Equipment Configuration and Procedures: Preferences for Interventional MicroTherapy

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Magnetic resonance imaging (MRI), computed tomography, and electron beam tomography scanners are built for radiologic diagnosis. With increasing frequency they are being used in the field of Interventional Microtherapy to permit transparent visualization of the therapeutic field. Each of these scanners can be combined with endoscopy, fluoroscopy/digital subtraction angiography, and ultrasound units for hybrid imaging techniques as well as with therapeutic systems like lasers or radiofrequency. MRI affords 3D localization without x-ray exposure. Open access and keyhole imaging allow nearly real time guidance of instruments. Minimally invasive techniques using endoscopes and hybrid tomographic guidance result in improved tip tracking of microinstruments and reduced complications. This safer access into the body will lead to interdisciplinary cooperation with the potential for large cost reductions. This report summarizes our experience regarding which of the hybrid imaging suites is best suited for procedures including among others drug instillations, prosthesis (stent) implantation, or microoperations (endoscopic diskectomy/sequestrectomy), and physiological measurements simultaneously.

KEY WORDS: interventional radiology, interventional cardiology, minimally invasive therapy, microtherapy, endoscopy, interventional computed tomography (CT), interventional electron beam tomography (EBT), interventional magnetic resonance imaging (MRI), computers, spine, heart, tumor, pain, macroscopy, voice control.

RECENT developments in the computer-based cross sectional imaging technologies of computed tomography (CT), ultrafast Electron Beam Tomography (EBT) and magnetic resonance imaging (MRI) allow almost real time high resolution visualization of organs for diagnostic and therapeutic purposes.[1] The physician can see only structures directly in front of his eyes in open surgery or in front of his extended eyes in endoscopy, whereas computer-based tomographic imaging provides a transparent picture of the entire operative field. Analogous to microscopy which obtains a transparent view of cells, the use of tomography during operations is called *CT or MRI Macroscopy,* because the therapist has a transparent view of the operation field. Thus, one can speak of CT-scopy, EBT-scopy, or MR-scopy when using these systems for interventional procedures. With the help of cross sectional tomography (macroscopy), the risk of complications of minimally invasive interventions may be reduced significantly. All instrument systems, including endoscopes, can be guided transparently with precision to the operative field by two or three dimensional (3D) imaging methods. This transparent visualization is of fundamental value, but in practice various other computer-based and conventional imaging modalities and other devices are used together to perform interventional procedures.

Imaging technologies allow visualization of therapy effects. Temperature induced signal changes, flow in vessels, or changes in metabolism can be directly identified.[2-5] Even high risk structures, such as nerves or vessels, which may not be visible during endoscopy when they are hidden in or behind the tissue can be visualized and protected. Therefore, the risk of injury is reduced significantly.

In combination operation, drug instillation, prosthesis (stent) implantation, or tissue activation (Fluorescence, photoablation) as well as physiological measurements are possible within the same image guidance procedure (Table 1).

In our University Institute several thousand microinvasive interventional treatments are performed annually, mostly under CT or MRI control. This has been enabled in no small part by the availability of open tomographic scanners. The presence of three types of digital tomographic modalities has permitted this com-

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Table 1. Possibilities of MicroTherapy in One Single Procedure

MicroTherapy

Measurements — IMAGING — Activating

Operation — Instillation Implantation

parison of which work best for various interventional procedures. In practice several hybrid interventional facilities (HIF) have evolved for macroscopic interventional procedures, each including various computer-based acquisition devices and centered about an open MRI scanner, a CT scanner or the ultrafast EBT scanner. X-ray, fluoroscopic ultrasound (US), and endoscopic methods are incorporated in some of these combinations. Also, therapeutic systems like lasers, radio frequency (RF), cryo, or hyperenergetic US are installed near the hybrid scanners.

Our large procedure volume and the presence of these three facilities has allowed us to determine which approaches work best for each situation. The purpose of this report is to present our observations on the suitability of these hybrid imaging suites and their strengths and problems.

Equipment

CT HIF. A conventional CT scanner is combined with a C-arm fluoroscope equipped with digital subtraction angiography (DSA). Various monitors, laser systems, endoscopy, and US units are placed close to the gantry.

Our treatments are performed in a Somatom Plus S (Siemens, Erlangen, Germany) with a 70 cm gantry opening. For minimal access during procedures CT scanners with gantry openings of more than 60 cm are required. A distance of about 0.5 to 1.0 meters is required between the patient couch and gantry to install a fluoroscopic unit close to the gantry while maintaining working space for the therapist in all directions. During a procedure the table has to be moved to defined positions inside and outside the gantry to permit access to the operative field.

EBT HIF. This facility features an ultrafast CT scanner using the EBT technique (Imatron C150 LX and Evolution-EBT, Siemens) in conjunction with C-arm fluoroscopy/DSA, endoscopy, and US units (Fig 1). The scanner gantry opening is 90 cm. Also a voice controlled table (Tables 2 and 3) and a special laser positioning

Fig 1. Ultrafast EBT HIF. The fluoroscope is installed close to the gantry, and other electronic equipment is nearby.

Table 2. Voice Control System: Technique

SCOSY—Medicun *S*peech *C*ontrolled *S*ystem for *Med*ical *Un*its	
Features	
• Modular concepted	• Wireless microphone
• Single word recognition	• Reconition rate up to 98%
• Up to 1,000 commands	• IBM compatible
• Infra-red remote control	• Windows 95

Git Inc (Mülheim, Germany).

system for optimizing guidance procedure and sterility was developed (also for CT) (Tables 4 and 5).

Scanning is done by deflecting an electron beam focused to 1 mm to 2 mm size focal spot across a series of 4 semicircular tungsten targets around the patient. Each target can produce a beam of x-rays. Frame rates of up to 34 images per second (v 1 per second for conventional CT) are possible (simultaneous multilevel scan acquisition in 50 msec). Two detector rings are installed above the patient so that a pair of EBT images can be obtained each time any one of the tungsten rings is "swept" by the electron beam. Thus, up to 8 levels can be scanned at the same time without moving the patient table. Scans can be acquired at two, four, six, or eight levels during a single acquisition. Slice thickness can also be varied from 1.5 mm to 8 mm.

Ultrafast EBT was developed for noninvasive screening for coronary artery calcification (Imatron, San Francisco, CA). We initially reported about these guidance techniques in 1989.[1]

Open MRI HIF. Open MRI tomographic scanner are combined with endoscopy, DSA, or US units. Our group has designed and developed an Interventional-MRI-scanner based on the Toshiba ACCESS system in collaboration with Radiologic Imaging Laboratory at the University of California in San Francisco (ACCESS; Toshiba MRI Inc, San Francisco, CA). Special features include fluoroscopy and keyhole software[6,7] for nearly real time imaging, an open gantry with a flat transmission coil, a laser positioning system, and optimizing of the gantry level by elevation of the magnets (Fig 2).

