Advances in Image-Guided Therapy

John A. Carrino, M.D., M.P.H.
Assistant Professor of Radiology, Harvard Medical School
Clinical Director, Magnetic Resonance Therapy Program
Co-Director, Spine Intervention Service

Minimally Invasive Therapies

• Smaller operational volume
• Limited access
• Limited visualization
• Tissue damage limited to target volume
• Less complication
• Faster recovery
Bringing Advanced Technology to the Operating Room

Laparoscopic Procedures

Endo-video, Instruments

PC’s, Remote Monitoring, Communications

Wireless, New Devices

Models, Grid Computing

Advanced Procedure Room

Real Time Image Guidance

Integrated OR

High Technology Base

What is surgery?

Hand – eye coordination
The role of Image-guidance

• Beyond the surface visualization
• Target definition

Image-Guided Procedures

• Localization
• Targeting
• Navigation
• Monitoring
• Control

Diagnostic Imaging
Surgical Planning
Interactive Imaging
Dynamic Imaging
Quantitative Imaging
Why use MR for image guidance?

• Flexibility of image contrast
• No ionizing radiation
  - safe for patients & staff
• Cross-sectional technique
• Adjustable imaging plane

Technical Aspects

• Magnet
• Devices
• Spatial accuracy
• Imaging techniques
• Guidance methods
The Magnet

• Configuration
  - access to patient vs. field homogeneity

• Field strength
  - safety vs. image quality/speed

• Gradient strength
  - spatial resolution vs. artifacts

Magnet Configurations

- Cylinder
- “Clamshell”
- “Double Donut”
i-MRI Systems: Demand new navigation and monitoring systems

 Courtesy of Dr. Roberto Blanco Sequeiros, Oulu University Hospital, Finland
In 1989, BWH Radiology and Harvard Medical School initiated a project to develop MR-guided interventional and intraoperative guidance for surgeries.

**MR Safety of Devices**

- Safe in magnet room
  - low forces on device
  - device works in magnetic field
- Safe around patient
  - device does not distort or degrade image
  - device does not arc during imaging
  - magnet room safe
MR Safety of Devices

• Safe to use in a patient
  - no local heating from RF deposition
  - device and target visible
  - no significant artifacts
    • position correct?
    • target visible?

Many Objects are Not MR Room Safe

• Test all objects with strong magnet prior to entry into room

• Keep all unsafe objects out of MR area entirely

• Train all personnel about magnet safety
RF Deposition - Heating

• Field strength dependent
  - changes as square of field strength
  - e.g. RF deposition at 1.5T > 0.5T by 9X

• Antenna concept
  - needles, wires, etc. act as antennas
  - needles can heat more easily at higher frequency RF (higher Tesla, shorter wavelength)
  - higher frequency RF has greater energy

Spatial Accuracy

• Procedures demand exact localization

• Location determined by frequency
  - static magnetic field, $B_o$
  - switched gradient fields

• Accuracy of localization dependent on:
  - $B_o$ homogeneity
  - gradient field homogeneity
Geometric Distortion: Shift Artifacts

- Imaging assumes uniform $B_0$
- Local frequency changes cause “shift artifacts” - analogous to chemical shift
- Shift artifacts displace pixels in frequency direction
Minimizing Shift Artifact

• Frequency direction orthogonal to long axis of needle - most accurate tip position
• Spin echo & FSE *not* gradient echo
• Wide bandwidth (more Hz per pixel)
• Low field strength magnet
• Lower spatial resolution

Effect of Frequency Direction on Needle Artifact
Guidance Methods

• Externally referenced - prone to distortion errors
  - optical guidance
  - RF guidance

• Self-referenced - minimizes distortion errors
  - anatomical landmarks (your finger!!)
  - fiducial markers

• MR tracking - uses MRI hardware - distortion free

Optical Tracking

• LED’s on device tracked by cameras
• Position update 6 per sec.
• Device must remain in clear view of cameras
• Optics independent of MR image distortion – may cause errors
Image Tracker Interactive Scanning

