Prospective Motion Correction: Is it better?

J. Andrew Derbyshire
Functional MRI Core
NIMH

Motivation

- MRI is a slow imaging technique
  - Vulnerable to motion during acquisition
  - Motion of 50% pixel size can yield significant artifacts

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  - Vulnerable to motion during acquisition
  - Motion of 50% pixel size can yield significant artifacts
    (Oliver Speck says it is more like 20%)

Why will motion tracking be important?

- Higher resolution scanning
  - Increased scan time
    - Increase resolution by 2x requires 64x scan time!
    - Increased likelihood of subject motion
  - Smaller motions become significant

Sources of motion

- Physiological
  - Cardiac motion
  - Respiratory
  - Blood flow
  - CSF Flow
  - Swallowing
  - Coughing
  - Sneezing
  - Blinking
  - Peristalsis
- Tremors
- Children

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- Motion types:
  - Fast versus slow
  - Periodic
  - Continuous/sporadic
  - In/through plane
  - Local / global
  - Translation
  - Rotation
  - Expansion/contraction

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Do we need motion correction? ... YES!

Effects of motion in MRI

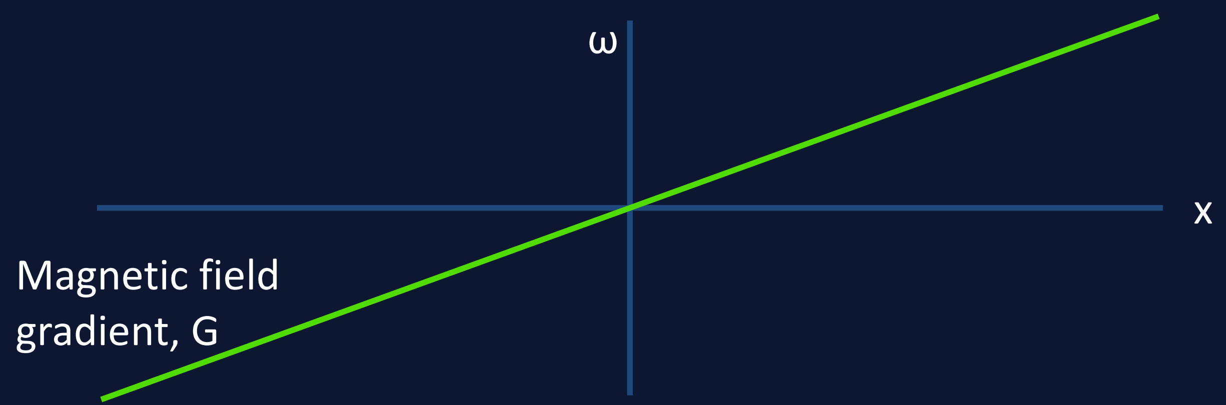
- Useful to revisit the MR image acquisition process

  - MR image formation is based on the equation: $\omega = \gamma B$
  - In the main magnetic field, B_0, we have: $\omega_0 = \gamma B_0$
  - Superimpose a spatial magnetic field gradient,

$$G = (G_x\ ,\ G_z\ ,\ G_z\ )^T$$

then:

$$\omega = \gamma(B_0\ +\ G_x x + G_z y + G_z z)$$



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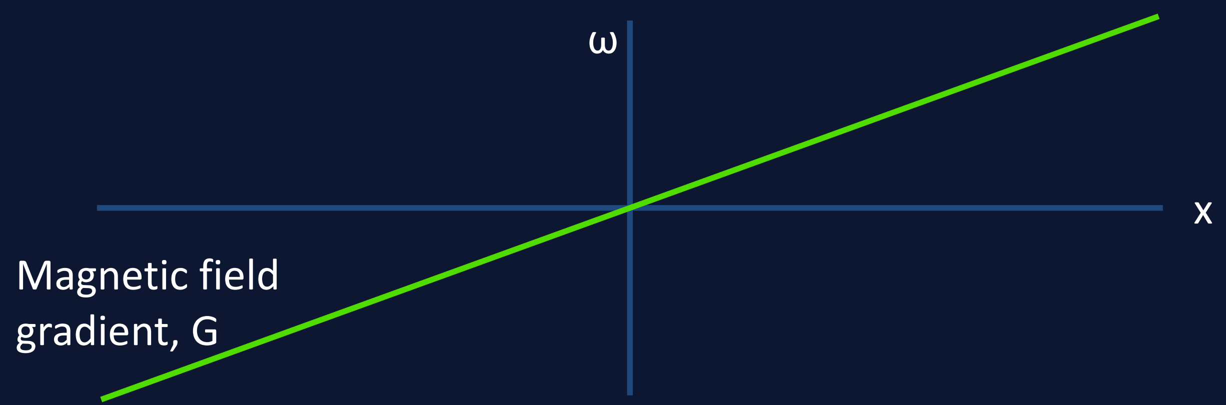
then:

$$\omega = \gamma G_x\, x + G_z\, y + G_z\, z = \mathbf{G.r}$$



Effects of motion in MRI

- Consider the green blob of tissue

$$\delta\omega(\mathbf{r},t) = -\gamma \mathbf{G}(t)\cdot\mathbf{r}$$

$$\delta\theta(\mathbf{r},t) = -\gamma \int_0^t \mathbf{G}(t')\,dt'\cdot\mathbf{r}$$

- So, the signal from the whole slice is:

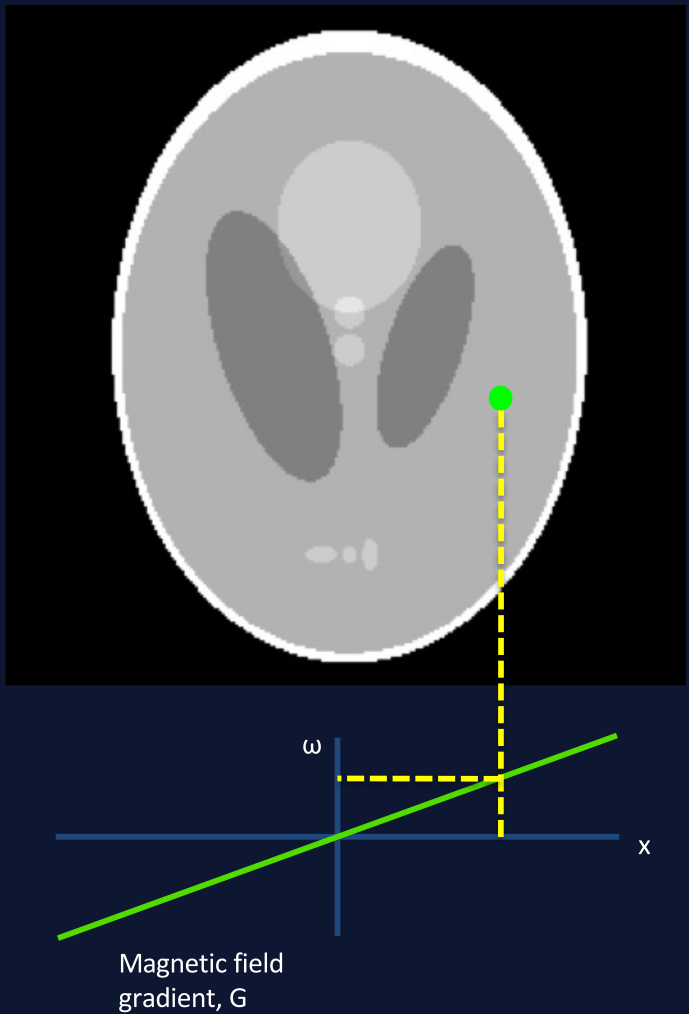
$$S(\mathbf{G},\,t) = A\int_V \rho(\mathbf{r})\exp\left[-i\int_0^t \gamma\mathbf{G}(t')dt'\cdot\mathbf{r}\right]\,d^3\mathbf{r}$$

- Write:

