance of the different MRI-compatible devices used in the procedures. The times required for the intervention were measured, excluding the time for patient preparation and aftercare. Immediate complications during the procedure or delayed complications during the follow-up period were noted. Additional imaging examinations and catheter exchange were performed as needed during the follow-up period. The follow-up period for the nephrostomy patients lasted until the
catheter was electively changed or removed. For the patients with pancreatic fluid collections, the catheters were removed when the symptoms resolved, no fluid collection was seen in control imaging, and the daily drainage output was less than 10 ml. The drainage was considered a clinical failure if surgical intervention was required for resolution of the pancreatic fluid collection after catheter drainage.

4.6.3 Laser ablation of RCC (IV)

Native and contrast-enhanced MR imaging with a 1.5 T system was performed within four days after the treatment to document technical success, assess possible complications and to provide a basis for future imaging. Follow-up CT or MR imaging without and with contrast material was performed at 3 months and 6 months after the treatment, and thereafter at 6-month to yearly intervals (Figure 5). Tumors were considered completely ablated if there was no enhancement by intravenous contrast material in any portion of the tumor. Images were also reviewed for any new metastatic disease, and for recurrent tumor, which was defined as new enhancement developing after initial complete necrosis. During the follow-up the patients were monitored for change in serum creatinine levels and for complications.

Fig. 5. Follow-up imaging after laser ablation, same patient as in Figure 4. 1.5 T MRI showing the involution of the ablation zone (arrow) at six months (A) and at two years (B).
5 Results

5.1 Needle biopsy (I)

All the 31 lesions could be seen in low-field MRI both in the preprocedural scans and in the fast imaging sequences used during the procedure. In two of the 14 liver lesions contrast-enhanced imaging was applied because the delineation of the lesion was less than optimal on the precontrast imaging; however, this resulted in marked improvement in visualization of the lesion in only one of these cases. Optical tracking enabled rapid and reliable planning of a safe puncture route in each case, and it also proved useful during the procedure if the angle of approach had to be changed. In each case, the MRI-guided technique used provided adequate guidance for positioning the needle within the lesion.

The FNA biopsy specimens were adequate for interpretation in 27 of 31 cases. In the rest of the cases, the sample was either nonrepresentative (n=1) or insufficient (n=3). All of these lesions proved to be benign in later operation (n=2) or follow-up (n=2), but were nevertheless regarded as false negatives owing to error in sampling. In addition, there were two definitive false-negative FNA biopsy results, also indicating sampling error. One patient had a cystic pancreatic lesion and the FNA biopsy results revealed benign cystic material. The patient refused an operation, but developed liver metastases later on during the follow-up. For another patient with a suspected liver metastasis the FNA biopsy result was benign, but the core biopsy taken in the same procedure was malignant. In 15 patients, FNA biopsy results revealed malignancy. The diagnoses were as follows: metastatic tumor consistent with the patient’s known primary malignancy (n=8); adenocarcinoma of the pancreas (n=3); malignant lymphoma (n=2); rhabdomyosarcoma (n=1); and cholangiocarcinoma (n=1). In the remaining ten patients, no malignancy was identified in the biopsy specimens. Because none of these patients underwent open surgical biopsy, clinical and imaging follow-up findings were used to confirm that the disease process was benign.

The mean length of the follow-up period was 10.5 months (range, 4–21 months). The sensitivity, specificity and accuracy for FNA biopsy are shown in Table 1. Eighteen patients underwent both core biopsy and FNA biopsy. One of the core biopsy samples of a benign lesion was classified as false-negative because it was considered nonrepresentative by a pathologist. This along with another case described earlier were the only ones where histological and
cytological diagnoses did not concur. Seventeen of the core biopsy samples were either true-positives or true negatives, generating the sensitivity, specificity and accuracy rates for the core-needle biopsy shown in Table 1.

The overall needle time was on average 19 min. The mean needle time for core biopsy and FNA biopsy combined was 20 min, while for FNA biopsy alone the needle time averaged 17 min. The average room time was 1 h 48 min. No immediate or late complications occurred.

### Table 1. Biopsy results in 31 patients examined.

<table>
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<tr>
<th>Type of biopsy</th>
<th>Patients</th>
<th>TP</th>
<th>TN</th>
<th>FP</th>
<th>FN</th>
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<td>0</td>
<td>1</td>
<td>90</td>
<td>100</td>
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</tbody>
</table>

TP = true positive findings, TN = true negative findings, FP = false positive findings, FN = false negative findings

5.2 Drainage of pancreatic fluid collections and nephrostomy (II–III)

The low-field b-FFE sequences provided a reliable visualization of all the pancreatic fluid collections, as well as all the dilated (grade 2 and 3) urinary tracts. The optical tracking enabled rapid planning of the puncture route, and the needle could be successfully inserted into the target calyx or pancreatic fluid collection under MRI guidance. The two orthogonal image planes helped to detect any deviation from the optimal puncture path, and the needle could be readjusted to the correct trajectory. The interventional MRI system also provided adequate guidance to position the catheter with the Seldinger technique correctly within the renal collecting system or pancreatic fluid collection, as verified by both imaging and by aspiration of fluid through the catheter.

In one patient with a minimally dilated (grade 1) collecting system, puncture of the calyx was unsuccessful, and the procedure was abandoned after two attempts. In all but three patients, the MRI-compatible drainage kit enabled performing PCN or the drainage of a pancreatic fluid collection with the Seldinger technique. These patients were obese, and the guide wire gave
inadequate support to allow placement of the catheter; an additional stiffener from a non-MRI-compatible trocar kit was used in these cases.

