Technology for Adaptive MR Guided Brachytherapy

Robert Cormack PhD
Dana-Farber Cancer Institute & Brigham and Women’s Hospital
Acknowledgements

- Patents submitted for IP related to actively tracked stylets
- Sequences and devices do not have regulatory clearance

Support
- NIH U41-RR019703
- AHA 10SDG261039
- NIH P41RR019703-07
- NCI R01CA111288-01 BRP
- BWH Radiation Oncology Kaye Award
- Siemens, IMRIS Healthcare, IMRIS

Radiation Oncology
- Anthony D’Amico MD
- Akila Viswanathan MD
- Antonio Damato PhD

Radiology
- Clare Tempany MD
- Kemal Tuncali MD
- Wei Wang PhD
- Ehud Schmidt PhD
Educational Goals

• Review justification of MR for brachytherapy
• Review different means of incorporating MR imaging into brachytherapy
• Discuss technology that facilitates MR guided brachytherapy

Outline

• Brachytherapy
  – Implant evaluation
  – Image based
  – Image guided
  – Adaptive
  – Role of MR
• MR based brachytherapy
• MR guided brachytherapy
• Applications of microcoils in brachytherapy
Ferenc Jolesz (1946-2014)
Brachytherapy

- **Sites**
  - Breast
  - Skin
  - Prostate
  - GYN
    - Cylinder
    - T&O
    - Interstitial
Applicator Based Brachytherapy

- **Cylinder**
  - Rx to surface (depth)
  - Plan determined by diameter and length

- **Mammosite**
  - Rx: 1cm from surface

- **Postimplant dose evaluation**
  - Dose calculation based on source

- **Plan determined without anatomic information**
  - Imaging provides information about source or applicator
Image Based Brachytherapy

- **Imaging timing**
  - After placement
  - Before dose

- **Image provides**
  - Applicator geometry
  - Anatomy

- **Dose planning** incorporated anatomic (image based) dose goals/constraints
Image Guided Brachytherapy

- Incorporates image based brachytherapy (volume study-preplan)
- Uses images to guide placement of applicator (needles)

Nag: Principles of Brachytherapy
Adaptive Brachytherapy
(Dosimetry Guided Brachytherapy)

- Image guided
- Treatment planning in procedure room
  - planning
  - image based applicator updates
- Dosimetric feedback
- Update plan throughout procedure
Adaptive Brachytherapy
(Dosimetry Guided Brachytherapy)

- Image guided
- TPS in procedure room
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Adaptive Brachytherapy
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Why MR for Brachytherapy?

- Pelvis
  - CT anatomy
  - MR anatomy

- GEC-ESTRO guidelines for target definition
MR Dose Evaluation

- **MR**
  - T2 anatomy
  - T1 sources (ambiguity)

- **CT**
  - Sources

- Sources provide registration landmarks

- Fusion allows dose evaluation to MR based anatomy
MR Based Brachytherapy

- Applicators
  - MR safe
  - MR compatible
- Applicator can facilitate registration
- Model based applicator digitization helpful
- Needles identification challenging
MR Adaptive Prostate Brachytherapy

- **TPS**
  - Incorporate needle information
  - Efficient feedback
  - Passive needle identification (few needles at a time)

- **Technology**
  - MR compatible needle
  - Template registration
  - Survey meter
  - Pulse sequences
    - T2 anatomy
    - T1 devices

- **Passive tracking**
GYN Interstitial HDR Brachytherapy (Passive Tracking)

- Trajectory planning
- Needle placement
  - scanner control
  - tracking out of plane
- Needle digitization
  - time consuming
  - subject to ambiguities
  - rely on post-implant CT
Device Tracking in MR

**Passive Tracking**
Device is visualized within images
- 3D: Slow
- 2D: Only in-plane part of device visible

MR Sequences optimized for device

**Active Tracking**
Device emits or receives a tracking signal
- 3D, Fast, High res

Unambiguous tracking
- Special device
- Integration with imaging system

- Magnetic field tracking
- MR Tracking
MR Tracking
Simple MR Tracking Sequence

RF pulse

Acquisition

Frequency $f \propto$ Magnetic Field $B$

Body Coil

Position

$\gamma B_0$
**MR Tracking**

**Simple MR Tracking Sequence**

- RF pulse
- Gradient
- Acquisition

**Microcoil Limited Sensitivity Profile**

\[
\Delta z = \frac{\Delta f}{\gamma G_z}
\]

**Same coordinate system as MR images!**
Active tracking with micro-coils measures position by:

A. Sampling the spatially uniform magnetic field to determine spatial location

B. An RFID chip embedded on a non-magnetic stylet

C. Sampling spatially varying magnetic fields (gradients) superimposed on the static field to determine location

D. An active radiologist to measure location of MR artifacts on ultrafast 3D volume scans

E. Change in T2 weighted time constant resulting from the presence of 0.1 g of ferromagnetic material embedded in the coil.
Active tracking with micro-coils measures position by:

C: Sampling spatially varying magnetic fields (gradients) superimposed on the static field to determine location.

Active Tracking on Metal I -- Coil Design

EM simulation of different coil geometries on metallic surface

Electromagnetic simulation of $B_1$ field
Active Tracking on Metal II -- Construction of active device

multi-layered printed circuit coil

Tracking Signal to Noise Ratio

20 - 250 (mean: 160)

Sagittal MR image acquired by the microcoil
Active MR Tracking on Metal

- **High Spatial Resolution**: $0.6 \times 0.6 \times 0.6$ mm$^3$  
  **Accuracy**: $\sim 0.5$ mm (static)

- **High Temporal Resolution**: 40 updates/sec (N = 1)

- **Heating**: $< 0.6 \, ^\circ C$ increase for a 15-min scan (3.3 W/kg)

- **Visualization Interface**
  - Real-time needle display
  - Overlaid on 3D image

Active track the shaft of metallic devices

3D Slicer

coil

coil

coil tip
Applications of Active Tracking

• Trajectory planning: projecting needle path through imaging volume based on tracked position and orientation

• Needle placement: Identifying needle of interest, controlling scanner to image at needle tip

• Adaptive planning: reconstruct catheters in seconds, adjust treatment plan
Projected trajectories in imaging volume: animal model
Real-time Imaging with Tracking for Needle Placement

New position & orientation

Tracking → Imaging → Tracking → Imaging → ....
Real-time Imaging with Tracking for Needle Placement
Catheter Visualization and Scanner Control
Human Study

Axial MR Image (Body Array + Tracking Coil)

Tracking SNR: 18 – 130 (mean 100)

Needle placement in a 84 y/o woman with recurrent uterine adenocarcinoma
Catheter Trajectory Reconstruction by MR Tracking Phantom Study

Fifteen needles: 9 parallel + 3 pairs crossed
Through two templates with 5 mm grid of holes

A. MR-image based needle digitization (clinical standard)
B. Active Tracking during stylet pull-out

3D distance: 1.1 ± 0.9 mm

3D MP-RAGE, resolution: 0.5 × 0.5 × 1 mm³

Two bent needles
Two crossed needles
Catheter Trajectory Reconstruction by MR Tracking

Compared to CT
Active tracking can facilitate MR guided brachytherapy implants by providing the following functions except:

A. Control of MR scan plane
B. Efficient measurement of catheter location
C. Absolute measurement of tissue oxygenation
D. Projection/extrapolation of catheter trajectories based into MR volume
E. Both A and D
Active tracking can facilitate MR guided brachytherapy implants by providing the following functions except:

C: Absolute measurement of tissue oxygenation

Brachytherapy does not require information about oxygenation, while all other functions are mentioned in slides 25-31
Conclusions

- MR imaging is the modality of choice for pelvic imaging
- MR compatible applicators devices are readily available
- MR imaging can be incorporated in brachytherapy over a wide range of complexity and resource demands
- Many on-going efforts to facilitate MR brachytherapy
  - Transfer tables
  - Robotics
  - Tracking devices
  - Pulse sequences