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

- To obtain the MRI signal equations

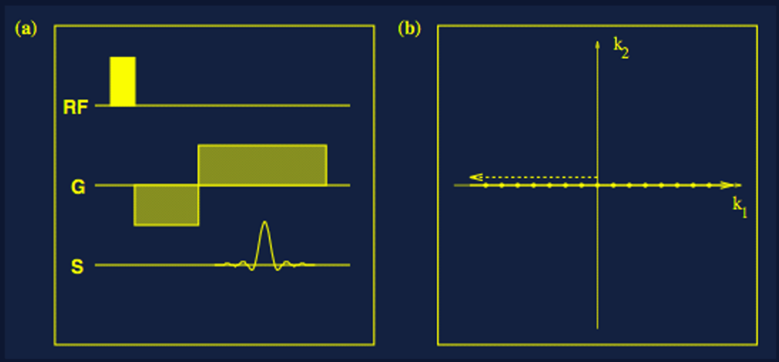
$$\begin{aligned} S(\mathbf{k}) &= \int_V \rho(\mathbf{r})\exp(-i2\pi\mathbf{k}\cdot\mathbf{r})\,d^3\mathbf{r} \\ \rho(\mathbf{r}) &= \int_{\mathcal{R}^3} S(\mathbf{k})\exp(i2\pi\mathbf{k}\cdot\mathbf{r})\,d^3\mathbf{k} \end{aligned}$$



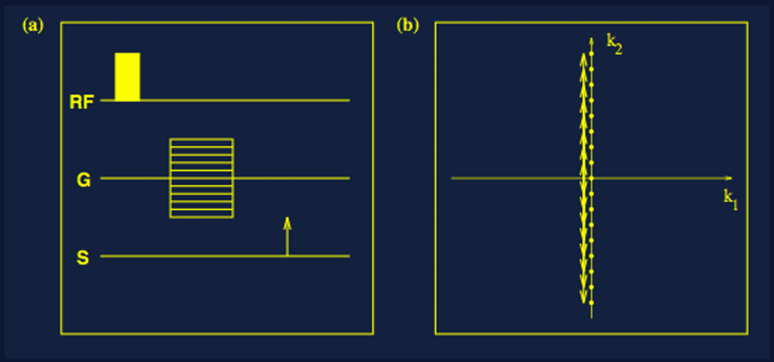
Effects of motion in MRI

MR image acquisition revisited

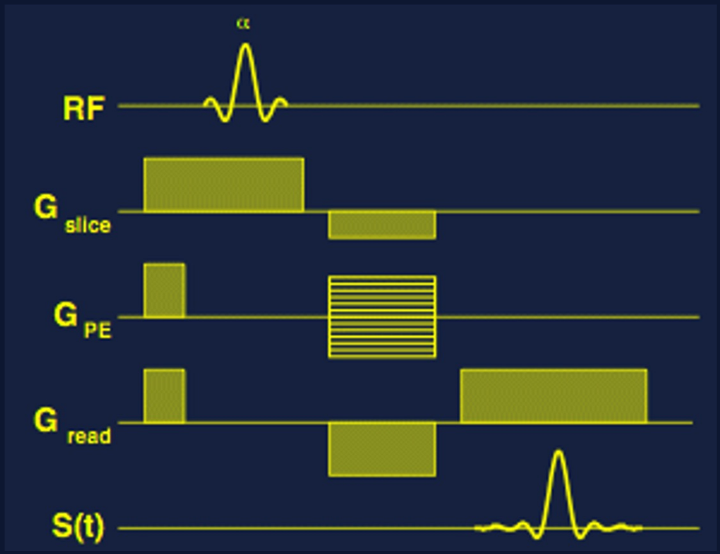
$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$



Frequency encoding



Phase encoding



MR image formation assumes that spins are not moving.

Effects of motion in MRI

- MRI scans typically comprise multiple repetitions
  - Each repetition of the basic pulse sequence is separated by TR
  - Phase encode steps (or similar)

- Useful to distinguish between motion time-scales:
  - intra-TR : i.e. motion within each measurement
  - inter-TR : i.e. motion across / between measurements

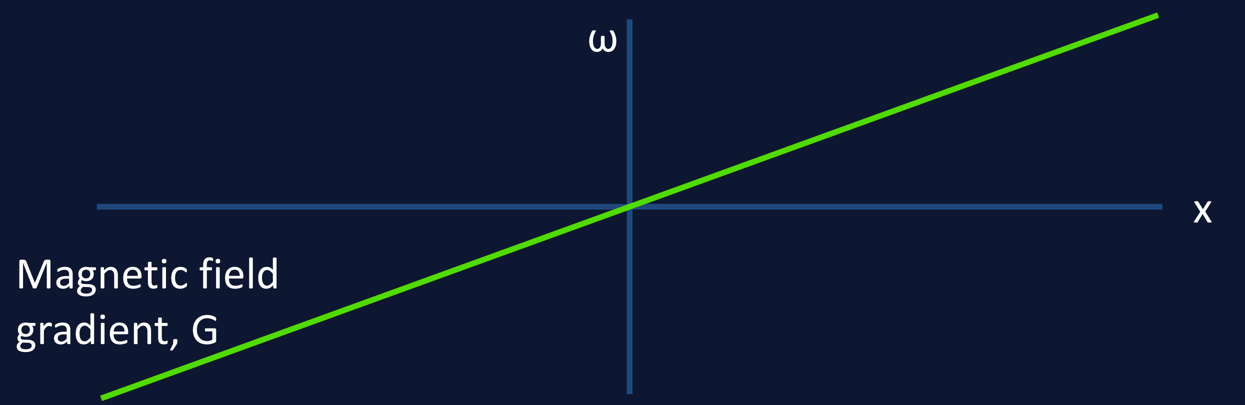
Intra-TR motion and Gradients

- MR image formation is based on the equation: $\omega = \gamma B$
- In the main magnetic field, B_0, we have: $\omega_0 = \gamma B_0$
- Superimpose a spatial magnetic field gradient,

$$G = (G_x\ ,\ G_z\ ,\ G_z\ )^T$$

then:

$$\omega = \gamma G_x x + G_z y + G_z z = \mathbf{G.r}$$



Intra-TR motion and Gradients

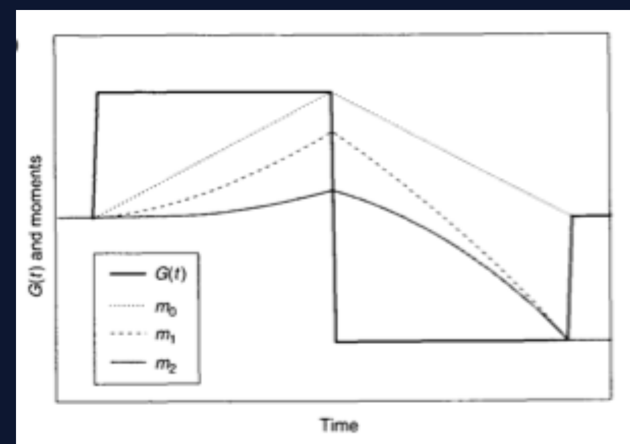
- Moving spins:

$$\begin{aligned}\mathbf{r}(t) &= \sum_{n=0}^{\infty} \frac{1}{n!} \left.\frac{d^n\mathbf{r}}{dt^n}\right|_{t=0} t^n \\ &= \mathbf{r}(0) + \left.\frac{d\mathbf{r}}{dt}\right|_{t=0} t + \frac{1}{2}\left.\frac{d^2\mathbf{r}}{dt^2}\right|_{t=0} t^2 + \dots \\ &= \mathbf{r}(0) + \mathbf{v}(0)t + \frac{1}{2}\mathbf{a}(0)t^2 + \dots,\end{aligned}$$

- Accumulated phase in presence of gradient:

$$\begin{aligned}\phi(t) &= -\gamma \int_{-\infty}^{\infty} \mathbf{G}(t') \cdot \mathbf{r}(t')\, dt' \\ &= -\gamma \sum_{n=0}^{\infty} \frac{1}{n!} \left.\frac{d^n\mathbf{r}}{dt^n}\right|_{t=0} \cdot \int_0^t \mathbf{G}(t') t'^n\, dt' \\ &= -\gamma \sum_{n=0}^{\infty} \frac{1}{n!} \left.\frac{d^n\mathbf{r}}{dt^n}\right|_{t=0} \cdot \mathbf{m}_n(t)\end{aligned}$$

$$\mathbf{m}_n(t) = \int_0^t \mathbf{G}(t') t'^n\, dt'$$



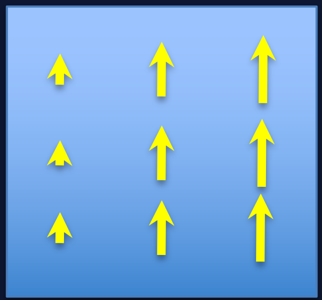
- In particular, for uniform motion: $\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{v}_0 t$, we have additional phase:

$$\Phi = \mathbf{m}_0 . \mathbf{r}_0 + \mathbf{m}_1 . \mathbf{v}_0$$

where $\mathbf{m}_1$ is the first moment of the gradient waveform.