Two advantages of open MRI systems are the absence of the x-ray and the capability of scanning the patient inside the magnet by means of a so called fluoroscopic mode. The ultra low-field MRI scanner developed by Kaufman[1] in 1988 was the first open MRI system. This MRI unit uses a permanent magnet with a field strength of 0.064 Tesla. The vertical field magnets of this scanner permit circumferential open access at the four lateral sides. Since 1993 other open MRI-unit configurations with different field strengths have been developed (C-shaped 0.2 Tesla (Siemens; Picker International, Cleveland, OH), Midfield: 0.5 Tesla (GE Medical Systems, Milwaukee, WI), and 0.2 to 0.3 Tesla temple (Hitachi, Hitachi City, Japan; GE).

In the past, the usefulness of low-field MRI scanners was underestimated. The efficiency and possibilities of permanent magnets and low-field MRI is currently undergoing extensive research. An advantage of permanent magnets in comparison to other types of magnets is relatively low maintenance cost because of no requirement for cryogens or electricity to maintain the magnetic field. Also, the distance between the poles of the Gantry is between 40 cm (Siemens, Picker), 55 cm (GE), and 60 cm (Toshiba).

The open design scanners are generally more comfortable than the closed, narrow tube-like

Table 3. Voice Control System SCOSY: Benefit

SCOSY—Medicun *S*peech *C*ontrolled *S*ystem for *Med*ical *Un*its	
Benefits	
• Sterility • Time saving • Reduce complex processes • Reduction of personel costs • Any extention you like	Git-Gesellschaft für Interventionelle Therapy, Mülheim, Germany.

Table 4. Laser Positioning System: Technique

Laser Positioning System LPS II
Features
• Laser beam
• Motor
• Detectable laser head
• cm scale
• IBM PC
• Windows

Micromed Inc (Bochum, Germany).

Table 5. Laser Positioning System: Benefit

Laser Positioning System LPS II
Benefits
• Sterility
• Defining entry point
• Defining puncturing angle
• For all CT/EBT-scanners
• Easy installation

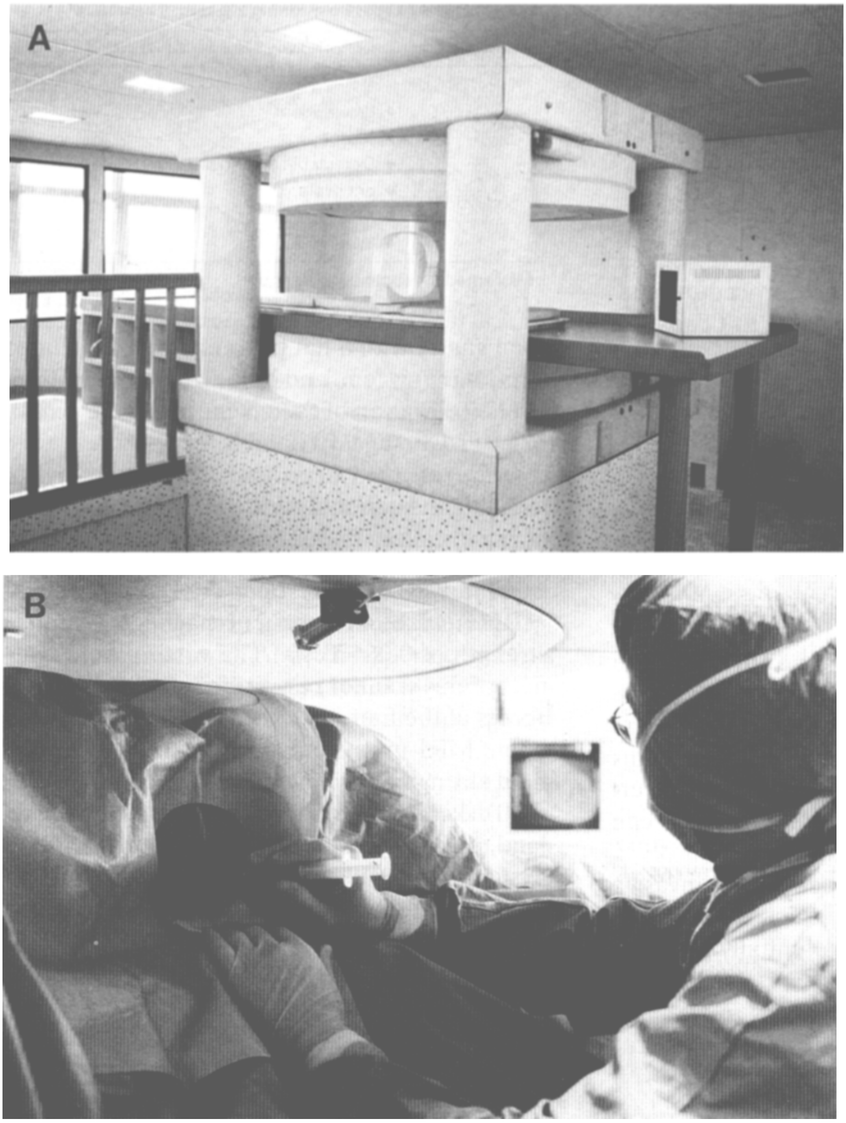


Fig 2. (A) Hybrid open MRI Facility with a Toshiba ACCESS MRI scanner. (B) Minimally invasive therapy inside the magnet.

design MRI-scanners. As a result, patients tend to be more cooperative and amenable to percutaneous procedures. Additionally "claustrophobic" as well as frightened patients can be examined with more convenience. The almost complete absence of gradient acoustical noise in ultralow field permits communication with the patient at all times. The open structure of the system also allows continuous observation with the ability to apply medications during the procedure. Higher field strengths allow faster imaging and higher quality of images in lower acquisition time.

Lastly, the location of the 5-Gauss line of the open ACCESS (Toshiba), which delimits the safety control area only approximately 60 cm from the edge of the magnet is important as it permits installation of conventional electronic systems in operation facilities. In all other MRI-units the line takes much more space around the magnet (both sides, above and below to other floors) creating more difficulties in siting.

We are using two ACCESS (Toshiba) and 1 Magnetom OPEN (Siemens) units for our interventional MRIscopic treatments.

Procedures

General approach. Certain steps are common to almost all procedures regardless of which HIF is used.[1-7] The patient is positioned in accordance with the best possible access to the lesion, mostly in the prone or in the lateral position. Premedication is not required in most cases as local anesthesia usually provides adequate comfort for the minimal trauma from the microinstrumentation. After positioning, a CT, EBT, or MRI scan is performed of the region of interest. An intravenous contrast injection is required in CT and EBT cases in those regions where vascular structures (eg, in the mediastinum) are not visible in soft tissues. For MRI imaging intravascular contrast media is only used for tumor and scar tissue differentiation.

The entry point, the puncture angle, and the distance to the therapeutic region are then visualized on the monitor and electronically determined. In EBT or CT the entry point and the puncturing angle is beamed onto the skin by using a special laser positioning system. After skin preparation and local anesthesia, a special guidance coaxial set is positioned, and the direction and position of the canula are checked with a second CT, EBT, or MRI scan. MRI fluoroscopy makes the safe interactive guidance technique possible. The therapy cannula is placed into the therapy region under local anesthesia. Contrast media is injected locally before imaging in all scanners to document drug distribution before drug instillation. The interventions are performed with special microinstruments (in MRI with nonferromagnetic materials like nitinol, titanium, platinum, carbonfiber, etc) with a diameter of 18 to 25 gauge, flexible microendoscopes of 0.3 to 1.5 mm, and 0.2 to 0.4 laser fiber (Micromed Inc, Bochum, Germany; Cook Inc, Blumington, IN). Instruments such as lasers, endoscopes, or forceps are all introduced through the guidance cannula. The distances from the skin level to the structure at the tip of the cannula is visible on the centimeter scale on the instrument shaft.