The size of the artifact produced by the MRI-compatible needle was 4–5 mm in diameter, allowing accurate demarcation of the needle from the surrounding tissue. The artifact widths of the dilators and drainage catheters on MR images ranged between 12–15 mm. The artifact induced by the guide wire was less than 3 mm in diameter, which made it reliably visible only when surrounded by liquid.

The durations of the PCN procedures ranged from 20 min to 45 min, with a mean time of 26 min. No major complications occurred during the procedures or the follow-up period (mean, 2.1 months). One minor complication (transient hematuria) requiring no therapy was encountered.

The durations of the drainage procedures for pancreatic fluid collections ranged from 29 min to 75 min, with a mean time of 44 min. No immediate complications occurred. Clinically successful drainage of the pancreatic fluid collection was achieved in seven of the ten patients. None of these patients had recurrence of their fluid collection during the follow-up, which ranged from 6 to 40 months (average 16.8 months). Drainage failure occurred in three patients. One patient had an unrelenting sepsis and required surgical drainage and necrosectomy four days after the percutaneous drainage. Another patient developed recurring abscesses, and surgical exploration with debridement was subsequently performed six times. One delayed complication, spontaneous fistulization in the gastrointestinal tract, occurred 20 days after the percutaneous drainage. It was treated successfully with resection of the colon and colostomy.

There was no mortality among the patients. The average duration of catheterization was 40 days, ranging from 4 to 66 days. The original MRI-compatible drainage catheter was left in place for the whole of the catheterization period in only three patients; the rest of the catheters were exchanged for larger 12-F or 14-F catheters under fluoroscopic guidance owing to obstruction. In one patient two additional catheters were inserted under CT-guidance during the course of the disease to achieve adequate drainage of the fluid collection.

5.3 Laser ablation of RCC (IV)

Ten tumors were treated in eight patients. All patients were treated in one ablation session, including the two patients with two tumors. All but one tumor were completely ablated. The first patient treated showed residual enhancing tumor in the first MRI control after the ablation. A second ablation session was offered, but
the patient has thus far declined retreatment, and the tumor has shown no progression in follow-up imaging. Complete results are summarized in Table 2. No local recurrence or new metastatic disease was discovered in any of the patients during the follow-up period. Two patients died during the follow-up: one died of acute myocardial infarction nine months after the ablation, and another died of lymphoma two years after the ablation. Neither patient had evidence of recurrent tumor at the time of death. The length of the follow-up for surviving patients ranged from 12 to 30 months (mean, 20 months).

There was one major complication. Five days after the ablation, one elderly patient with several comorbidities suffered a periprocedural myocardial infarction, which was complicated by respiratory failure and pneumonia. Her hospital stay was prolonged, but she recovered completely later on. One patient with a solitary kidney experienced a transient rise in the serum creatinine level after the treatment; afterwards the value returned to baseline. All other patients tolerated the procedure well.
Table 2. Summary of patients and laser ablation data.

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<td>85/86</td>
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</table>

**Preoperative/postoperative**

RT = residual tumor; NFS = not fit for surgery; NNST = need for nephron-sparing treatment; NH = no enhancement
6 Discussion

6.1 MRI-guidance

The purpose of this study was to develop percutaneous abdominal diagnostic and therapeutic procedures in MRI surroundings. The rationale behind such research is that the same distinct advantages of MRI that have made it the primary imaging modality for a variety of diagnostic indications could also bring added value to interventional procedures. At the present stage of this research, MRI cannot replace the traditional imaging modalities; however, there are certain procedures that cannot be performed safely using other imaging modalities due to lack of tissue contrast. It is these procedures that currently provide the best area for MRI-guided techniques, but as data on the clinical benefits of MRI-guided and monitored procedures accumulate, the range of applicable interventions is expected to increase.

Compared to the traditional imaging modalities, several aspects favor the use of MRI in guidance. In relation to both fluoroscopy and CT, the lack of ionizing radiation and the high intrinsic soft tissue contrast with multiple contrast mechanisms, if needed, without the use of contrast media, are important advantages. Furthermore, in contrast to CT, multiplanar imaging with arbitrary plane orientation is possible with MRI, and in open configuration magnets, unrestricted access to the procedure area can be obtained. Compared to US, the principal benefit, in addition to better soft tissue resolution, is that air-filled structures, such as bowel or pleural space, present no problem for MRI guidance. An advantage of MRI over all other imaging modalities is its unique sensitivity to thermal changes, enabling monitoring of thermal ablative therapies.

The fact that percutaneous abdominal procedures often deal with different liquid-filled structures makes them especially tempting to be guided with MRI, because of its high sensitivity for materials characterized by long T2 relaxation times, such as fluid collections. Another potential benefit of MRI guidance is the possibility to perform the procedure with only one imaging method instead of two, as is sometimes the case with standard techniques.