Intra-TR motion

- Motion within a TR
  - undesired velocity-proportional phase accumulation
  - $\Phi = \mathbf{m_0 . r_0} + \mathbf{m_1 . v_0}$
- For complex / dispersive motions
  - e.g. complex flows, rotational flow, high shear, turbulence
  - multiple velocities present within a single voxel
  - phase cancellation
  - signal dropout



Inter-TR motion

- Motion that varies between TRs will
  - cause phase changes from one TR to the next (gradient m1 effect)
  - possibly cause amplitude changes (e.g.) through plane motion

- This causes modulations of the expected MRI signal in the phase encoding direction, resulting in motion artifacts.

- Artifacts are always in the phase encode direction!
  - independent of the actual direction of motion

- Periodic / pulsatile motions (e.g. blood flow) causes ghosting artifacts

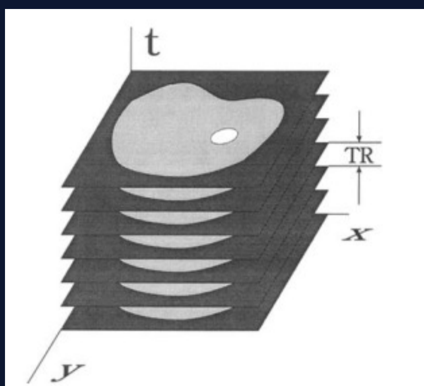
Flow Ghosting

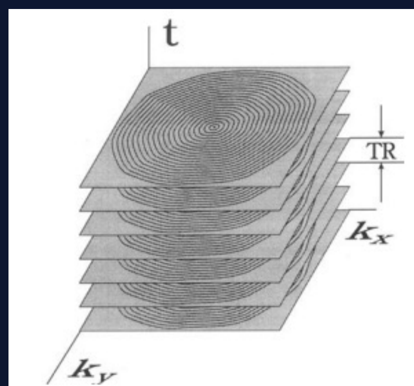
_K_-Space Description for MR Imaging of Dynamic Objects

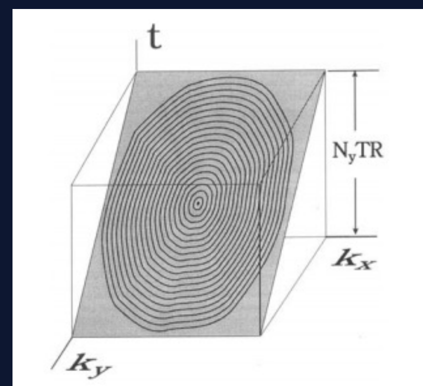
Qing-San Xiang, R. Mark Henkelman

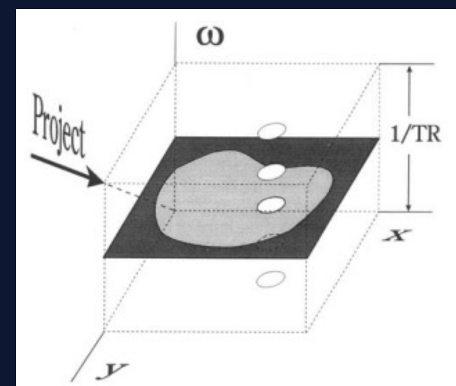
MRM 19:422:1993

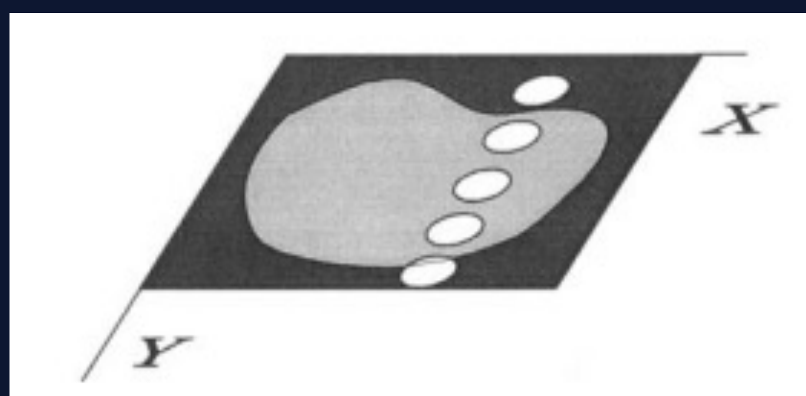
- Provides an elegant *geometric* description of the flow ghost formation











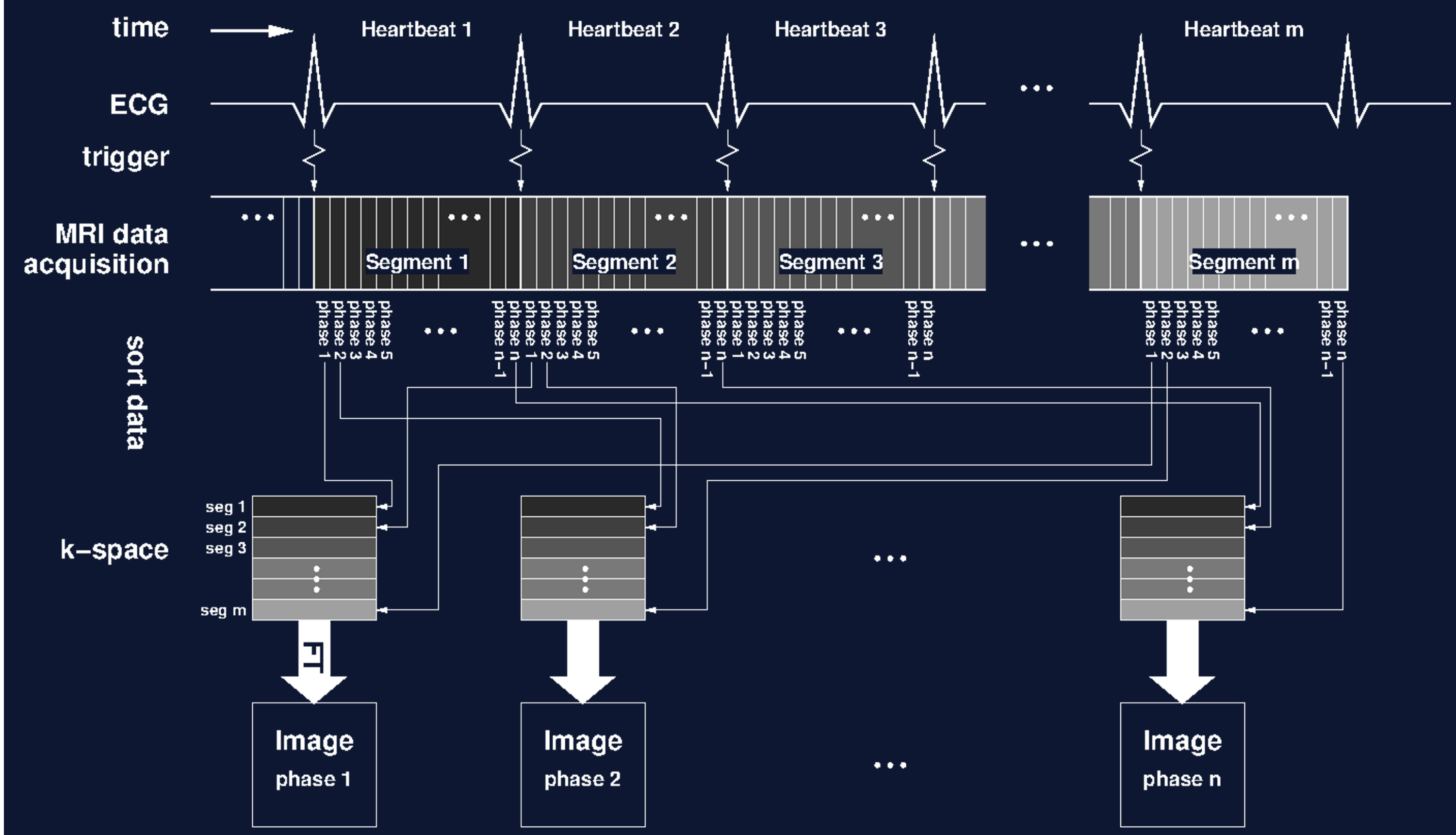
Motion Correction Strategies

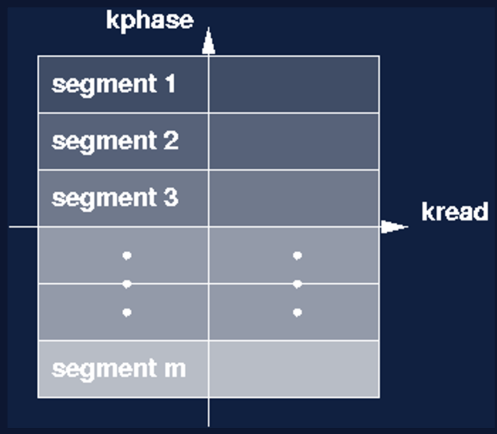
- Non-motion tracking
  - Immobilization
  - Signal averaging
  - Saturation bands
  - Gradient moment nulling
  - short TE
  - k-space trajectory
    - radial
    - spiral
- Motion tracked
  - ECG / respiratory gating
  - View re-ordering (e.g. ROPE)
  - *Navigator* acquisitions
  - self-navigated
    - propeller
  - Slice tracking
    - MR based
    - Optical
    - Other

In practice, available methods and choices are application dependent

Periodic motion

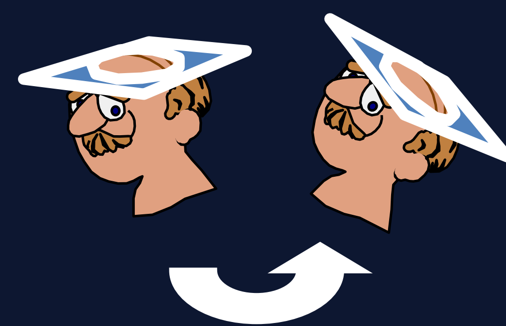
- Cardiac motion
  - ECG/Plethysmograph/Acoustic cardiac signal
  - Triggering : Wait for trigger, then scan
  - Gating : scan until trigger



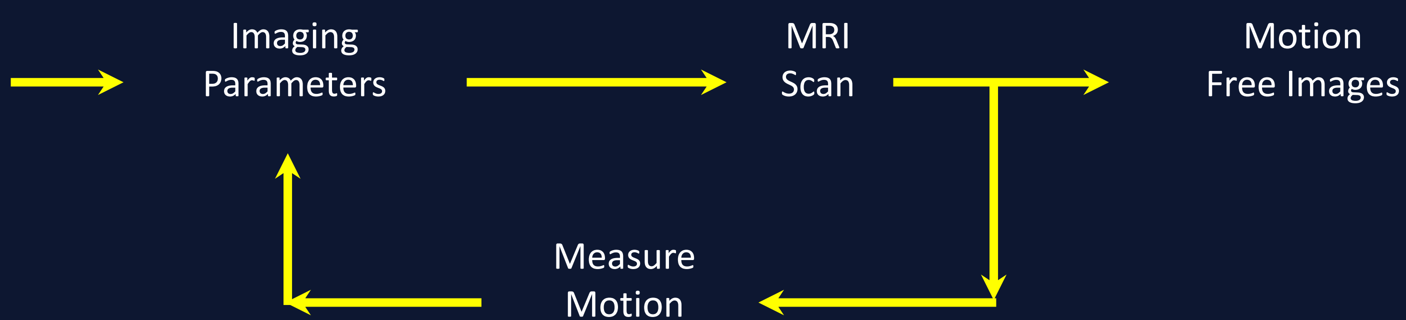


Prospective Motion Correction

- Track scan-plane with patient motion
  - track scan-plane with subject motion
  - reduced motion artifacts



- Two steps:
  - Detecting and measuring the motion
  - Real-time scan plane updating



Prospective Motion Correction

- Multiple approaches to position measurement are possible
  - MR based navigator echoes
  - MR based external tracking
  - Optical based tracking
  - Other methods

- Imaging scan-plane feedback: similar for all approaches
  - Typically model motion as rigid body
  - Global motion model for whole image

Motion Correction: what is possible?

- MR scanning is performed in k-space

Translation	⟷	Phase roll modulation
Rotation	⟷	Rotation
Stretching	⟷	Compression
Shearing	⟷	Orthogonal shearing

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- Rigid body motion
  - Global motion model for whole subject
  - 6 parameters
    - 3 translational
    - 3 rotational

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  - Global motion model for whole subject
  - 6 parameters
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- Non-rigid body motion corrections are very difficult

Rigid body scan plane update

For a Cartesian (phase encoded) sequence, the scan plane update [R, (r, p, s)] is applied as changes to:

- Update to image plane rotation matrix:
  - Defines read, phase and slice directions in terms of magnet X, Y, Z
- Slice/slab selective RF pulse frequency:
  - Translates scan-plane to the new image center in the new slice direction
  - $\omega_{slice} = Yg_{slice}\, s$
- Readout frequency:
  - Effects FOV shift to the new image center in the new readout direction
  - $\omega_{readout} = Yg_{readout}\, r$
- Readout phase:
  - Effects FOV shift to the new image center in the new PE direction
  - $\theta = 2\pi\, (p\, /\, FOV_{phase}\,)\, PE_{step}$

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Note that no changes to gradient waveforms are required!

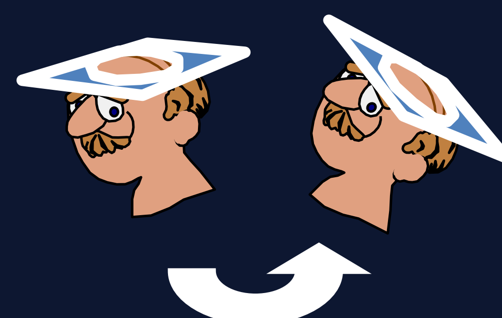
Prospective tracking using MR markers

Dynamic Scan-Plane Tracking Using MR Position Monitoring

J. Andrew Derbyshire, PhD • Graham A. Wright, PhD • R. Mark Henkelman, PhD • R. Scott Hinks, PhD

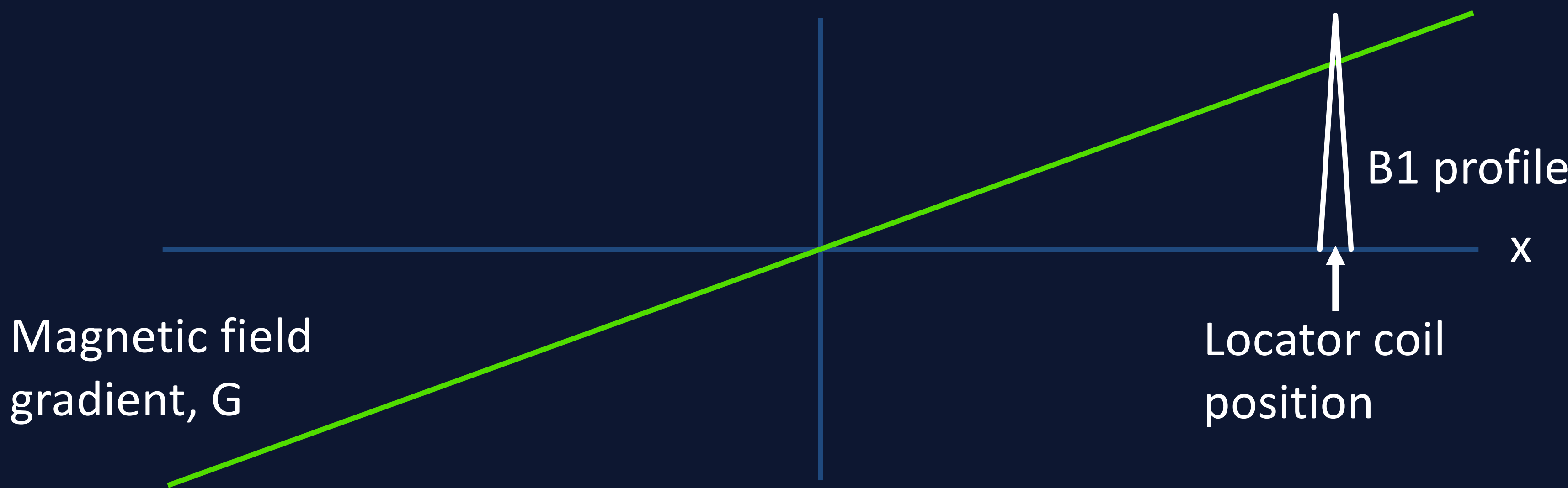
JMRI 8:924, 1998
Patent: US 5947900

- Track scan-plane with patient motion
  - Keep ROI in scan-plane
  - track scan-plane with surgical instrument
  - reduced motion artifacts



MR-based position tracking

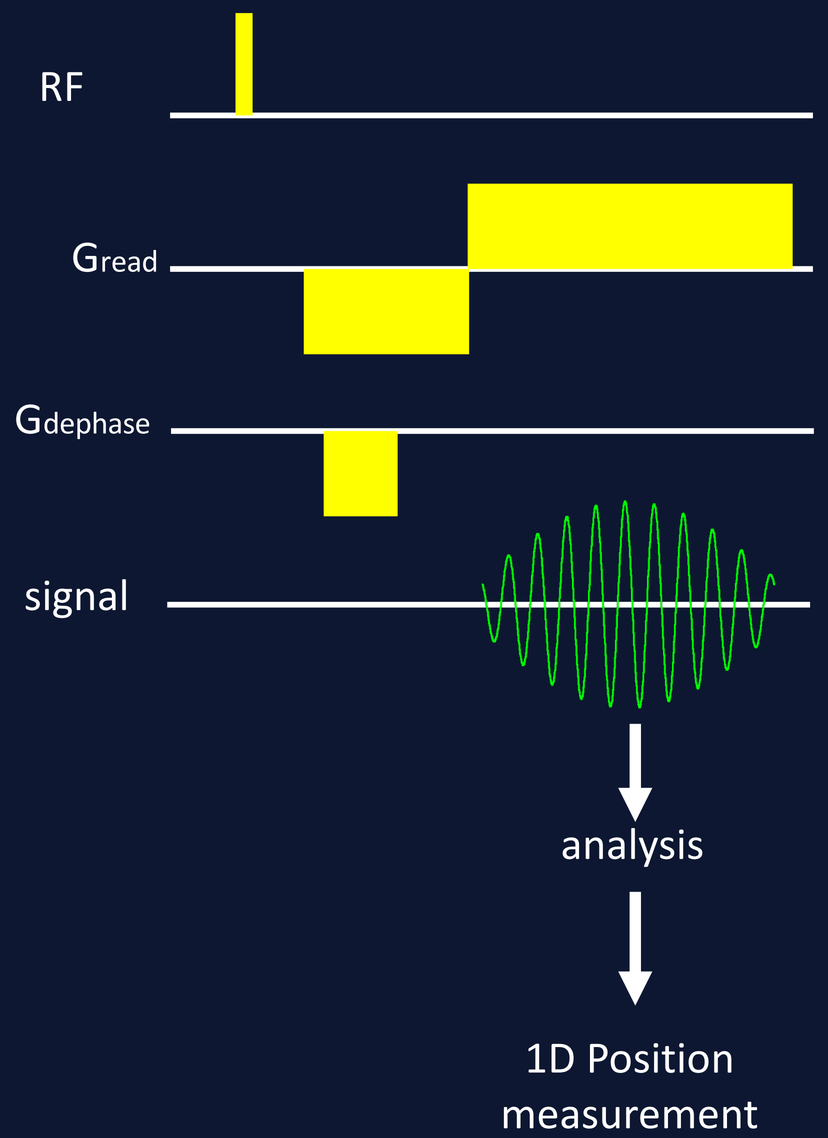
- Small RF *locator* coil for identifying position
  - 2mm i.d. solenoidal tuned MR coil
  - Internal spherical sample (doped water)
- MR signal with frequency, ω



Dumoulin et al. MRM 29:411:1993

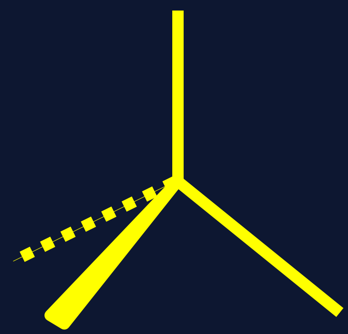
Position Measurement

- Gradient echo
  - excite sample and read out signal from RF coil
  - signal at characteristic frequency, ω
- Signal analysis
  - centre frequency provides position: $\omega = \gamma G x$
- Repeat process
  - for G in x, y and z directions to find 3D position of locator coil



Position Measurement

- Local B0 inhomogeneities:
  - offset frequency: $\omega' = \omega + \Delta\omega$
- Acquire 4 gradient echoes directed tetrahedrally



- Hadamard encoding scheme:

$\omega_x = \omega'_{D1} + \omega'_{D2} - \omega'_{D3} - \omega'_{D4}$

$\omega_y = \omega'_{D1} - \omega'_{D2} + \omega'_{D3} - \omega'_{D4}$

$\omega_z = \omega'_{D1} - \omega'_{D2} - \omega'_{D3} + \omega'_{D4}$

- Eliminates spurious $\Delta\omega$ term

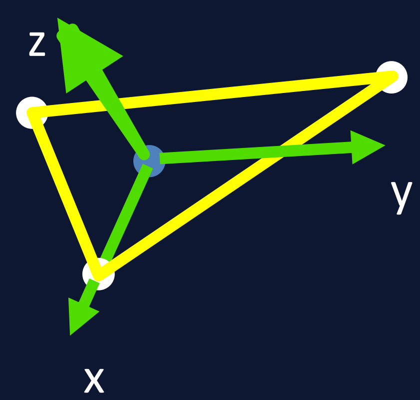
	X	Y	Z
D1 =	(1,	1,	1)
D2 =	(1,	-1,	-1)
D3 =	(-1,	1,	-1)
D4 =	(-1,	-1,	1)

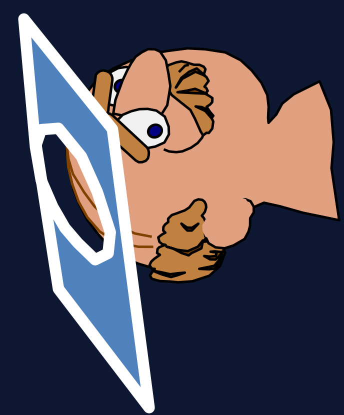
Dumoulin et al. MRM 29:411:1993

Scan-plane tracking

- Three or more position markers (e.g. triangle) fixed to subject
  - At least three non-colinear markers are required identify rigid body motion
- Define local co-ordinate system relative to triangle
- Define position & orientation of scan-plane in local co-ordinate system

Reference triangle



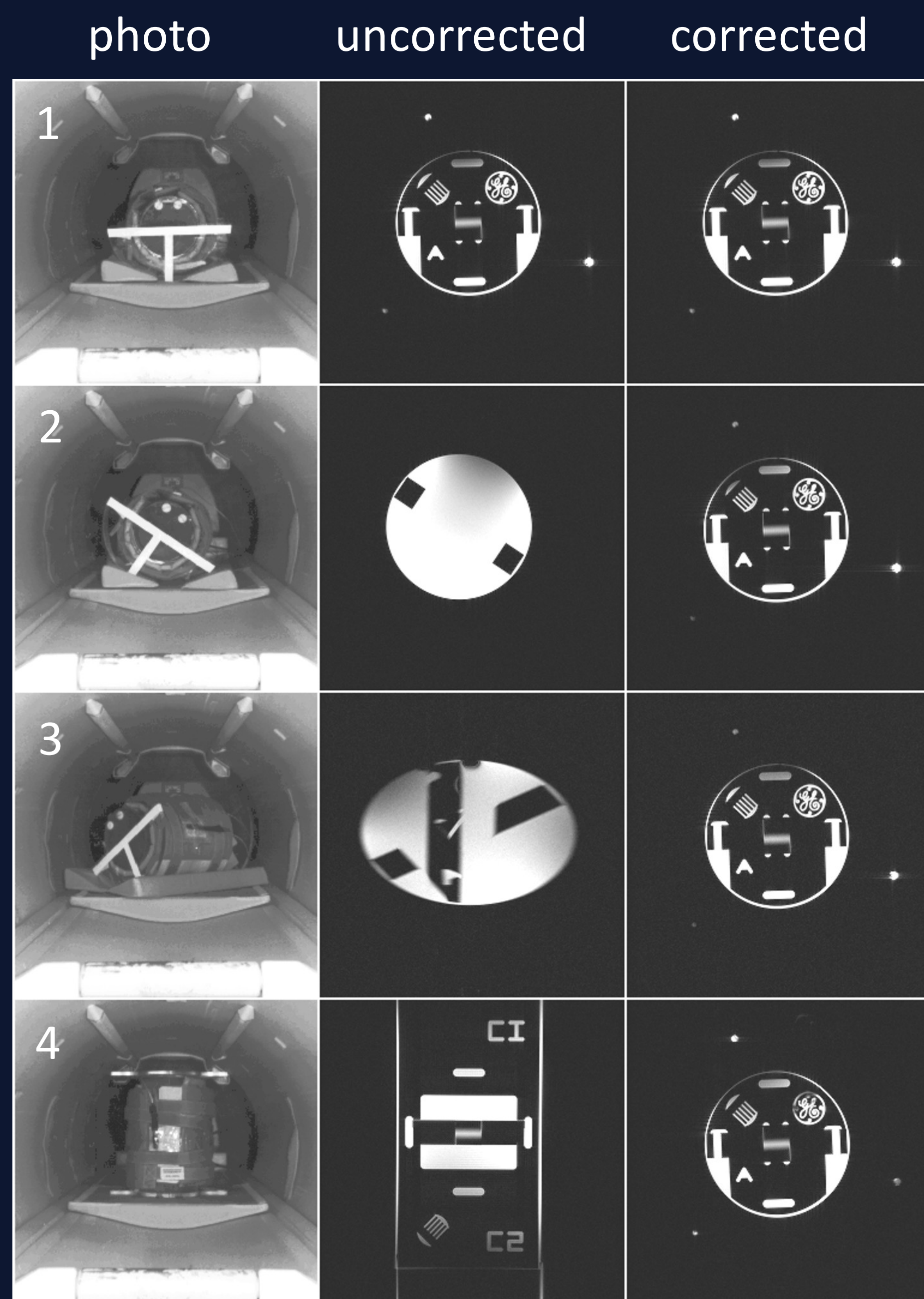


MR scan-plane

- Scan-plane tracking:
  - Update rotation matrix
  - Update slice frequency and phase
  - Update readout frequency and phase
  - Update phase encode (per PE line) frequency and phase

Results
Phantom study

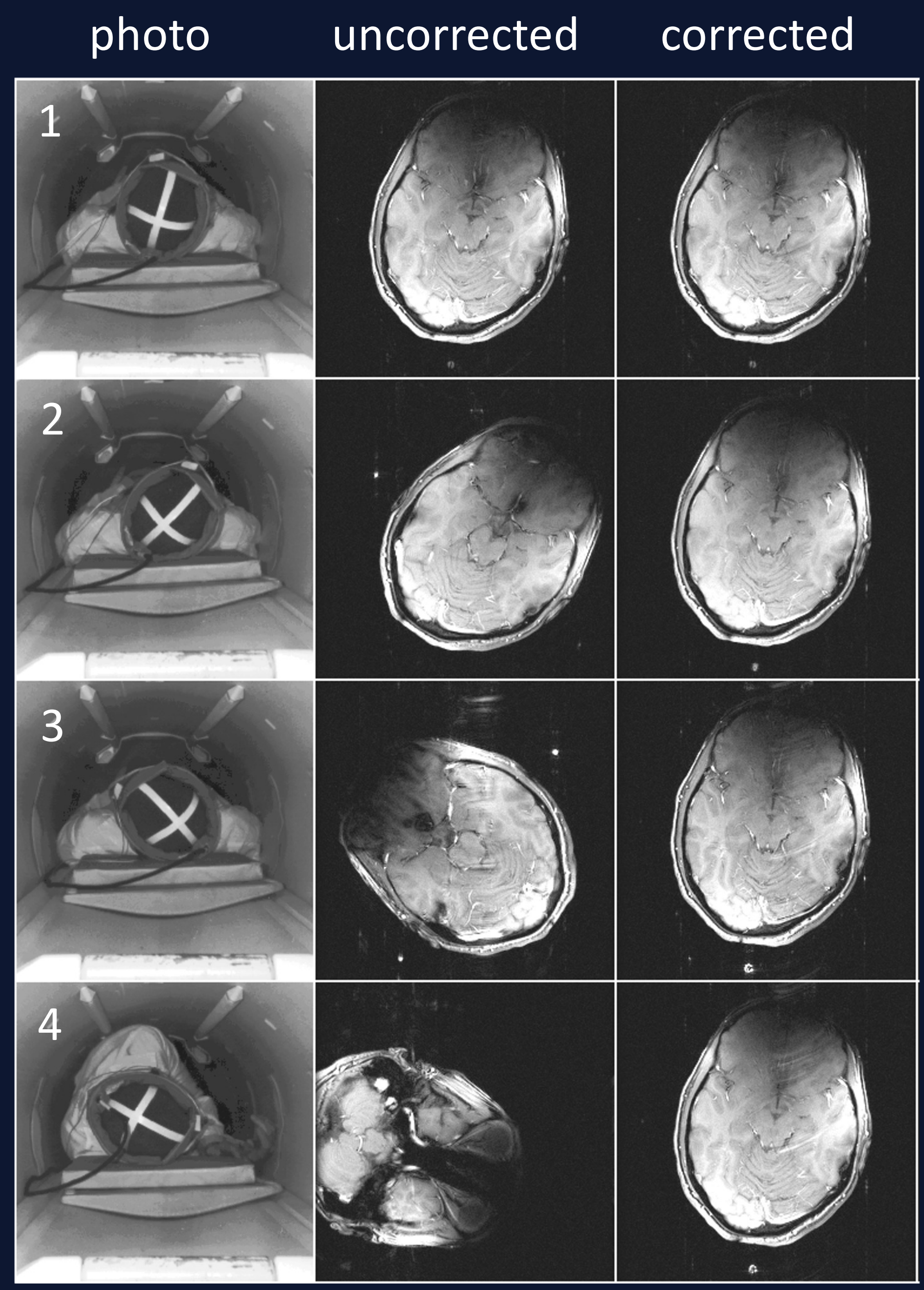
- Images of standard phantom
- Object moved between successive imaging scans
- Tracking system provides images from the same section of the object



Results

Human head

- Transverse images of brain of human volunteer
- Subject requested to move between scans
- Tracking system provides images from the same section of the subject



Prospective tracking using MR markers

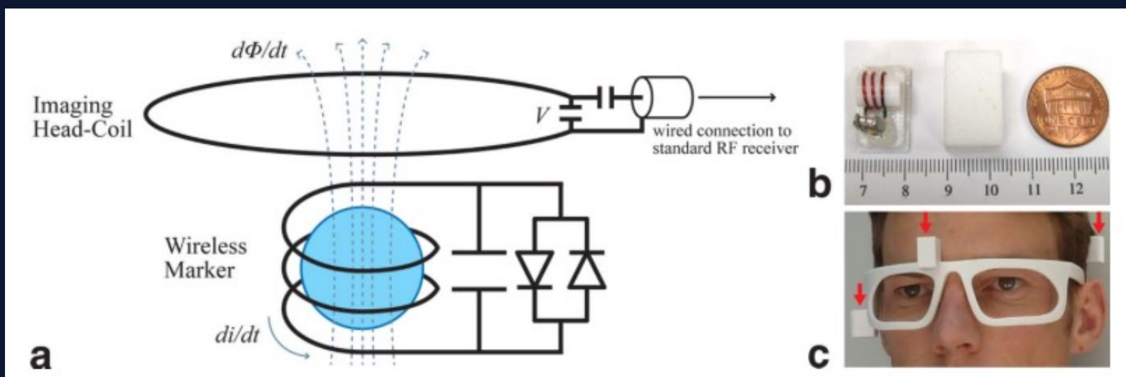
- Intra-image scan-plane updates
  - once per full image scan
  - Slow-tracking for GRE type scans, OK for EPI
- Inter-image scan-plane updates – OK for small motions
  - B0 non-uniformity – changes phase mid scan
  - B1 non-uniformity – changes phase mid scan
- Precision
  - Position measurements ~ 0.1mm
  - Rotation/Tilting
    - Slice distance from reference markers
      - Angular amplification of errors.
    - Need triangle to be close to scan-plane of interest
- Time required for MR position measurement (15-20ms)

Wireless RF micro-coils

Magnetic Resonance in Medicine 70:639–647 (2013)

Prospective Motion Correction Using Inductively Coupled Wireless RF Coils

Melvyn B. Ooi,* Murat Aksoy, Julian Maclaren, Ronald D. Watkins, and Roland Bammer



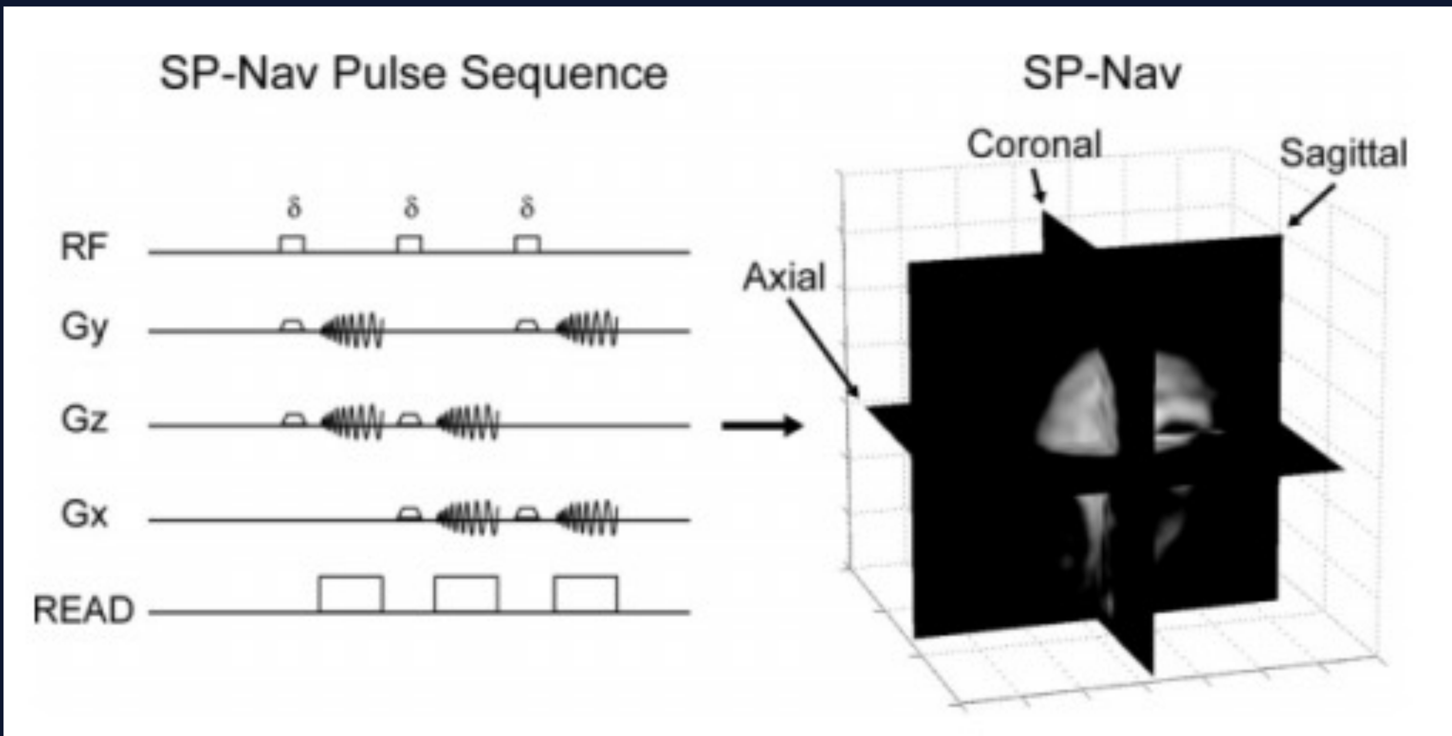
- Inductive coupling with head coil
- Microcoil is de-tuned during RF transmit
- Huge Rx signal enhancement from marker sample in the microcoil

MR based image tracking

PROMO: Real-Time Prospective Motion Correction in MRI Using Image-Based Tracking

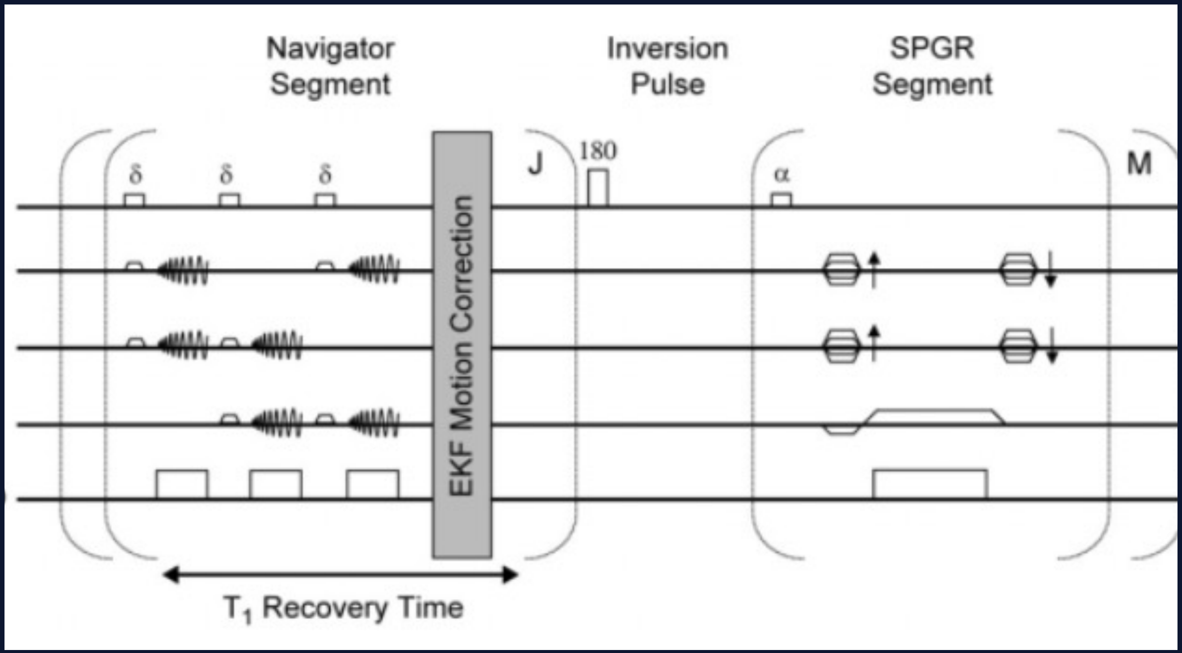
Nathan White,[1] Cooper Roddey,[2] Ajit Shankaranarayanan,[3] Eric Han,[3] Dan Rettmann,[3] Juan Santos,[4] Josh Kuperman,[5] and Anders Dale[2,5*]

MRM **63**:91:2010



- 3 orthogonal 2D navigators with Kalman filter based motion estimation

PROMO

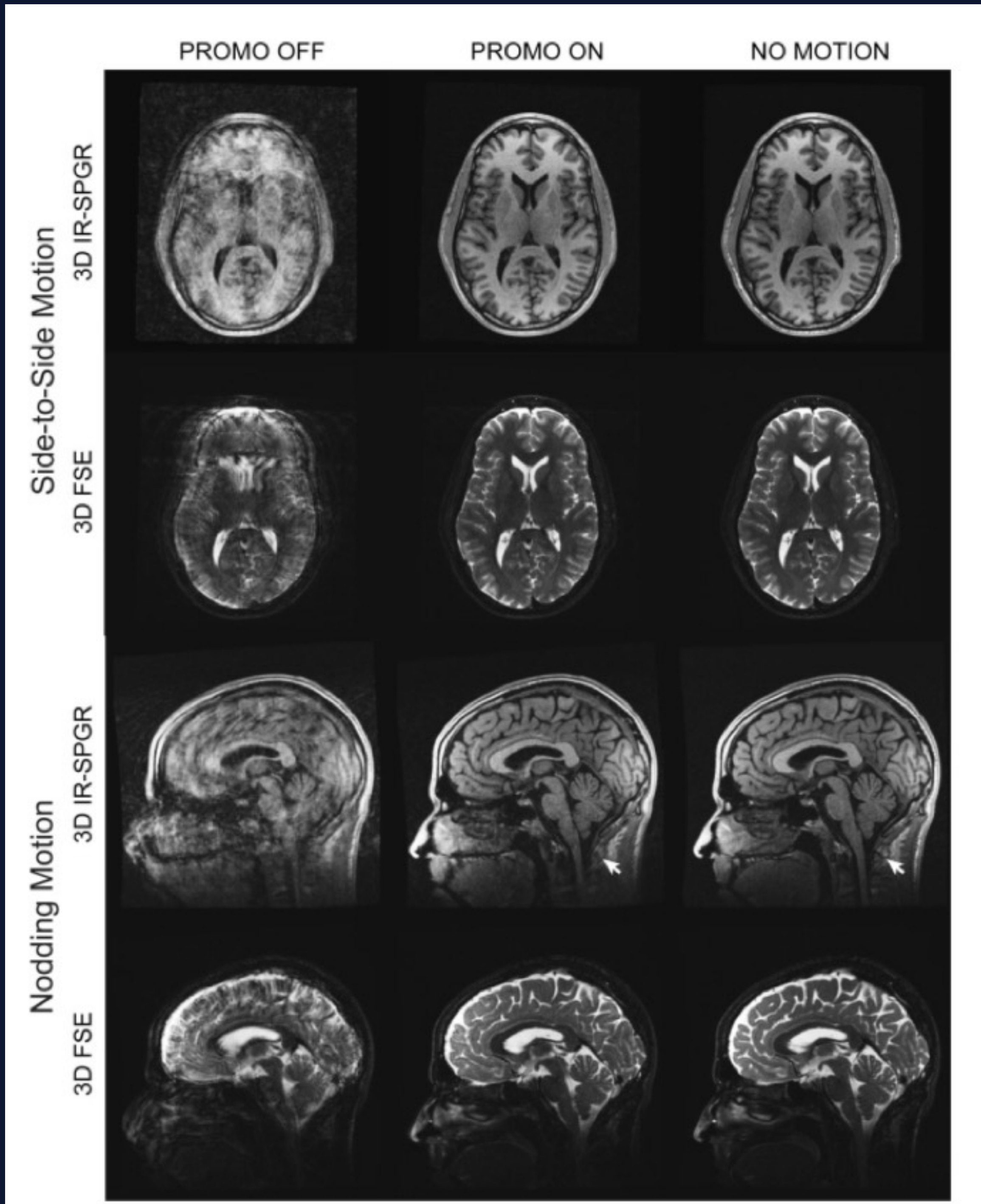


Sequence Design:

Spiral tracker:

3 spiral AQs:	3x 14ms
Flip:	8°
Voxel size:	$1cm^3$
Reconstruction:	3x 2ms
$TR_{spiral\text{-}tracker}$:	100ms
Repeat J=5 times:	500ms

- Requires time for Navigator AQ, reconstruction and tracking calculations
- Useful for inversion recovery (T_{IR} = ~1100ms)
- Less useful for non magnetization prepared sequences
- Must use low flip angle to avoid spin-history effects during IR time
- Can be compared to other MR super-navigators methods
  - EPI based instead of spiral
  - Orbital navigators
  - Cloverleaf, etc.



PROMO

- Spiral nav images:10mm x 10mm x10mm
- 3x14ms total AQ time for tracking sequences
- 100ms for AQ, recon & tracking calculations etc.

PROMO at NIH

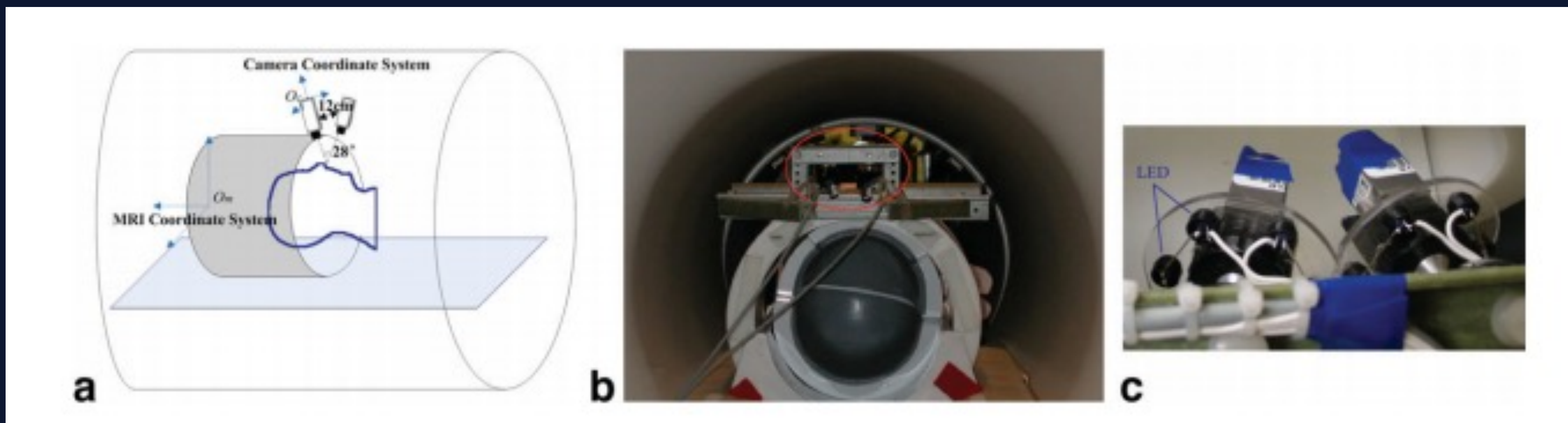
- Multi-echo MP-RAGE implementation (Vinai Roopc)
  - Available on GE 3T scanners (3TA, 3TB, 3TC)
  - