MRI physics for radiotherapy applications
Uulke van der Heide

MRI for radiotherapy
- Soft tissue contrast
- Variation in contrast mechanisms
- Anatomical and functional imaging

Anatomical and functional imaging
- T1gd
- T2
- T2-flair

Impact of MRI on delineation
- Inter-observer variation
- Delineation of nasopharynx tumor
- Left: CT, with MRI available, not fused
- Right: CT, with fused MRI


The potential of MRI for Radiotherapy
- Improved visualization of anatomy and pathology allows better targeting of the tumor
- Visualization of biological function may help defining the right dose for the tumor

What properties can be imaged?
- Cell density
- Microvessel density
- Oxygenation of capillaries
- Metabolism


Critical issues for application in radiotherapy
- Geometrical accuracy
- Patient positioning
- Adaptation of scan protocols for radiotherapy
- Image registration
- Multi-modality contouring
- Treatment planning on MRI alone
- Scanners for radiotherapy
Longitudinal magnetization $M$

Strong magnetic field spins align in magnetic field

Precession: up or down

Net longitudinal magnetization

Magnetisation vector precesses around $B_0$ with the Larmor frequency:

$$\omega_l = \gamma \cdot B_0$$

$\gamma$ is a constant: gyromagnetic ratio

Precession

The combination of magnetic moment and impulse moment causes a clockwise precession

The (N)MR signal

Precession of the transversal magnetisation $M_{xy}$ induces a signal in the receive coil

From transversal magnetisation $\rightarrow$ signal

The transversal magnetisation rotates with the Larmor frequency

Current induced in receive coil

Detection of the MRI signal

Position encoding

Patient in 1.5 T MR scanner $\rightarrow$ spins resonate at 64 MHz in ideal homogeneous magnetic field

$$\omega = \gamma B_0$$

Linear magnetic gradient fields $(x, y, z)$ create spatial differentiation of the signals

$\rightarrow$ 3D images

Slice selection

Z

X

Y

Patient orientation
**Slice selection: transversal**

Resonance condition:
\[ \omega = \gamma (B_0 + xG_x) \]

**RF transmitter**

**Slice selection: sagittal**

Resonance condition:
\[ \omega = \gamma (B_0 + zG_z) \]

**RF transmitter**

**Slice selection: oblique**

Resonance condition:
\[ \omega = \gamma (B_0 + xG_x + xzG_{xz}) \]

**RF transmitter**

**Phase encoding**

\[ \omega = \gamma B_0 \]

**G-phase**

**B_0 only**

**Phase encoding**

\[ \omega = \gamma (B_0 + yG_y) \]

**G-phase**

**B_0 + y-gradient**

**Phase encoding**

\[ \omega = \gamma B_0 \]

**G-phase**

**B_0 only**

**Phase encoding**

\[ \omega = \gamma (B_0 + yG_y) \]

**G-phase**

**B_0 + y-gradient**

**Phase encoding**

\[ \omega = \gamma B_0 \]

**G-phase**

**B_0 only**
**Phase encoding**

Weak phase encoding gradient: strong signal

Strong phase encoding gradient: weak signal

**Phase reconstruction (example for 2 pixels)**

\[
\begin{align*}
S_1 &= M_1 + M_2 \\
S_2 &= M_1 - M_2
\end{align*}
\]

\[
M_1 = \frac{(S_1 + S_2)}{2}
\]

\[
M_2 = \frac{(S_1 - S_2)}{2}
\]

**Frequency encoding**

MR signal: 

\[
\omega = \gamma (B_0 + xG_x)
\]

**Position encoding in a spin-echo sequence**

RF pulse

Slice selection gradient

Phase encoding gradient

Frequency encoding gradient

Signal detection

**Artifacts**

- $B_0$ inhomogeneities
- Gradient artifacts
- Susceptibility artifacts
- Water-fat shift

**Position errors: slice selection**

A deviation of the magnetic field during the 90° pulse results in a shift in the selected slice:

\[
z_i = z - \frac{(\Delta B_i + \Delta B_{i-1})}{G_i}
\]
Position encoding in a spin-echo sequence

2D Fourier transform imaging

rth time sample of the signal after the mth phase encoding step:

\[
S(u,v) = \int_{-\Delta v/2}^{\Delta v/2} \int_{-\Delta u/2}^{\Delta u/2} A(x,y,z) e^{j2\pi \Delta u x} e^{j2\pi \Delta v y} dz dx dy.
\]

Discrete 2D inverse Fourier transformation:

\[
\tilde{A}(u,v) = \sum_{m=-\Delta m/2}^{\Delta m/2} \sum_{n=-\Delta n/2}^{\Delta n/2} S(n,m) e^{-j2\pi \Delta n v} e^{-j2\pi \Delta m u}.
\]

with

\[n \in [-\Delta n/2, \Delta n/2)\] and \[m \in [-\Delta m/2, \Delta m/2).
\]

gives complex image \(\tilde{A}(u,v)\).

Position errors: phase encoding

Phase evolution in a Spin Echo experiment:

\[
l(t) = \frac{-\gamma B_0}{2} \Delta v (n - \frac{1}{2}) - \gamma G_x (x - \frac{1}{2}) - \gamma G_y (y - \frac{1}{2}).
\]

With a balanced read-out gradient:

\[G_x (x - \frac{1}{2}) + G_y (y - \frac{1}{2}) = 0.
\]

And in the absence of field inhomogeneities:

\[
l(t) = -\frac{\gamma B_0}{2} \Delta v (n - \frac{1}{2})
\]

echo centered in the acquisition window at \(t=0\) (n=0, m=0).

Geometrical accuracy: read-out direction

Insert all deviations of the magnetic field: \(\Delta B_0, \Delta B_x(G_x), \Delta B_y(G_y)\)

\[
x_i = x + \frac{\Delta B_x}{G_x} (x, y, z) + \frac{\Delta B_y}{G_y} (x, y, z)
\]

In SE imaging, static field inhomogeneity and non-linearity of the frequency-encoding gradient cause geometric distortions in the frequency-encoding direction.

Geometrical accuracy: phase encoding direction

Insert all deviations of the magnetic field: \(\Delta B_0, \Delta B_x(G_x), \Delta B_y(G_y)\)

\[
y_i = y + \frac{\Delta B_y}{G_y}
\]

In the phase-encoding direction, distortions are solely caused by non-linearity of the phase-encoding gradient.

Imperfections of \(B_0\) and gradient fields

Imperfect magnetic field homogeneity:
- divergence of the magnetic field lines at the end of the coil.
- imperfect winding the superconducting wire.
- variations of current densities in the wire.
- Distortion of the magnetic field by metal close to the scanner.

Gradient artifacts

Philips 1.5T MRI scanner

[Graph showing gradient artifacts with distortion values]
Correction of imperfect $B_0$ and gradient fields

Image distortion and correction on a 0.23 T open MRI scanner

Magnetic susceptibility

Magnetic susceptibility $\chi : M = \chi H$
- diamagnetic materials: $\chi < 0$ (tissues ca. $-9 \times 10^{-6}$)
- paramagnetic materials: $\chi > 0$
- ferromagnetic materials: very large susceptibility
- air: $\chi = 0$

Susceptibility artifacts

- Markers around head

- Markers without head

- Overlay of images

Susceptibility artifact

$\chi_x = x + \frac{\Delta B_x(x,y,z)}{G_x} + \frac{\Delta B_z(x,y,z)}{G_z}$

Read out gradient
**Susceptibility artifacts**

Susceptibility artifacts at rectum prostate interface

**Water-fat shift**

Magnetic field at the nucleus depends on magnetic shielding of surrounding electron clouds, depends on molecular environment.

- **example:** resonant frequencies of protons in fat and water differ by 3.4 ppm.

\[
3.4 \times 10^{-4} \times 1.5T = 5.1 \mu T
\]

at 1.5 T

\[
=5.1 \mu T / 3 mT/m = 1.7 mm
\]

at 1.5 T and read out gradient 3 mT/m

- artifact
  - increases with \( B_0 \)
  - decreases with gradient strength

**Practical consequences**

Largest distortions at the edges of the MRI bore

Markers on the skin not reliable as reference for beam setup

\[ \Rightarrow \] Registration of planning CT and MRI

**MRI-guided interventions: needles**

Spin echo images of needles (18G/1.3 mm) in a 1.5 T B0 field

0 degrees with respect to Bo field

40 degrees

Titanium

Stainless steel

Distortions depend on material, shape and orientation

**Water-fat shift**

- artifact
  - increases with \( B_0 \)
  - decreases with gradient strength

- Geometrical accuracy is usually worst at the edge of the image, near body contour