Along with all the benefits, MRI also has limitations as a guidance method for percutaneous procedures. It provides near-real-time imaging rather than real-time image update. This is sufficient for basic abdominal interventions, but precludes the use of MRI as guidance for more sophisticated procedures requiring
extensive guide wire control and manipulation. In addition, in abdominal procedures, lengthy image acquisition times necessitate breath-holding technique, which may require general anesthesia in elderly patients. Another problem affecting MRI, together with other cross-sectional imaging techniques, is the fact that an image contains only portions of curved wires and catheters on individual planes. In MRI, this problem can at least partially be dealt with by using thicker slices or packs of thinner slices and multiplanar imaging. Safety demands and image quality requirements necessitate that all equipment used in interventional MRI is MR safe, or MR conditional for a given MRI system (Shellock et al. 2009). This restricts the use of conventional interventional radiology equipment; however, a limited assortment of MR-compatible instruments suitable for abdominal procedures is commercially available. The costs of MRI-guided interventional procedures have been estimated to be significantly higher than the costs of comparable procedures performed with CT-guidance (Lewin 1999, Alanen et al. 2004). However, when an MRI-guided percutaneous procedure is compared to open surgery in the treatment of the same disease, an MRI-guided procedure has been found to be cost-effective (Ronkainen et al. 2006).

The procedures in this study were performed with a 0.23 T biplanar open-configuration magnet. Although the line between open low-field and closed high-field systems has been blurred by the recent introduction of short wide-bore 1.5 T (Stattaus et al. 2008, Fritz et al. 2008a, Fritz et al. 2008b) and open 1.0 T systems (Fischbach et al. 2010, Streitparth et al. 2010), this scanner design provides the widest access to the patient for the interventionist, as well as adequate working space for other staff. The low field strength has been considered a drawback because of lower temporal and spatial resolution of the imaging. However, the image quality in this study was found to be sufficient to perform all but one of the intended procedures. In terms of procedure times, compared to closed-bore systems, the reduced imaging speed in low-field open systems is easily compensated by not having to move the patient in and out of the magnet during the intervention. Another factor favoring the use of low-field systems in abdominal interventions is that the potential risk of RF-induced heating of the instruments is lower at 0.23 T compared to high-field MRI (Liu et al. 2000). Additionally, in low-field scanners operating at 0.23 T, the five-gauss line is located less than two meters from the scanner’s side, which allows MR unsafe devices, such as intraoperative ultrasonography, to be used in the MRI room.

Optical instrument tracking, which was used in all procedures during the initial needle puncture, offers several advantages. It helps imaging during
targeting by enabling automatic scan plane orientation in relation to the position of the needle. In addition, as it operates in real time, it reduces the need for imaging during the intervention, which in turn leads to reduction of the procedure time. However, since the graphic overlay of optical tracking is projected on previously acquired images, it is insensitive to inaccuracy caused by needle bending or respiratory motion. Therefore, confirmatory imaging with instrument-generated susceptibility artifact was necessary during targeting.

6.2 Needle biopsy (I)

MRI-guided abdominal biopsies were performed with a horizontally open 0.23 T MRI scanner with a C-arm configuration. Compared with closed-bore systems, the main advantage is better access to the patient without the need to move the patient during the procedure. This benefit is emphasized in abdominal procedures, where the lesion is moving with respiration and targeting such lesions usually requires multiple needle adjustments. In closed systems, this results in repeated movements in and out of the magnet bore, which is awkward and time-consuming. This is reflected in reported biopsy times, which for traditional closed-bore systems tend to be longer (from 35 to 44 min on average) (Rofsky et al. 1998, Langen et al. 2000, Langen et al. 2002) than for open systems (from 2.5 to 26 min on average) (Lu et al. 1997, Lewin et al. 1998, Schmidt et al. 1999, Konig et al. 2003, Fischbach et al. 2010). The needle time in this study (19 min) falls within the range reported for open systems, although detailed comparison is hindered by differences in the definitions of times. The relatively long room time of 1 h 48 min on average is explained by the fact that a large number of the procedures were performed under general anesthesia, and the time required for the anesthesia was included in the room time.

At least a theoretical drawback for the C-arm configuration magnet design used in the current study is the small superoinferior gap, which, together with the vertically orientated external magnetic field, prevents needle placement from above the patient. Therefore, for a biopsy requiring a direct anterior approach, e.g., a pancreatic lesion, the patient was placed in the decubitus position. In contrast to suggestions by some authors (Lu et al. 1997, Schmidt et al. 1999), this approach was not found to be cumbersome, and all patients could be positioned this way, if needed. The pole-to-table distance in the scanner used is 44 cm, which is enough to be able to position all but very few patients (usually very obese) in the decubitus position. This position can be well tolerated by the patient if proper
measures in the patient setup are considered, including careful patient positioning and supporting the body weight with an adequate amount of padding.

Owing to the study design, all the targets in this series were small and of low contrast in nature. Nevertheless, the image quality of the 0.23 T scanner was sufficient to visualize all lesions. Because the targets in the abdominal area move with respiration, breath-holding technique was used. To enable this for elderly and pediatric patients, the majority (21 out of 31) of the procedures were performed under general anesthesia. Furthermore, a one-slice mode was used whenever possible in order to shorten the acquisition time. A multislice mode was necessary if bending or deflection of the needle was suspected; however, with a coaxial 16-gauge system, bending was seldom encountered. One possible solution to avoid the problems associated with respiratory movements is to use non-breath-holding respiratory gated image sequences (Langen et al. 2000). So far this technique has not gained wider acceptance. Respiratory motion can be somewhat tolerated by using real-time MRI. In low-field systems (Konig et al. 2003), however, the spatial resolution with real-time MRI is too low to enable safe and accurate positioning of the needle into small targets located at the end of a narrow access route between vital structures, as the majority of the lesions in this series were. On the other hand, first reports of real-time MRI with 1.0 T and 1.5 T systems have shown promising biopsy results (Stattaus et al. 2008, Fischbach et al. 2010).