Injury to high risk structures like lung, nerves, or vessels in the path of the instruments is avoided by injecting local anesthesia and/or saline solution while advancing the cannula. This so called "hydraulic assisted canula insertion (HACI)" helps to push these structures away from the cannula tip (Fig 3). Percutaneous procedures using the low-field MRI HIF are approached in similar manner with either fluoroscopically or sonographically guided technique. The patient is then treated inside the gantry or removed from the center of the magnet for performing major interventional procedures when greater access is needed.

In CT or EBT the patient couch is moved out of the gantry as needed for the procedure. Only for laser treatments in, eg, percutaneous diskectomy or hyperthermia of cancer tissue, the long laserfiber is introduced into the body and fixed with the patient table, so that the therapy and the documentation can be realized inside the gantry without moving the table.

Therapy phases. There are 4 major therapy phases for each procedure, which acquire different imaging modalities: (1) *Localizing:* slice definition and electronic measurement (High resolution); (2) *Guidance:* introduction of instruments (Fast imaging, Low resolution); (3) *Treatment:* controlling of therapeutic effects (High resolution, 3D imaging); (4) *Documentation:* of

Fig 3. Biopsy inside the mediastinum with CT guidance. The microinstrument was guided carefully and precise into the tumor without damaging the segmental nerve, lung, esophagus or arteries (high risk areas [HiRA]). The space between lung and spine normally has a diameter of 1 to 2 mm. With 2 cannulas this space can be dilated with local anesthesia and saline solution.

treatment (High resolution, several planes, 3D imaging)

Selected Examples of Microtherapy Procedures

Chronic disk herniation. Two hundred-thirty five patients with chronic disk herniation were treated by periradicular therapy technique[8] (see Fig 4) with cristalline Cortison (Triamcinolon: 40 mg Volon A; Bristol Myers Squibb, Princeton, NJ) 8 times over 24 weeks. Good results (pain reduction of more than 50% and/or decrease of neurologic deficits, mean: 1.8 years follow up) were obtained in 155 patients (66%). The most effective cycle phase was the 2 and 3 treatment (more than 50% improvement). Side effects were as follows: edema in 1, weight gain in 4, and leg cramps in 11 patients. One complication was seen, acute, but reversible paraplegia in both legs over several months.

Acute disk herniation. One hundred sixteen patients with acute herniation underwent a percutaneous laser nucleotomy.[9] Acute disk herniations are treated with the Nd Yag laser (Dornier, Germering, Germany) (1,064 nm): using 10 watt, 1 second treatments with 1 second interruption and up to 150 pulses. Overall improvement of pain symptoms was more than 50% at follow up (mean: 17 months) was observed in 94 patients (81%). Pain medication was taken by 20 patients (17%) more than 6 months after the treatment, disability pension was registered in 10%. One patient suffered from spondylodiskitis; a second herniation was registered in 5 patients; 9 had nerve root irritation, which was effectively treated by micro-PRT. (Fig 5A, B and C)

Sequestrectomy of fragments in the spinal canal. The best view was obtained with 1.4 mm diameter endoscopes with an angle of 100°. The field of interest in the spinal canal is easily visualized after injection of saline or insufflation of air. Under endoscopic guidance and CT control the sequestrectomy can be safely performed through a second puncture. The nerve root is difficult to see in the spinal foramen because of surrounding fat. In addition to sequestrectomy a percutaneous laser nucleotomy was performed in all patients to reduce the volume and pressure of the affected disk. The nucleotomy was always performed with the Nd Yag laser (Dornier). In the present study the sequestrectomy was performed on 12 patients, 4 of which had free fragments in the spinal canal. In seven cases lateral herniation with one free fragment was treated. In one patient herniation in a foramen was removed (Fig 5C). No major complications were noted. The clinical success in these cases was very good.[10]

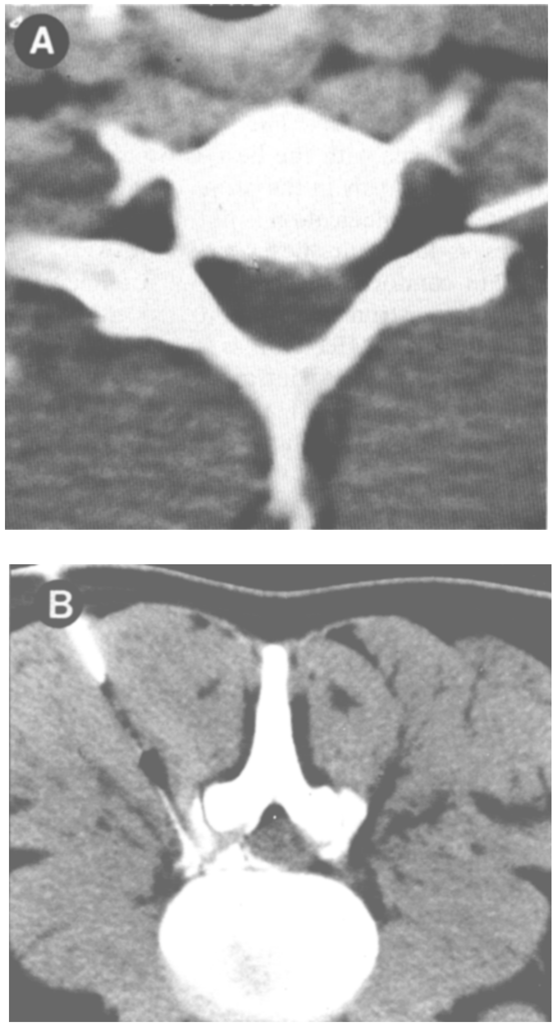
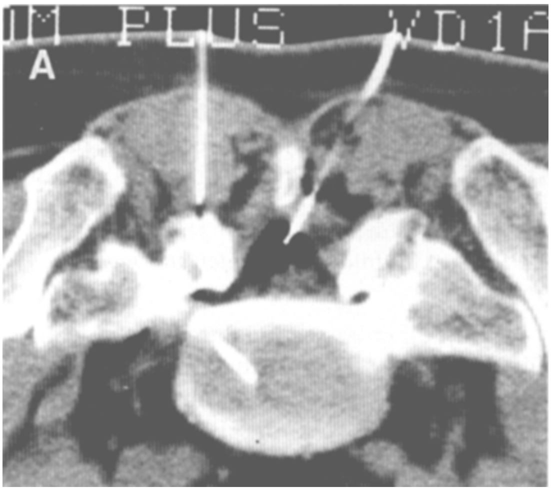
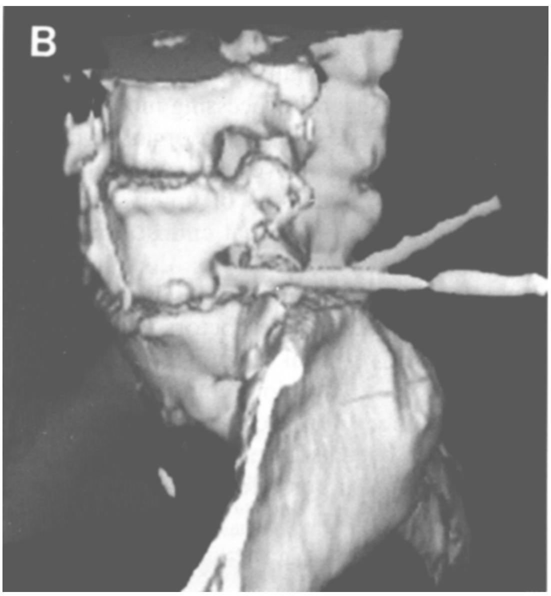