Aaxes of Scanner

90 deg

Tracker Axis

0 deg

Image Plane

Fixed Camera I

Fixed Camera II

Fixed Camera III

Image Tracker

Perpendicular

Image Tracking Wand

LED’s
Optical Tracking for Needle Placement

Guided Sagittal FSPGR
Guided Axial FSPGR

Self-referenced Guidance:
anatomical landmarks

Finger
Lesion

Soft-tissue Biopsy: PVNS
SOFT-TISSUE BIOPSY: PVNS

Fiducial Markers

• MR visible markers close to target
• Trajectory calculated from position of target relative to markers
• Shift & warp artifacts similar for markers and target
• Impact of distortion dependent on distance of markers from target
Guidance by Fiducial Markers: Breast Biopsy

Radiofrequency Tracking

• Device localized by external RF transmitters
• Device may be within or outside of patient
• Objects absorbing RF may interfere with device localization
• RF field & MR image distortion independence potentially causes errors
**MR Tracking**

- MR receive coils on device track location
- Same imaging parameters localize device & image
  - inherent self-referencing
  - MR image shows true device position
- Localization interleaved with image sequence
  - rapid position updates (80 per sec.)
- Can work with any pulse sequence

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**Catheter Placement by MR Tracking**

CL Doumilin, PhD; JA Debatin, MD
Clinical Aspects

• Why use MR guidance for procedures?
  - Diagnostic
  - Therapeutic

MRT Volume by Service FY '03 to date (4/30/03)

N = 175

- MSK
- Cryo
- NS
- Brachy
- Organ Bx's
- Imaging
- Other

Magnetic Resonance Therapy
Interventional MRI: Broad Categories

- Percutaneous Procedures
- Intraoperative Procedures
- Thermal Ablations
- Vascular Interventions

MRI-guided Biopsy - Techniques

MRI system:
OPEN / VERTICAL
Imaging:
PRE-PROCEDURE /FAST
CONVENTIONAL
Targeting:
FRAMELESS STEROTAXY

Silverman et al. Radiology 1995
Why use MR guidance for biopsies?

- lesion not visible (or visualized well enough) by other modalities
- Limited access route/complex trajectory
- collections/lesions near hardware
- target a specific portion of lesion
- Pregnancy

BONE BIOPSY DURING PREGNANCY:
38 y.o. woman 23 weeks gestation with history of breast cancer. A small iliac bone lesion found on an MR imaging study for hip pain.

Pre-procedure T1W (A) and STIR (B) axial images show a small lesion (<1cm) in the left ilium (arrows).

Procedure:
With the patient in the right lateral decubitus position, a 6 mm trephine needle (arrowheads) was positioned at the lesion (C,D). 2 contiguous core biopsies removed all visible lesion. FNA samples were performed through the corticotomy. Post-procedure T1W image (E) shows the biopsy tract (arrows) after removal of the cores. The use of MR-guidance avoided radiation exposure to the fetus.

Diagnosis: Metastatic Breast Carcinoma

Both the core & FNA samples were diagnostic.
74 y.o. woman with lung cancer. Femoral lesion by PET scan. Is there metastasis?

**Results:** No Metastasis

Core biopsy specimen showed lamellar bone but no tumor. Aspirate was insufficient. No clinical progression of lesion at 20 months.
Pre-procedure axial T2W FSE image (A) shows abnormal signal in the thenar eminence & first 3 web spaces that is worrisome for tumor. If 3rd or 4th web space were involved, resection of the ring finger ray would be required & hand amputation would have been performed.

Results:
FNA & core biopsies of the thenar eminence (B), 3rd & 4th web spaces (C), properly staged the tumor showing involvement of the thenar eminence, but not either web space. Resection of 1st 3 rays was performed with thumb reconstruction. Surgical pathology confirmed biopsy staging.

34 y.o. man with recurrent epithelioid sarcoma of the hand pre-op for resection.

• MR compatible needles:

Core - Biopsy gun: (16 or 18G, MRI Biogun™ E-Z-EM, Inc., Westbury, NY)

Trephine 3, 4, or 6 mm: (Bone Biopsy™, MRI Devices Daum GmbH, Schwerin, Germany)

Vacuum needle 16G: (MD Tech, Manan™ MRI Techna-cut, Karlsruhe, Germany)

FNA - 20G or 22G: (MRI Histology™, E-Z-EM, Inc., Westbury, NY)
Aspiration & Steroid Injection

Axial T2W FSE

Axial T2W FSE

Clinical Course

MR 1 year after aspiration

- Symptoms resolved within days
- Muscle weakness & atrophy resolved
- 3.6 years after therapy shoulder remained asymptomatic