There are some differences between this series and the other two previous studies (Rofsky et al. 1998, Schmidt et al. 1999) with similar types of study designs in terms of patient selection. In this study the patients were all uniformly found not to be eligible for an imaging-guided procedure with one modality, i.e., US, whereas in the other studies the patients were selected for an MRI-guided procedure because one or the other of the two modalities (CT or US) was not applicable. Also, in contrast to the other two studies, this series did not consist solely of liver biopsies. At our institution the primary method for guiding percutaneous abdominal biopsies is US. Therefore, all the patients included in this series were scheduled for an US-guided procedure, but were rescheduled for MRI-guided biopsy because the lesion could not be visualized with US (27 cases) or US-guided biopsy was rendered unsafe by intervening structures (four cases). The patients were not systematically screened for the possibility to perform the biopsy under CT guidance. Instead, the majority of the patients were referred directly to the MRI unit. This reflects the fact that the procedure time was more expeditiously obtainable from the open MRI unit dedicated for interventional use than from the CT unit with a high workload. However, nine of the patients were
first evaluated for a CT-guided biopsy, and were found not to be suitable candidates because the lesion could not be seen in precontrast imaging.

The intention in this study was to obtain both histological and cytological samples from the same lesion, because there is evidence to suggest that the combined use of FNA and core-needle biopsies in soft tissue lesions increases the proportion of correct diagnoses without increasing complications (Tikkakoski et al. 1993). When using a coaxial needle technique, the increase in needle time is not significant either, as shown by 17 versus 20 min in this series. The combined technique was, however, possible in only 18 (58%) out of 31 cases. This was due to the fact that a large proportion of the lesions were under 2 cm in diameter and adjacent to a vessel or other vital structure, so the use of a needle with a cutting length of 17–20 mm was considered hazardous, especially knowing that the needle is not always in line with the longest dimension of the lesion.

There are different methods of reporting success rates for MRI-guided tissue sampling. In other studies the reported sensitivities vary between 75–95%, accuracies between 78–96%, and specificities being 100% (Schmidt et al. 1999, Salomonowitz 2001, Stattaus et al. 2008, Fischbach et al. 2010). The sensitivity, specificity and accuracy for FNA biopsy of 71, 100 and 81%, and for core biopsy of 90, 100 and 94%, respectively, in this series, compare favorably with these results.

The most common method of reporting success for MRI-guided abdominal biopsies is based on adequate tissue collection for pathologic diagnosis. The limitation of this method is that possible false-negative results might not be taken into account. Nevertheless, with this method, the success rate in this study for FNA biopsy of 87% (27 out of 31) is slightly below the range reported in other studies, in which the tissue sampling success rates varied between 89 and 100% (Silverman et al. 1995, Lu et al. 1997, Lewin et al. 1998, Rofsky et al. 1998, Lee et al. 1998a, Langen et al. 2002, Konig et al. 2003). There are two likely explanations for this result. First, the average size of the target of 2.2 cm in this series was smaller than in previous series, in which, whenever reported, it was 4.2 cm (range, 2.8–7.1 cm) (Silverman et al. 1995, Lu et al. 1997, Rofsky et al. 1998, Lee et al. 1998a, Schmidt et al. 1999, Langen et al. 2002, Konig et al. 2003). Second, unlike in many of the previous series, a cytopathologist was not present in the imaging suite, and the adequacy of the cytologic specimen had to be estimated by the macroscopic appearance of the catch. On-site cytopathology interpretation is known to improve the diagnostic yield of an FNA biopsy
(Klapman et al. 2003), and it would have undoubtedly diminished the number of insufficient specimens in this series as well.

The results of this study confirm that abdominal biopsies can be performed successfully under MRI-guidance. However, at the moment, MRI cannot replace US as the modality of choice for guidance of these procedures for several reasons. US-guided biopsies have the advantage of better availability and lower cost, but at least an equally important drawback for MRI guidance is the lack of true real-time imaging. This inevitably means that any biopsy under MRI-guidance in traditional closed systems or in open low-field systems has to be done in an incremental fashion, which in turn leads to a prolonged and cumbersome procedure. This is especially true when approaching moving targets, such as abdominal lesions. Low-field real-time MRI is hampered by the reduction of spatial resolution, and even with novel latest generation MRI scanners, frame rates of only one to two images per second have been achieved, which is not true real-time imaging. Therefore, with currently available techniques MRI-guided abdominal biopsies are indicated only in lesions that are not suitable for guidance with other modalities.

6.3 Drainage of pancreatic fluid collections (II)

Percutaneous drainage with either CT- or US-guidance is an established therapy in selected patients with pancreatic fluid collection (Adams & Anderson 1992, Wittich & vanSonnenberg 1996). These collections are usually deeply situated and, unless they become large and displace the neighboring organs, surrounded by bowel loops. The overlying bowel gas limits the visibility in US and can render US-guided drainage impossible. The purpose of this study was to find out whether MRI-guidance was feasible in patients who for this reason were not suitable for US-guided procedure.