Fig 4. Microperiradicular therapy for chronic disk herniation. (A) C spine on the tip of the cannula is located 3 mm beside the a. vertebralis and (B) L spine (after instillation of contrast media around the segmental nerve and epidural space).

Low back pain. Ethanol is used for facet joint denervation for the treatment of chronic low back pain. Also, 10 to 40 mg triamcinolon (crystal cortisone: Volon A) is helpful for therapy of ilio-sacral joint pain. Sixty interventional MRI/CT-guided facet joint therapies and 30





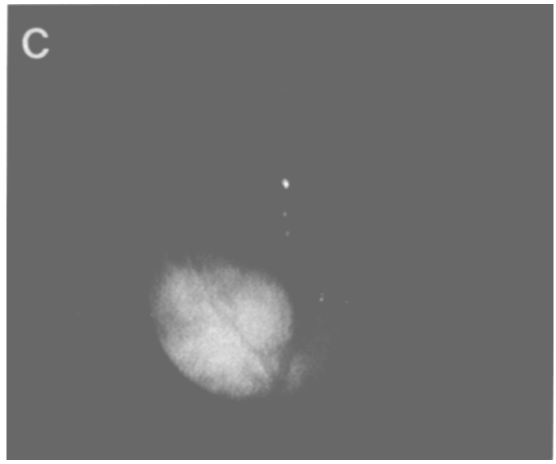


Fig 5. CT-scopic intraspinal control of microinstruments. (A) The tip of the cannula is placed under CT-scopy close to a herniated intervertebral disk. Microendoscopes, laser fibers, or microforceps are then inserted through this cannula. A further instrument is inserted into the intervertebral disk for laser nucleotomy. Another cannula is placed for local anesthesia of the small facet joints. (B) 3 D reconstruction of the spine with instruments. (C) Endoscopic view inside the spinal canal onto the herniation.

treatments of the ilio-sacral joints with cortisone were evaluated.[11] Ninety-two percent (n = 82 of 90 patients) were free of pain after the facet joint infiltrations and ilio-sacral joint therapies. No complications were seen (Fig 6).

Cancer therapy. For specific local cancer treatment 50% to 96% ethanol or chemotherapeutic agents like Mitoxantron (Novantron) (Wyeth-Lederle, Münster, Germany) are carefully instillated into the tumor mass. These palliative micro Percutaneous Ethanol Instillations were performed on 87 patients; 298 treatments, 41 patients with skeletal metastases (Group 1: 146 single treatments) and 46 patients with vertebral metastases (Group 2: 152 single treatments). The tumor volume was measured in three dimensions before and after ethanol instillation or local intratumoral chemotherapy. This cancer treatment strategy includes a biopsy (Fig 7) and a sympathectomy at the upper pole of the tumor before intratumoral therapy.[12] Also, a therapy with local anesthetics to sympathetic nerves, like the ganglion stellatum, for pain therapy are possible (Fig 8).

In Group 1 pain reduction of 75% or more was achieved in 33 patients (80%). A reduction in tumor size concomitant with a stabilization and calcification of the tumor region could be shown in 27% (11 patients) in this group, no change in 66%, and tumor progression in 10%

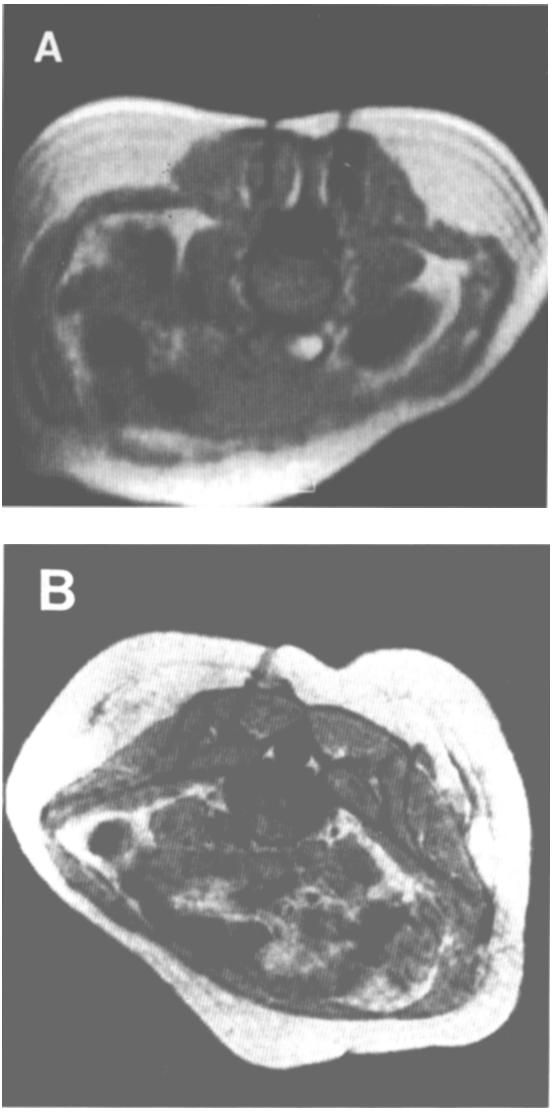


Fig 6. MRI-scopic treatment for low back pain (low risk area [LoRA]). (A) facet joints and (B) ilio-sacral joints.

(4 patients). In Group 2 pain reduction greater than 75% was achieved in 84% (39 patients) as well as a reduction in tumor size (< 50%) in 22% (10 patients). No change in tumor size was found in 36 patients (78%), but stabilization and calcifications in the tumor area without tumor reduction occurred in 15 patients (33%). All treatments were free of complications, but 2 patients suffered from back pain after the vertebral treatment for 2 weeks[12] (Fig 7).

Arterial occlusive disease. Three hundred sixty sympathectomies were performed at the L3/L4 level with 3.5 mL 96% ethanol[13] for avoiding amputation and infections or for reducing pain in cases of arterial occlusive disease. Downgrading from stade IVa to III in 31%, from III to IIa in 85%. Only 1 complication (fistula of the ureter) was seen as 2 patients suffered from back pain after the vertebral treatment for 2 weeks.