Computer-Integrated Surgery

Integration with imaging

Integrated Navigation System

Provided by D. Gering
INTERACTIVITY
NAVIGATION

Brain Tumor Resection
Radiographically Occult Lesion for Excisional Biopsy
Optical Guidance for Needle Localization

Open Excision Through Drill Hole
- Small drill hole rather than 1 cm cortical window
- Enchondroma
- Patient returned to marathon running w/o symptoms
Prostate cancer imaging and Brachytherapy program-Today

- Pre clinical testing, feasibility testing and Clinical trial, designed and established by Drs D’Amico & Tempany
- 1997 First patient treated in MRT (GE Signa SP 0.5T)
- Pt selection criteria-T1C, PSA<10, GG<3+4
- Ecoil- no extra-glandular disease

MR-guided prostate biopsy program

- Rising PSA after negative TRUS
- S/P APR
- Need target validation method
- Need ‘free-hand’ aspiration > Robot

3D-Slicer adapted for prostate procedures and target definition, trajectory planning and guidance
MR guided biopsy-3D slicer

Treatment monitoring/needle

Provided by Cormack Tempany, D’Amico et al.
Brachytherapy planning

Robot Assisted Procedures
CISST 1: CT-guided Prostate Biopsy Robot

MRT Robot 1999-2001

Mechanical Configuration

32 sec
Robotic Assist for MR-guided Prostate Brachytherapy

Pre-clinical evaluations

Chinzei et al., MICCAI-2003 (accepted)
Spine Procedures

• Biopsies
• Injections
• Disc procedures
• Cryotherapy of facets
• Vertebral augmentation

SACROILIAC JOINT ASPIRATION
SACROILIAC JOINT ASPIRATION

Gadolinium in SI joint

3 POINT DIXON FSE

Discography

Courtesy of Dr. Roberto Blanco Sequeiros, Oulu University Hospital, Finland
Periradicular Injection

Facet Syndrome
Cryoablation
Neurotomy

Technique

freezing cycles

ice ball diameter control by MRI visualisation

du Centre Hospitalier Universitaire de Québec (CHUQ)
Tumor Ablation

MR is temperature sensitive & can monitor treatment

• Cryotherapy
• Radiofrequency (RF)
• Laser Interstitial Treatment (LIT)
• Focused UltraSound (FUS)

ELEMENTS OF THERMAL ABLATION

• Planning
• Targeting
• Monitoring
• Controlling
• Assessment

*Imaging plays a key role in each*
## 193 Percutaneous Ablations

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<th>Organ/Agent</th>
<th>CT/US-Guided</th>
<th>MRI-Guided</th>
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<td><strong>Totals</strong></td>
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Per 7/31/03

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## CT-GUIDED RF ABLATION

Standard CT scanners can provide guidance for interventional procedures including thermal ablation. While thermal monitoring is sub-optimal, targeting tumors with radiofrequency (RF) electrodes benefits from quick scan times and CT-fluoroscopy.
CT-GUIDED RFA - LIVER

Intraprocedural CT @ 12 min RFA

Post-RFA MRI

CT-GUIDED RFA - MSK

CT PRE

CT INTRA

MRI POST
CT-GUIDED RFA - LUNG

RFA

Post-RFA MRI Coronal

MRI THERMAL MAP of RFA

Radiofrequency ablation in liver in vitro at 1.5T
Image plane perpendicular to long axis of Boston Scientific array-style electrode (shown at right).
Above images acquired with RF "off" at progressively longer exposures.
Vertically open 0.5T MRI scanner provides access to patient for percutaneous thermal ablation; gas-based cryo technology allows for multiple, small diameter cryo-needles to freeze tumors.
Cryotherapy Needle Placement

Monitoring of Ice Ball
MR Following Cryotherapy

Axial STIR FSE

MRI-GUIDED CRYO - KIDNEY

Pre-Procedure

Post-Procedure
Computer-assisted planning of cryotherapy can assist in the optimization of probe placement. Multiple elliptical volumes are used to approximate coverage of a tumor (green), A and C. For research, such idealized plans can be compared retrospectively against actual ice formation (yellow), A, B and D. A global view of the anatomy provides visualization of possible probe trajectories (liver, pink; vessels, blue), E and F.