Two approaches can be used for percutaneous drainage of a fluid collection, the Seldinger or the trocar technique (Clark & Towbin 1983, vanSonnenberg et al. 2001). The Seldinger technique was used in this study, since MRI-compatible trocar drainage equipment is not available at the moment. A basic prerequisite for a successful completion of an MRI-guided abdominal drainage procedure with the Seldinger technique is the visualization of all the devices used. With the technique described here, the needle, dilators and drainage catheter were readily displayed in the MR-images. The guide wire could be seen as it exited the needle, but its entire course in the fluid collection was difficult to assess in the majority of the
cases. This was partly due to the small artifact produced by the wire and partly due to fact that any wire inside a cavity tends to conform to the outer margins of the collection, and the contrast resolution of the wire is smaller in soft tissue than in liquid. Another factor adding to this phenomenon is the fact that an image contains only portions of curved wires on individual planes. This, however, affects all cross-sectional imaging and can be dealt with by using packs of thinner slices, such as the 3D b-FFE used in this study.

The MRI-compatible guide wire is not as stiff as non-MRI-compatible stiff guide wire because it cannot have a steel core, but has to be composed of softer alloys. In difficult circumstances the support of the MRI-compatible guide wire may prove insufficient for the placement of the catheter. There were two such patients in this series, and the solution was to use an extra non-MRI-compatible stiffener in these cases. Owing to the lack of real-time imaging capability, the guide wire and catheter had to be advanced without continuous monitoring. As a result of this, it was not possible to steer the wire or the catheter into specific parts of the fluid collection. However, steering of the wire is not usually required during a drainage procedure. Another consequence of the incremental fashion of the imaging is that if kinking or deflection of the guide wire occurs, unlike in fluoroscopy, instead of being seen it has to be suspected by the manual feel of the device’s movements. This calls for an experienced interventionist and familiarity with MRI-compatible equipment.

Depending on the nature of the pancreatic fluid collection, the consistence of the collection varies. In infected collections, the liquid is more or less viscous and can contain debris. In these instances, the 8-F catheter is too small to accomplish adequate drainage of the collection, and seven out of ten catheters in this series had to be exchanged for larger catheters owing to obstruction. This is a limitation of the presented technique, but at this time there are no larger MRI-compatible drainage catheters available and the exchange procedure under fluoroscopic guidance, if needed, is quick and straightforward, since the tract already exists. The catheter does not have a locking mechanism; however, no catheter dislodgements occurred in patients in this study. Owing to long catheterization, most patients leave the hospital with a drainage catheter in place. For patience comfort a soft catheter would be desirable, and the MRI-compatible drainage catheter is not as soft as traditional catheters. Despite this, compliance with catheterization among the patients was good: no catheters had to be exchanged for this reason.
The time required for the MRI-guided drainage averaged 44 min. This is acceptable, but somewhat more than with a real-time guiding modality, such as US, and reflects the incremental nature of the procedure. If multiple catheters were to be placed at the same time, the time loss would be repeated, reducing the usefulness of the MRI-guided technique compared to real-time modalities. The goal of the catheter drainage is the resolution of the pancreatic fluid collection. This was achieved in 70% of the patients, which is in line with previous results (Adams et al. 1990, vanSonnenberg et al. 1997, vanSonnenberg et al. 2001); however, the number of patients is too small to draw any firm conclusions in this respect. The relatively long durations of the catheterization, which ranged from 4 to 66 days, are also comparable with other studies (Freeny et al. 1988, vanSonnenberg et al. 1997, Fotoohi et al. 1999).

There are few previous reports of abdominal drainage procedures performed in the MRI environment. In an early study vanSonnenberg et al. (1988) developed and used a special wire-sheath system in five drainages of abdominal fluid collections in different anatomical locations. The procedures were performed in a closed high-field MRI system with the trocar technique and non-MRI compatible catheters. Gehl et al. (1996) used same type of horizontally open low-field magnet as was used in this study, although without an external referencing system, to perform seven percutaneous drainages of abdominal fluid collections, including one pancreatic pseudocyst. They also used non-MRI compatible catheters and mention the poor visibility of the catheter as the major drawback of the technique. This problem can be avoided by utilizing dedicated, fully MRI-compatible instruments. Buecker et al. (2001) adopted a different approach to solve the problem with the visualization of the guide wires and catheters. They combined a closed-bore 1.5 T MRI scanner with a shielded C-arm fluoroscopy unit to perform percutaneous drainages of three abscesses and one splenic cyst. However, it would be advantageous to be able to perform a procedure solely under guidance of one imaging modality instead of two. Few institutions have this kind of hybrid system available, which diminishes the applicability of this concept. Furthermore, with this technique, the radiation-free nature of the procedure is lost.

At this stage of development, MRI cannot compete with the traditional methods, US and CT, in guiding percutaneous drainage of pancreatic fluid collections in daily clinical practice. This is partly due to the better availability and lower cost of the conventional methods, and partly due to the specific technical restrictions of the MRI-guided procedures, i.e. lack of real-time imaging, longer procedural times, as well as limited assortment and performance of MRI-
compatible devices. Furthermore, many patients with pancreatic fluid collections are extremely ill, with multiple supportive devices, making their transportation and monitoring in the MRI unit difficult. Nevertheless, MRI is a promising new addition in the therapeutic armamentarium of this severe disease, and there are already some situations where a clear-cut advantage over conventional methods can be seen. These include cases where it is imperative to avoid ionizing radiation, the approach by US is prevented by intervening gas, or CT-guidance is limited by a heavily angulated access route.