2D Versus 3D Imaging for Interventional Procedures

Today, all cross-sectional imaging modalities like US, CT, MRI, positron-emission tomography (PET), single-photon emission computed tomography (SPECT) or EBT allow 3D reconstructions in the postprocessing mode. A real time processing is not yet possible. The advantage of 3D imaging over 2D is the fast understanding of anatomic regions, especially for doctors without specialty training. Transparent surfacing and several processing modalities enable the doctor to look onto organ structures like surface, vessel, nerves, etc. Also, more and more 3D reconstructions of inner surfaces of intestinal organs for virtual endoscopy are under development.

But in comparison to cross-sectional 2D slices, 3D images enable doctors to look at the surfaces of anatomical structures. The regional density resolution is low compared to cross-sectional images. For access and guidance techniques, the therapist needs high resolution for tip tracking and if possible also ultrafast or real

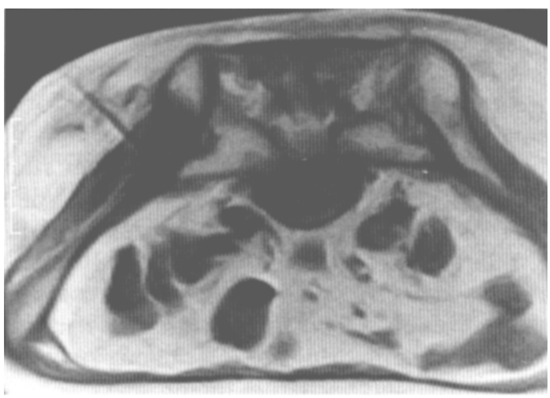


Fig 7. MRI-scopic interventional tumor biopsy of a bone metastasis within the os ilium. The special cannula made of titanium alloy is placed in the tumor. No endangered structures are located nearby (LoRA). A percutaneous drug instillation could be possible in a second step. The guidance procedure is identical (ACCESS, Toshiba).

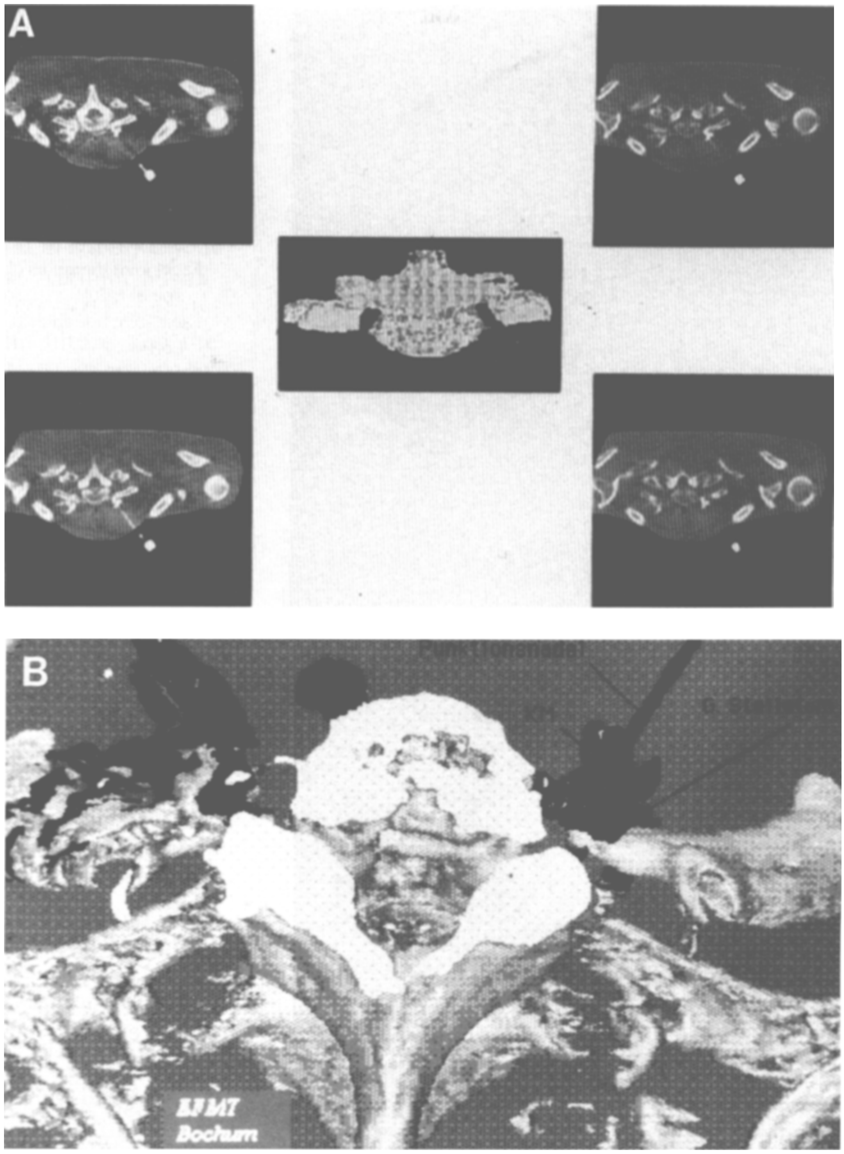


Fig 8. Injection of 1 cc of local anesthesia into the ganglion stellatum for pain treatment. (A) EBT-guidance of the cannula and instillation of contrast media and drugs. (B) 3D reconstruction of EBT images during the procedure with the ganglion stellatum labeled.

time imaging. Tissue changings like regional edema, bleedings, or lesions caused by energetic treatments (laser, RF, cryo, etc) in between operating manipulations can only be controlled by high resolution imaging. For this reason, 3D or virtual guidance must be combined interactively with actual and not with prescanned slices.

3D imaging is also a wonderful tool for postprocessing documentation of therapeutic effects like drug distribution (eg, percutaneous ethanol instillation for cancer therapy or sympathectomy), laser induced disk shrinking, or implantations. 3D models are very helpful for operation planning as well as for education and training, especially if animal studies can be avoided.

Preferred Equipment Suites for Various Procedures

Some procedures require a specific approach, whereas some can be done comfortably with more than one of our three imaging suites. Tables 6 and 7 summarize our observations.