**Geometrical accuracy**

- Gradient artifacts are machine specific
- Susceptibility artifacts and water-fat shift are patient specific
- Geometrical accuracy is usually worst at the edge of the image, near body contour

\[ \Rightarrow \] Distortions due to \( \Delta B_0 \) (water-fat shift, susceptibility) can be reduced to < 1 mm by increasing gradient strength. However, gradient errors remain!
Critical issues for application in radiotherapy

- Geometrical accuracy
- Patient positioning
- Adaptation of scan protocols for radiotherapy
- Image registration
- Multi-modality contouring
- Treatment planning on MRI alone
- Scanners for radiotherapy

Patient positionering in Radiotherapy

- Positioning devices must be MRI compatible
- Regular RF coils may not be compatible with positioning devices
- Creative solutions must be developed

Selection of coils

- Integrated body coil
- Quadrature head coil
- Multi-element head coil
- Two-element flexible surface coil

T1-weighted MRI of healthy volunteer


Diagnostic protocols are not always the best for radiotherapy

Registration of bony anatomy

- MR
- CT
- Bony anatomy
- Registration of bony anatomy

Local registration

- Position verification with gold markers
- Local registration
Contouring on many MRI data sets simultaneously

- Delineation on many image data sets simultaneously
- Sometimes MRI scans are sliced in sagittal or coronal plane
- Use original images and transform the delineation

Combining multiple imaging modalities

- Combining multiple imaging modalities tends to increase sensitivity and specificity of an exam
- Do the techniques identify the same voxels as target?
- Identification of volumes depends on threshold setting
- Is there a combination of thresholds for which overlap between ADC and \( K_{\text{trans}} \) is high?

Results

- Currently a CT scan is always used for radiotherapy treatment planning
- MRI images are registered to the CT scan, and delineated structures are transferred from MRI to CT

Essential elements in radiotherapy dose calculation

- Body contour
- Electron density
- Ability to define a reference frame (skin markers)
Planning on MRI alone

For MRI a full density correction method does not exist. Using bulk densities for water and bone, derived from CT gives good results. Delineate on MRI, transfer delineations to bulk density image

Lee et al. 2003, Radiother. Oncol. 66:203-216

Skin markers

Read-out gradient 0.54 and -0.54 mT/m
WFS = 9 and -9 mm

Moerland et al.

MRI specifically for radiotherapy

- Open systems for
  - intervention
  - Simulation
- In-room imaging

Open MRI system

Image distortion and correction on a 0.23 T open MRI scanner


Open MRI system

1.0 T open MRI scanner

Specifically marketed for radiotherapy

MRI accelerator:
ring mounted linac around 1.5 T MRI
Linac next to magnet
Prototype at UMC Utrecht

Summary
• The soft-tissue contrast of MRI makes it well suited for delineation of tumor volumes and healthy structures
• Advanced MR imaging has great potential for characterizing tumors to support dose painting based on biological properties
• Geometrical accuracy requires attention. Distortions depend on the particular sequence and patient

Summary
• It is worthwhile to develop protocols specifically for application in radiotherapy
  – Sufficient spatial resolution for delineation
  – Slice directions compatible with functionality of delineation software
  – Patient position as in radiotherapy treatment
  – Choice of receive coils in line with patient position
  – Sequences with minimal geometrical artifacts, steep position-encoding gradients
  – Study the magnitude of geometrical distortions for a particular sequence

Summary
• MRI creates great opportunities in radiotherapy
  – Accuracy of delineation
  – Tumor characterization
  – Image guidance by in-room imaging
• work to be done:
  – How to deal effectively with all the images during delineation
  – How to deal with conflicting information
  – How to deal with changes during treatment
  – Use of MRI for in-room treatment guidance

Acknowledgments
• Wilbert Bartels
• Dennis Klomp
• Rien Moerland
• Marielle Philippens
• Bas Raaymakers