www.spl.harvard.edu

Real-Time Targeting  In-Plane  In-Plane 90 Perpendicular

Initial Probe

3 Probes

MRI-GUIDED CRYO RENAL
MONITORING

MRI-GUIDED CRYO LIVER
3 CRYONEEDLES AT 4 TIME-POINTS DURING A 15 MINUTE FREEZE ADJACENT TO KIDNEY

CONTROL

Computer-assisted control can be achieved by techniques such as optical flow (OF) which can both monitor and predict. The 3D computation augments the physician's visualization. 10 min freeze, MRI-guided cryo experimental liver:
Top left: 3D view, top right: in plane view of actual iceball;
bottom left: OF vectors identify growth; bottom right: predicted iceball.
ASSESSMENT

MRI-GUIDED CRYO - LIVER
Liver Cryotherapy

Provided by Silverman, Butz et al.

Ice Ball 3D
MRI-Guided Interstitial Laser Ablation

3D THERMAL MAP for ILT

3D Interstitial Laser Therapy (ILT) Surgical Guidance System. System is interactive with scanner to control image plane and range. Display allows various combinations of data display: multiple planes, multi-planar reformatted images, volume rendered data, image-derived data as overlays (i.e. temperature mapping)
Laser workstation

Laser 3D
MRI Guided FUS

The “ideal” Surgery:

• Tissue destruction only within targeted area
• No tissue damage outside the targeted area

**Single Focus Transducer**

- Ultrasonic Transducer
- Normalized Intensity
- Distance from transducer (mm)
Two goals, Two technologies

- **Target Definition**  Imaging
- **Energy Deposition**  Acoustics

Ultrasound Phased Arrays
Ultrasound Phased Arrays
Ultrasound as a Heat Source

Temperature Profile
Control of Sonication Volume

Phased Array Transducer = Dynamic Electronic Control of Spot Size

Temperature Images
Proton Resonance Frequency (PRF)

Perpendicular to ultrasound beam  Parallel to ultrasound beam
Thermal Development of a 10 Second Sonication

Temperature Graph
Sonication Monitoring (temperature, dose)

System Overview
FUS Treatment Plan

- Draw Treatment Region on 1 or More Slices
- Computer Fills All Layers With Sonications

Parallel to US Beam Direction
- Single Treatment Plane
- Two Treatment Planes

Perpendicular to US Beam Direction
Clinical Applications of MRgFUS

Pelvis

Breast
MRI-Guided Focused Ultrasound System
Treatment Planning

Axial  Coronal  Sagittal

Bowel in the way - Sagittal
Identifying Nerves Location

Identifying the spinal nerves roots, and avoiding them in the far field, is an important safety measure.

End of treatment

The treated layer with all the accumulated dose (blue).

Note: The red pinpoints are fiducial points
Breast cancer
FIBROADENOMA

MRI-guided FUS of the Brain
Focused Ultrasound in Brain with A Large Area Phased Array Transducer

Provided by Hynynen et al.

Ultrasound Phased Arrays
Ultrasound Phased Arrays

(Phase correction to compensate for skull thickness)

64 Element Hemispherical Array
Rabbit Brain In Vivo

- Focal BBB Opening Shown by MRI Contrast Agent Injection

Provided by Hynynen et al.

FUS Monkey Brain

Provided by Hynynen et al.
Targeted Delivery of Macromolecular Agents by FUS induced cavitation energy

1. Focal opening of blood brain barrier

2. Increase in permeability of blood vessels

3. Increased cell membrane permeability

Localized Gene Therapy using Focused Ultrasound
MRI Guided FUS
Summary

1. Noninvasive Image Guided Focal Energy Delivery:
   - On-line Localization
   - Exposure Monitoring
   - Close loop control of Energy Delivery

2. Clinical Applications:
   - **Tumor**: Tissue coagulation, vaporization, debulking
   - **Blood vessel**: occlusion, thrombolysis
   - **Blood brain barrier**: targeted drug delivery
   - **Cell membranes**: gene therapy, drug activation

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Multimodality Intervention

Combination of fluoroscopy and MR imaging → complimentary
Concept for hybrid system

fixed anode x-ray tube with anode-cathode axis aligned with $B_0$

flat panel detector should (in principle) be immune to magnetic fields

Courtesy of Norbert J. Pelc, Sc.D.

APPLICATIONS

• should exploit relative strengths
• X-ray
  • speed
  • spatial resolution
  • projection format
  • ease of use
• MR
  • soft tissue detail
  • physiology
  • therapy monitoring
XMR configurations

- 2 gantry + “railroad track”
- front of conventional system
- vertical field “open”
- “double-donut” magnet

Reduced impact of each on the other
Higher performance
Increased integration
Safer

Applications of hybrid system

- Diagnostic procedures
  - Vascular interventions
  - Surgical guidance
- Chemoembolization
- Biopsies
- TIPS (Transjugular Intrahepatic Portosystemic Shunt)
  - PTHC (Percutaneous Transhepatic Colangiogram)
  - Vertebral Augmentation (Vertebroplasty)
  - Electrophysiology

Courtesy of Norbert J. Pelc, Sc.D.
3 generations

1. Fixed detectors (1 or 2 planes)
2. Rotating detector (C-arm)
3. MR alone
MRI/PET/CT/FLUORO/US
Endoscope, optical imaging,
Surgical microscope
Anesthesia
Monitoring
IT
I.G.O.R.
Image Guided Operating Room

Dr. F. Jolesz

Brigham & Women's Hospital
Combined MR/CT/PET Imaging for Surgery

- Neurological
- Oncology
- Cardiovascular
- Orthopedic
- Urology
- Gynecology

Combined MR/CT/PET Imaging for Surgery

- Open Surgery
- Endoscopic Surgery
- Percutaneous Procedures
  - Catheter based (vascular)
  - Probe placement (RF, cryo, laser)
- Non-invasive Surgery (FUS)
Justification for PET/CT

• Noninvasive, real time assessment of the safety of tumor resection margins
• Assessment of metabolically active tumor volume
• Metabolically guided tumor biopsy
• Synergism between IGOR and molecular imaging program

Potential Radiation Oncology Uses of Combined MR/CT/PET Suite

• Simulation
  - CT/PET Without MR
  - CT/PET With MR

• Brachytherapy
  - Head and Neck
  - Gynecological
  - Prostate
Incorporate PET (metabolic) CT/PET allows registration

Clinical Challenges

• Volume
• Efficiency
• Compensation
Research Framework

- Technical efficacy and safety
- Diagnostic impact
- Therapeutic impact
- Outcomes

VALUE = QUALITY

Uwe Reinhardt “The Physician Executive: Will Physicians Take Back Medicine?”

Image-Guided Therapy

- Image Processing for Planning, Targeting, Monitoring, Control
- New Dynamic Imaging Methods
- Biopsy, Open Surgery
- Ablative Therapies: Laser, RF, cryo, Focused Ultrasound
- HPC

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Future Performance Requirements for IGT

- Visualization: Computer Vision
- Registration: Multimodality Fusion
- Segmentation: Image Processing
- Quantification: Validation
- Regulation: Control theory
- Integration: System Engineering

Image-guided Therapy

- Multidisciplinary approach
- Interdisciplinary collaboration
- Multimodality approach
- Multiple vendors and industries
- Multiple funding sources
- New training tracks
Technical Improvements

• General
• Specific

Most important challenges of IGT

• Improving the combined presentation of pre-operative and real-time, intraoperative images
• Integrating imaging and treatment related technology into therapy delivery systems
• Testing the clinical utility of image guidance in surgery and cancer therapy
• Support multidisciplinary IGT Research Centers (including infrastructure)
IGT: Training Opportunities

• R25 (NIH sponsored Training Grant)
• Potential applicants include those PhDs and MDs who have already completed their graduate (specialty) training and who are interested in a career in image-guided therapy
• Scientists will be exposed to the "clinical mindset" of their peers, thus facilitating a richer understanding of how respective specialties respond to emergent issues and address patient care needs.

Real bottom line: patient care

• Provide new capabilities that transcend human limitations in surgery
• Increase consistency and quality of surgical treatments
• Promote better outcomes and more cost-effective processes in surgical practice
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Jorg A. Debatin, M.D.  Univ. Zurich
We live in a time of such rapid change and growth of knowledge that only he who is in a fundamental sense a scholar—that is, a person who continues to learn and inquire—can hope to keep pace, let alone play the role of guide.

Nathan M. Pusey (1)