DISCUSSION

Enormous cost savings can be realized by prevention of complications and long-term hos-

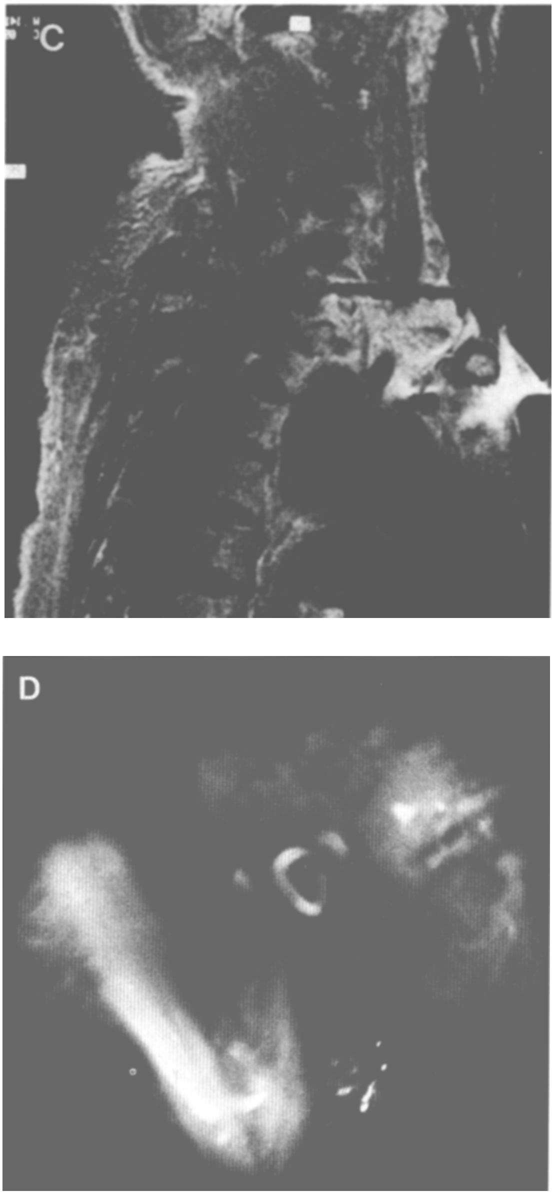


Fig 8. (C) MRI-scopic view (sagital plane). (D) Endoscopic view of the ganglion stellatum.

pitalization if our healthcare system, from medical checkup, to prevention programs, to rehabilitation, is optimized together with early use of modern imaging and minimally invasive treatments.

The tomographic scanner technology enables nearly real time transparency with high quality and local tissue discrimination for the first time. CT and MRI offer safe access in conjunction with minimal risk for vital structures. If there

Table 6. Equipment Suite Preferences by Procedure

	Best Imaging Suite	Good Suite(s)	Poor Suite(s)
Spine			
Percutaneous nucleotomy (acute herniation)	CT	MRI	EBT
Sequestrectomy	CT	EBT	MRI
Periradicular Therapy (chronic herniation)	CT	MRI	EBT
Facet joint therapies (C/T-spine: HiRA)	CT	EBT	MRI
Facet joint therapies (L-spine: LoRA)	MRI	CT	EBT
Ilio-sacral joint	MRI	CT	EBT
Biopsy			
Biopsies (thorax, heart, abdomen)	EBT	CT	MRI
Biopsies (LoRA)	MRI	EBT/CT	
Biopsies (HiRA)	CT	EBT	MRI
Cancer			
Local cancer therapy (LoRA)	MRI	CT/EBT	
Local cancer therapy (HiRA)	CT	EBT	MRI
Neurolysis			
Sympathectomies	CT	EBT	MRI
Endoscopy			
Thorax, heart, abdomen	EBT	CT	MRI
Joints	MRI	EBT	CT
Spine	CT	EBT	MRI
ENT (sinus, ear, throat, soft tissue)	MRI	CT	EBT
Brain (guidance)	CT	MRI	EBT
Brain (treatment, documentation)	MRI	CT/EBT	
Vascular			
Tip tracking	EBT	MRI	CT

are vital structures like nerves and vessels in the target region (High Risk Area [HiRA]), CT is our preferred technique of guidance-technology, but will be followed by EBT soon, especially when ultrafast reconstruction time will be available.[14] The puncture precision with CT is 1 mm.[3] Open MRI is useful in Low Risk Areas (LoRA). Organs that are affected by breathing should be punctured during breath holding and if possible under EBTscopic view. Furthermore, it is possible by special puncture techniques to approach structures that are located behind or

Table 7. Hybrid Imaging Facility Preference for Heart Procedures

	Exclusive Imaging Suite	Comments
Heart		
Biopsy	EBT	intra and extravascular
Endoscopy	EBT	intra and extravascular
Catheter guidance	EBT	future

in front of other organs without damaging these organs. For these special procedures, new methods of the 3D puncture technique have been developed by injecting saline solution "HACI" (eg, for the biopsy of tumors in the mediastinum) (Fig 3).

Flow measurements of arteries can be realized by using MRI or EBT[5] and in MRI without contrast media for visualizing. Another advantage of MRI in comparison to CT/EBT could be temperature mapping[2,4] in the future and the possibility of measuring metabolic changes with the spectroscopy mode in high field (1.5 Tesla) systems. In certain cases correct access can be gained by tomography for interstitial therapy such as drug injection, or placement of prosthesis, stents, implants, and gen-technical implants, or for drilling and screwing with the correct angle for osteosynthesis. Using an endoscope the therapist is enabled to recognize different organs and structures in preformed or artificially created cavities.

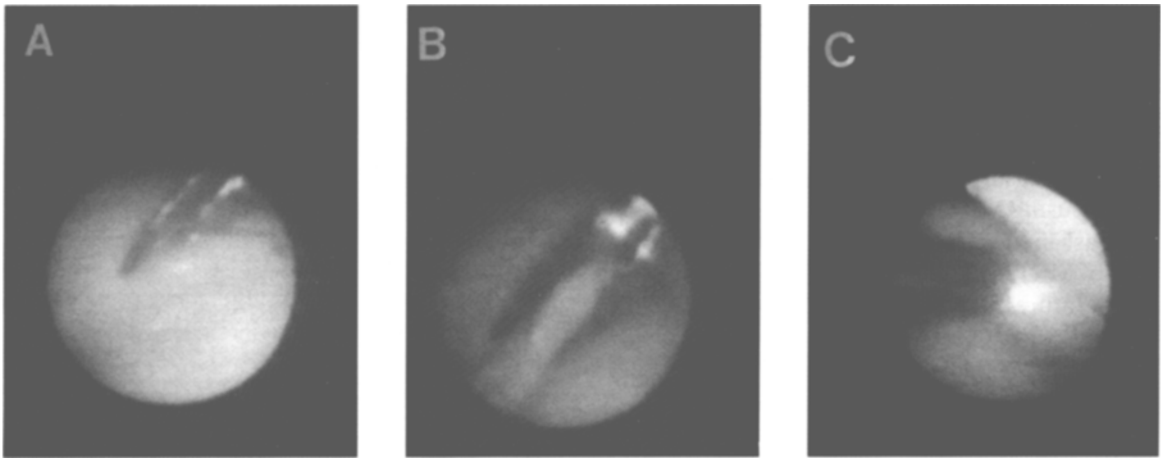
Because the transparency of the patient gained by MRI, CT, or EBT adds important information about spatial configuration of anatomical structures, image guided access techniques may help to avoid complications. The combination of endoscopy with scanner technology, fluoroscopy units, or intravascular US allows every structure in the body to be visualized and defined. In addition, the small diameter of instruments (<1 mm) reduces the risk of accidental injury to vital structures like arteries, nerves, renal vessels, or the colon and it is important that the therapeutic effect be visible at once within the surgical procedure (eg, shrinking of the disk) (Fig 5). This microinvasive technique permits the change from general anesthesia to local anesthesia and performance on an outpatient basis.