6.4 Nephrostomy (III)

The imaging method used to guide PCN varies at individual centers depends on local expertise and operator preference, as well as on the degree of hydronephrosis. Although there are no exact data in the literature about the frequency of different techniques, the most common method seems to be the combined technique, in which the renal calyx is punctured under ultrasound guidance, and the rest of the procedure is guided by fluoroscopy. This clinically well-proven technique utilizes the strong features of each guiding method, and it is the standard technique for performing PCN at our institution as well. The need for two different guiding systems can be considered only a minor disadvantage, since modern ultrasound machines are portable and can easily be accommodated in a fluoroscopic suite. Nevertheless, there are certain patients in whom PCN can be difficult or even impossible to accomplish with this technique. Problems may arise when an ultrasound-guided puncture is hindered by overlying intestinal gas or severe obesity, or due to presence of parapelvic cysts. In addition, ultrasound is of little use in kidneys with minimally or nondilated collecting systems, although some special techniques have been suggested for these cases (Gupta et al. 1998, Krombach et al. 2001). A more common solution to achieve nephrostomy in difficult circumstances is to perform the procedure entirely under fluoroscopic guidance (Patel & Hussain 2004). This, however, necessitates the visualization of the collecting system during the puncture with intravenous or retrograde iodinated contrast media. Using fluoroscopy as the sole guidance method also increases the amount of ionizing radiation for both the patient and the interventionist. Another technique for challenging cases is to employ CT in guidance, either alone (Egilmez et al. 2007) or in conjunction with fluoroscopy (Barbaric et al. 1997). The obvious disadvantage of this approach is poor radiation hygiene; moreover, the gantry of the CT scanner presents its own limitations, especially in large
patients. A totally radiation-free PCN can be accomplished by using ultrasound alone in guidance, as advocated by some investigators (Gupta et al. 1997). The downside of this technique is the reduced control of the guide wire and catheter due to their poor visibility in ultrasound. In addition, in demanding situations, ultrasound may provide inadequate guidance for the puncture, as discussed before.

The results in this study demonstrate that it is possible to place a nephrostomy catheter into a dilated (grade two or more) collecting system accurately and safely under MRI guidance. However, unlike in previous animal studies (Merkle et al. 1999, Nolte-Ernsting et al. 1999), the procedure could not be performed in a nondilated system, due to several reasons. Owing to the lack of real-time imaging capability, the needle had to be advanced without continuous monitoring. This aggravates the difficulty of reaching the tiny target of the tip of a normal calyx. In addition, in experimental studies, ideal conditions for the procedure can be created. These include general anesthesia, which abolishes all respiratory motion artifacts from MR images, and any imprecision during the puncture deriving from the movement of the target is also avoided. All procedures in this series were done in local anesthesia with breath hold imaging, which requires good cooperation on the part of the patient. Scan time for the 3D b-FFE sequences was 24 seconds, which resulted inevitably in some respiratory movement during data acquisition in elderly patients. Furthermore, because the kidney moves easily with even the slightest respiration, some inexactness ensuing from motion was encountered during the puncture as well. Nonetheless, in order for MRI-guided PCN to become a clinically accepted method, it must be able to be performed under local anesthesia. The use of general anesthesia is not justified, since PCN is routinely performed under local anesthesia with traditional techniques. Furthermore, in animal studies, intravenous MR contrast agent was administered to obtain MR urographic images with extremely high contrast between the collecting system and the renal parenchyma. MR contrast media were not used to depict the pelvicaliceal system in this study; it relied on the native contrast resolution generated by the b-FFE sequence, leading to a less conspicuous delineation of the target calyx.

The use of MR contrast agent is problematic for two reasons. First, the vast majority of nephrostomies are placed in patients with poorly or nonexcreting hydrenephrotic kidneys. In these patients, contrast media cannot be used to visualize the pelvicaliceal system. The second concern is that there are reports (Grobner 2006) linking the use of gadolinium-based contrast media in renal patients with nephrogenic systemic fibrosis. At this time, this phenomenon is not
fully understood, but it is recommended that caution be exercised when using any gadolinium-based contrast agent in patients with decreased renal function (Thomsen 2007). Therefore, as patients who receive a PCN almost invariably suffer from renal insufficiency, it would be preferable to come up with a technique that does not involve the use of MR contrast media. Nolte-Ernsting et al. (1999) suggested that contrast-enhanced T1-weighted imaging is indicated in dilated pelvicaliceal systems with the presence of parapelvic cysts to distinguish collecting system from the cysts. It was found in this study that while the signal intensity of a cyst was close to that of urine with the b-FFE sequence, they could still be readily differentiated from each other, without compromising the safety of the puncture. Consequently, it does not seem necessary to use contrast-enhanced imaging even in the presence of parapelvic cysts.

Outside of preclinical animal experiments, MRI-guided PCN has previously been investigated only in a case report of a single patient by Hagspiel et al. (1998). They used the same type of MRI hardware and software as was used in this series to perform a PCN of an obstructed kidney due to stones in a ureterocele. They also employed the Seldinger technique, with the difference that only the needle was MR-compatible, while the rest of the equipment was non-MR-compatible. They mention restricted visibility of the instruments as the major drawback of the technique. As a consequence, unlike in this study, they only used fast interventional MR sequences during the puncture; the rest of the procedure was monitored with gradient-echo sequences to increase the image quality. The lower temporal resolution of the traditional MR sequences is manifested in the time required for the procedure, 45 minutes, which is significantly longer than the mean time of 26 minutes in our study. Procedural times for an MRI-guided PCN seem to be somewhat longer than with the traditional methods, reflecting the non-real time nature of the technique. However, as PCN is a relatively simple procedure, the time loss is not significant, and the total time required for the MRI guided procedure is satisfactory.

A basic prerequisite for a successful completion of an MRI-guided abdominal nephrostomy is the visualization of all the devices used. Although the general performance of the instrumentation used in this series in terms of both MR visualization and carrying out the procedure itself was acceptable, the weak link of the kit is the guide wire. This did not hinder the placement of a nephrostomy, but it would certainly make more complex endourologic procedures (Wong et al. 1998) problematic.
The ultimate goal behind developing an MRI-guided technique for PCN is that it could replace the current techniques, which all have their shortcomings. Particularly challenging with the traditional methods is the PCN of a nondilated renal collecting system. Unfortunately, with the technique described here, MRI-guided PCN in a nondilated renal collection system is not feasible. Therefore, further investigation is clearly needed to perfect the MRI-guided technique before it can solve this obvious clinical need. As for the PCN in dilated systems, although feasible, MRI-guidance is still unlikely to spread into routine clinical practice, mainly because it is more expensive, time-consuming, and cumbersome than the traditional methods. Novel MR systems, whether being horizontally open low field scanners (Fritz et al. 2008a) or short closed bore wide aperture magnets (Stattaus et al. 2008), with sophisticated imaging features enabling MR fluoroscopy, may change this. For the time being, MRI-guided PCN is an alternative technique reserved for special circumstances, namely those where avoiding ionizing radiation is imperative (children and pregnant women), or a US-guided procedure is hindered by obesity, parapelvic cysts, or extensive gas.

6.5 Laser ablation of RCC (IV)

This study illustrates that percutaneous MRI-guided laser ablation is a technically viable approach to the management of small RCCs. Tumors in all but the first patient were successfully treated, and no recurrences have occurred during the follow-up. MRI system was utilized in the planning, targeting, monitoring, and controlling of therapy. However, to achieve quicker needle placement, the initial puncture of the tumor was performed under US-guidance whenever the tumor was visualized with US. MRI-guidance was used to confirm and adjust the position of the fibers to ensure optimal location of one or more laser application systems in three dimensions. The main advantage of MRI over other imaging modalities is its unique sensitivity to thermal changes (Vogl et al. 1995b, Germain et al. 2001a, Germain et al. 2001b), which allows visualizing the amount of induced necrosis in the tumor, thus overcoming the problem of the inherent variability of tissue response to heat. This enabled monitoring the heating process in near real time in all dimensions to ensure that the entire lesion had been treated, and to reposition the applicators in case of residual tumor, increasing the probability of treating tumors in one session. Monitoring thermal effects during ongoing therapy also helps to minimize destruction to surrounding healthy tissue, therefore increasing the safety of the procedure. Another technique to prevent
damage to nearby structures is hydrodissection (Gervais et al. 2005a, Lee et al. 2006), in which the renal tumor is moved away from an abutting organ by instillation of saline between the two structures. MRI-guided hydrodissection was used in two cases to protect the bowel from thermal injury during the ablation.

Previous experience on laser ablation of renal tumors is very limited; only one group has published their results (Dick et al. 2002). The technique in this series was in many aspects similar to theirs, but with a few significant variations. They used thermal mapping for monitoring the treatment, whereas the approach in this study was to rely on signal intensity decrease in heat-sensitive image sequences. The main difference was that they only used one laser fiber at a time, which presumably led to less energy delivered, although the total amount of energy is not specified exactly. Consequently, even with an average of two ablation sessions per tumor, no total necrosis of the tumors was achieved. The number of fibers and the length of active tip in this study was determined according to the size and morphology of the tumor, with the assumption that each fiber creates a necrosis with a diameter of 3 cm (Vogl et al. 2004b). However, the heat deposition in the tissue cannot be predicted exactly (Vogl et al. 2004a), and thermal MR imaging is therefore needed to monitor the treatment.

Compared to RFA, MRI-guided laser ablation offers some advantages. The majority of renal RFA seem to be done under CT-guidance, which not only involves radiation burden, but also does not allow monitoring of the thermal effects during the treatment. This may increase the risk of residual tumor and contribute to the need for retreatments. There are also MRI compatible RFA probes enabling an MRI-guided RFA (Lewin et al. 2004), but due to interference, the RF current must be interrupted during data acquisition. RFA is predominantly performed in local anesthesia, and general anesthesia might be considered a drawback of the technique in this series. MRI-guided laser ablations were, however, lengthy procedures, averaging around three and a half hours, including the time for the general anesthesia itself and, in four patients, a biopsy or another tumor ablation. In addition, the acquisition of the 3D b-FFE sequences used for monitoring the ablations required breath holding for 24 seconds, which is difficult for many patients. Therefore, general anesthesia both optimizes patient tolerance and minimizes the detrimental effects of respiratory motion on targeting and monitoring during the procedure.

When ablating renal tumors, a percutaneous approach has been shown to be safer and equally effective compared to an open or laparoscopic approach (Hui et al. 2008). By contrast, over 75% of the reported cryoablations have been
performed through an open or laparoscopic approach (Kunkle & Uzzo 2008),
diminishing the mini-invasiveness of the procedure. Compared to percutaneous
cryotherapy performed under MRI guidance (Silverman et al. 2005), clear-cut
benefits for laser ablation are hard to find. From an economic point of view, it
may be less expensive to start an ablation practice with a laser-based technology,
especially if an institute already has a suitable laser generator acquired for other
applications. From a technical standpoint, it is acknowledged that the demarcation
of the ice ball in MR imaging is sharper than the delineation of the heat effect
induced by laser. Nevertheless, the image quality was found to be sufficient for
each step of the treatment, including monitoring of the heating process. The
patients were treated in a low-field environment with known constraints in signal
yield; adaptation of the technique to high-field scanners would increase the
temporal resolution and monitoring capabilities of MR imaging (Boss et al. 2008).
However, open configuration MRI systems with wide access to the patient are
better suited for procedures to be done exclusively under MRI guidance, if needed,
as in two cases in this series.

The value of kidney tumor biopsy is somewhat controversial, and a recent
meta-analysis (Hui et al. 2008) showed that only 59% of percutaneously ablated
renal masses underwent biopsy. All tumors in this series were biopsy-proven
malignancies, although in two cases the tissue sample was obtained just prior to
the ablation. These two tumors could not be identified with US, and therefore
they underwent an MRI-guided biopsy. Because of a high probability of a
malignant tumor, a decision was made to treat the tumors in the same session to
avoid another procedure. It seems logical that a tissue diagnosis is of value
because it ensures that the mass is malignant and prevents patients with benign
tumors undergoing an unnecessary procedure and years of follow-up after the
treatment (Tuncali et al. 2004, Remzi & Marberger 2009). Furthermore, if a
tumor is ablated without a biopsy, patients will never know for sure whether or
not their tumor was malignant, which is a strong argument against this approach.
Some have argued that post-ablation biopsy is needed to confirm the positive
outcome of the treatment (Klingler et al. 2007, Weight et al. 2008), whereas
others put forth that imaging can reliably monitor treatment efficacy in the long
term (Raman et al. 2008). The elimination of contrast enhancement at follow-up
imaging was used as the criterion for successful ablation in this study. This is a
well-established practice for the assessment of treatment effect and, together with
emerging excellent long-term oncologic outcomes (Levinson et al. 2008), seems
to render post-ablation biopsy unnecessary.
Another treatment strategy for small RCC in surgically unfit patients is watchful waiting (Volpe et al. 2004, Kunkle et al. 2007). The rationale behind this approach is that a significant number of small tumors seem to have a slow growth rate and a limited tendency to progress. On the other hand, even some of the small renal tumors do grow rapidly (Zhang et al. 2009), and there are no established clinical parameters to predict the growth rate. Therefore, if surveillance is selected as the clinical management approach, it must be intensive. Furthermore, not all patients are comfortable with the idea of following up a malignant tumor. For these patients, percutaneous ablative therapies offer a good treatment option. Patients who have a high risk for the development of additional RCC in the future because of genetic syndromes associated with RCC are also potential candidates for thermal ablation, as are patients with synchronous RCC (Clark et al. 2009).

Tumors in a central location of the kidney are known to be more difficult to ablate than exophytic tumors (Gervais et al. 2005b). In this series, the morphology of the tumors did not affect the outcome of the ablation; however, the number of patients is too small to allow any firm conclusions in this respect. The one treatment failure is explained by inexperience, since it occurred to the first patient treated. Percutaneous MRI-guided laser ablation proved safe. Only one major complication was associated with the procedures; no other local or systemic complications requiring treatment occurred. In general, the ablation was well tolerated and patients were discharged from the hospital a few days after the treatment.

There are some obvious limitations in this study. In the light of the small number of patients, the results can only be regarded as preliminary, and further research is warranted to define the role of MRI-guided laser ablation, especially in respect to other percutaneous ablative techniques. In addition, bearing in mind the slow growth of many of the small RCCs, the mean follow-up time of 20 months is still relatively short, and prolonged follow-up will be necessary to prove the durability of laser ablation.
7 Summary and conclusions

1. Abdominal biopsies can be performed safely and accurately under MRI guidance whenever US guidance is not feasible.
2. MRI-guided percutaneous drainage of pancreatic fluid collections with dedicated MRI-compatible drainage equipment is feasible and safe.
3. MRI-guided percutaneous nephrostomy of a dilated urinary tract is feasible and safe. The limitations of the presented technique render it not feasible for use in nondilated urinary collecting systems.
4. Percutaneous MRI-guided laser ablation of small RCC in patients with high risk for a surgical procedure is safe and effective. Longer follow-up should provide further proof of the effectiveness of the technique.
References


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Original publications

This thesis is based on the following articles, which are referred to in the text by their Roman numerals.


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Original publications are not included in the electronic version of the dissertation.

1102. Pasanen, Annika (2011) Prolyl 3-hydroxylases and hypoxia-inducible factor 3: their roles in collagen synthesis and hypoxia response, respectively


1104. Harila, Marika (2011) Health-related quality of life in survivors of childhood acute lymphoblastic leukaemia


1106. Juuti, Anna-Kaisa (2011) Sleep disorders and associated factors in 56-73 year-old urban adults in Northern Finland

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MAGNETIC RESONANCE IMAGING-GUIDED PERCUTANEous ABDOMINAL INTERVENTIONS

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