Our current development program includes the design of a so called hybrid endoscopic radiologic operating system (HERO), which is considered to facilitate the combination of endoscopic surgical procedures in delicate high risk operative fields through the use of tomographic imaging. Thus, the simple surface view on structures and the lack of overview during endoscopic surgery can be overcome by means of either MRI or CT/EBT imaging in accordance with the therapeutic target. Intelligent surgical instrument systems[15] may be incorporated, if required, to solve the problems of tactile feedback kinematic response and remote handled control of dextrous instruments. Orthopedic arthroscopic, neuroscopic, and thoracoscopic operations in particular will be facilitated through the increased transparency of the patient's individual anatomy and pathology. Planning and training of specific operative procedures seems also enhanced, because all data acquired by the imaging technologies can be stored and used in surgical simulators.

Unlike the comparatively primitive fluoroscopic guidance used previously, computer technology has enabled us to control the guidance of operating instruments in organs with the help of tomographic systems and 3D reconstruction. The visualization of the therapeutic effect can be realized directly in high resolution and endoscopically. Because open tomographic systems are available, minimally invasive, and treatments of diseases in all disciplines can be realized.[14] This permits cost saving interventions for treatment of diseases of the spine, tumors, vascular occlusion, bile ducts, and urinary tract as well as to secure control of endoscopes and laser systems for treatment of paranasal sinuses and skull base, renal or gallstones, or in the case of an intervention in the brain.[16,17] Optimized tip tracking of catheters in cardiovascular system will be possible in EBT and MRI.

Techniques that are routinely used in the hybrid imaging facilities, mostly under CT guidance, include percutaneous nucleotomy[9] (mechanically or with endoscopy and laser), intraspinal lysis of scars, or sequestrectomies[10] (Fig 5), sympathicus obliterations[13] or pain therapy (Fig 8), local tumor therapies with alcohol or laser,[12] biopsies and pain therapies for treatment of chronic and strong pain (neuralgias, tumor pain (Fig 7) as well as joint treatments[7] with microinstruments (Fig 9).

MR-scopic treatments in open systems that can be realized without ionizing radiation are very new and are not yet used world wide as routine procedures. In 1986, Thomas et al[16] were the first to describe MRI-guided techniques for biopsies in the brain and Lufkin et al[17] in 1987 in head and neck. Also in 1986, Mueller et al[18] reported the successful construction of a MRI compatible needle. Using this



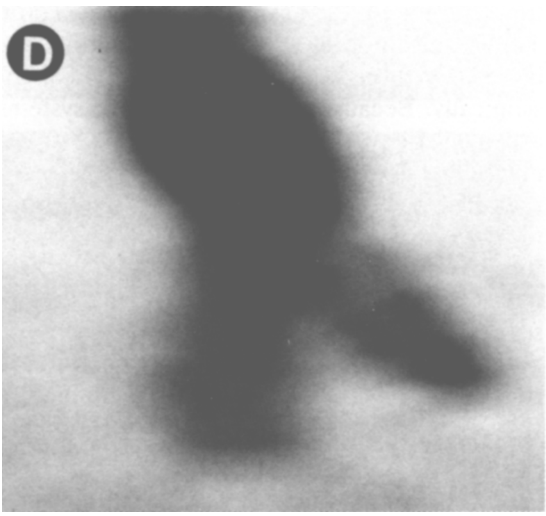
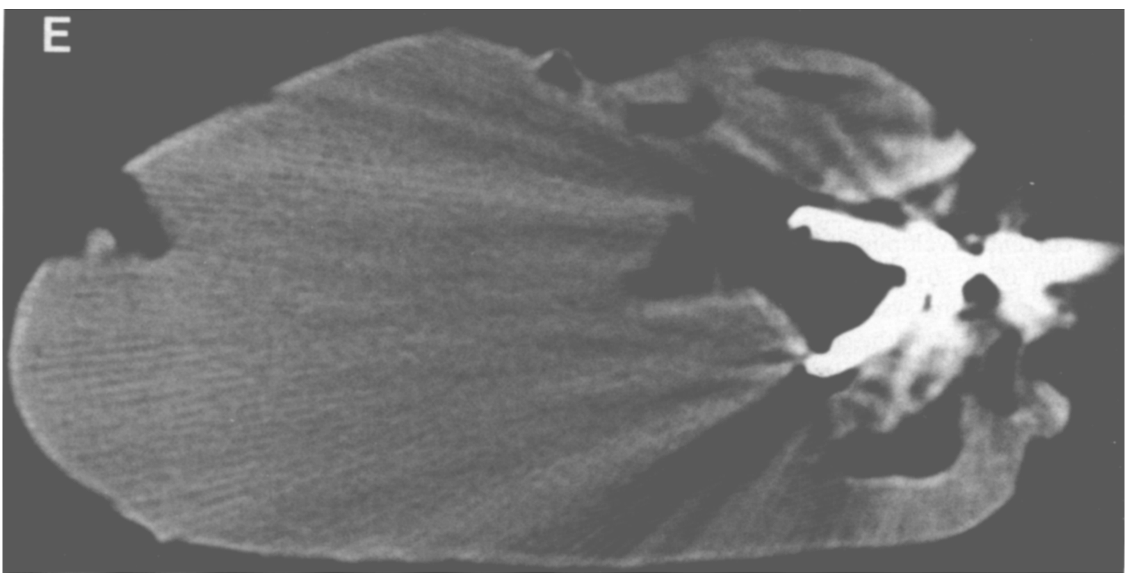


Fig 9. Visualizing microinstruments inside the knee-joint for meniscus-surgery. (A) scissors, (B) forceps, (C) laser, (D) forceps seen through the MRI opening, (E) in the heart (cadaver study) forceps seen through the EBT opening.



instrument the first liver biopsies were performed and also in that same year a series of prostate biopsies were realized.[19] Additionally in 1986, van Sonnenberg et al[20] described the clinical use of MRI compatible interventional materials, specifically plastic catheters and stents for drainage procedures. In 1987, Hamilton et al[21] developed special needles for head and neck biopsies in MRI.

So far, the possibilities for interventional procedures using MRI had been limited by the narrow tube-like design of the magnet and the long acquisition time, when compared to other guidance methods. Therefore up until today, MRI interventions have been rather complicated and difficult to perform. But now open designed MRI-systems are developed from different companies for interventional and surgical procedures. A listing comparing MRI open systems is presented in Table 8.

In 1994, the first MRI-guided interventions in the United States with a dedicated midfield system from General Electric (0.5 Tesla) were performed in Boston under the direction of F. A. Jolesz of Harvard Medical School.[22] A C arm designed open MRI system is being installed also in 1994 by Siemens (Magnetom Open, 0.2 Tesla) at the University of Los Angeles and the interventional procedures were realized by the group of R. Lufkin.[23] The first interventional procedures in an open MRI system in Europe were realized by our group in 1988.[24]

As A. Adams[25] proposed, the best way forward for learning new treatments and for training lies in large minimally invasive therapy units (MITUs). These MITUs are multidisciplinary centers in which all specialities undertaking the direct treatment of patients using minimal access/microinvasive techniques are represented.

Although CT is our current "preferred technique" for instrument guidance, MRI will gain more importance because of the new developed "open" systems. CT has to be used for high risk procedures like inside the spinal canal and for treatments in bony structures. EBT is preferred technique for guidance of instruments in thorax, abdomen, and heart. Especially for microinvasive heart treatments like biopsies, endoscopies, and future tip tracking procedures hybrid ultrafast EBT is the key technique. In comparison to

Table 8. Open MRI Units for Interventional Procedures (Increasing Field Strength)

Producer	Field Strength (T)	Magnet System	Design	Comments
Toshiba Access	0.064	Permanent	Open 4-sided (360°) (temple)	Open system with vaste vertical access fluoroscopy, general interventions
InnerVision	0.14	Permanent	Open 3-sided	Dedicated system for head and extremities, restricted vertical access
Siemens Open	0.2	Resistive	C form Open 3-sided	Open system, suitable for intervention, fast imaging possible, restricted vertical access
GE Open	0.2	Permanent	Open 2-sided	Open system, suitable for intervention, fast imaging possible, restricted vertical access
Picker Outlook	0.23	Resistive	C form Open 3-sided	Open system, suitable for intervention, fast imaging possible, restricted vertical access
Fonar	0.3	Hybrid, permanent	Open 4-sided	Open system, suitable for interventions
Hitachi Airis	0.3	Permanent	360° access	Open system, suitable for intervention, fast imaging possible, restricted vertical access
Magnalab	0.3	Permanent	C form Open 3-sided	Dedicated system for extremities
GE "Double Donut"	0.5	High-temperature supraconducter	Open 2-sided vertical access	Developed especially for intervention, fast imaging possible
Picker asset	0.5	Supraconducting	Tube Open 2-sided	Only restricted suitable as tube system
Philips NT 5	0.5	Supraconducting	Tube 2-sided	Only restricted suitable as tube system integrated LCD monitor
Fonar	0.6	Hybrid permanent	Open 4-sided	Open system, suitable for interventions

MRI there are less tip artifacts in EBT/CT on the instruments, which are caused in the MRI by the magnetic field.

In contrast to CT, MRI does not produce x-rays. This is important not only for the therapist, but also for the patient. Moreover, imaging in three planes can be gained almost in real time. Also, without contrast media, arteries and veins can be documented as well as changes in tissue contrast after heating with laser or cooling with cryotherapy or using hyperenergetic US for tissue ablation in cancer therapy. In the case of diagnostic investigations, motion studies of the spine and joints can be realized. Furthermore, swallowing can be examined. The use of this patient-friendly open device is not only advantageous to corpulent persons but also to children and persons who suffer from claustrophobia. The advantage becomes apparent when parents, relatives, or medical staff can accompany anxious patients. In open MRI systems, operations can be performed quite comfortably inside the gantry without the patient being moved with nearly real time guidance using fast keyhole sequences.[6,27]

We believe that in about 10 years this tomography systems CT, EBT, or MRI will exist in many operating theaters as a hybrid combination of endoscopy systems[10,14,26,27] and US or x-ray units.[7] The conventional x-ray devices that only provide a shadowy image of the body structures will disappear. At the same time, prices of high-tech systems will be comparable with classical x-ray units because of the widespread installation of tomographs.

We define the transparent tomographic guidance of instruments with diameters below 1 mm for the procedures as *MicroTherapy* or *MicroInvasive Therapy* as a subdiscipline of Minimally Invasive Therapy. The highest precision can be achieved by microinvasive CT-scopy. Thus, instruments below 1 mm diameter (thinnest laser and endoscopes 0.2 to 0.3 mm, thinnest instruments 0.89 mm) can be placed precisely within $\pm$ 0.2 mm. Using nonmagnetic materials for MRI-scopy, such as titanium, platinum, nitinol, carbon fiber, ceramics, or special plastics,[24] the localization only is $\pm$ 3.5 mm.[14] However, MRI guidance avoids x-rays and provides almost real-time visualization of the instruments by means of keyhole fluoroscopy. The majority of classical operating sets or endoscopes do not allow MRI application because artifact is caused by ferromagnetic materials. Therefore, appropriate instruments for MRI procedures have to be developed.

If there are vital structures like nerves and vessels in the target region HiRA, CT is our preferred technique for guidance technology.[14,27] The tip guidance precision with CT is 1 mm.[3] In the near future this standard could be changed to EBT with the huge 90 cm gantry and acquisition of 34 scans per second, when reconstruction time reduced to less than a second. We are combining fluoroscopic units with CT or EBT (2D: x and y direction) in a so called hybrid technique to obtain a real time guidance in the z direction. Open MRI is useful in LoRAs.[27] Organs that are affected by breathing should be penetrated during breath holding. Furthermore, it is possible to start with CT for safety of the guidance procedure and then change to MRI for visualization of treatment effects like laser ablation (Fig 10).

Preoperative planning in all tomographic systems is also possible as well as 3D reconstruction before and after the treatment. Blood flow measurements in arteries can be realized by using MRI or EBT and in MRI without contrast media for visualization. In many cases correct and safe access can be gained by tomography for

Fig 10. MR-scopic diskectomy for low back pain (high risk area). This percutaneous laser nucleotomy was performed inside the foramen intervertebrale and the herniation directly behind the segmental nerve. A 2nd cannula is placed to the facet joint for local anesthesia.

interstitial therapy such as drug injection or placement of prostheses and implants[28] and also in future for gen-technical implants. Another field will be the drilling and fixation with the correct angle for osteosynthesis or hybrid tomographic systems for balloon dilatation as well as for laser treatments in all organs or stent implantation. With this kind of technique the tip of the catheter can be placed very precisely inside the vessel in precise position to the artery or venous wall.

In the future, dedicated systems (Fig 11) should be available for all diagnostic or microinvasive procedures. The different imaging procedures are complementary to and not competitive with each other. EBT, CT, and MRIscopic treatments widens considerably the therapy spectrum of common diseases like disk herniation, cancer, arterial occlusive diseases, and low back pain and should be integrated into interdisciplinary routine concepts. An effective changing from treatments inside hospitals to safe procedures on an outpatient basis are possible. This will reduce costs in healthcare systems worldwide dramatically.[29-31]

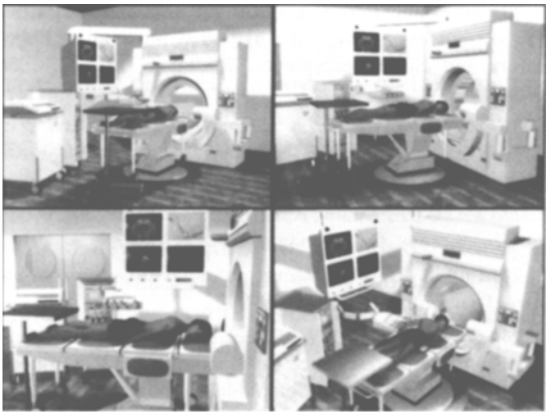


Fig 11. Virtual Operation Room of the future. Hybrid integration of EBT, C-arm (fluoroscopy with digital subtraction angiography), US, and endoscopy in a single imaging facility with combined monitoring: HERO and a special patient couch, laser positioning system, and therapy/measurement units.

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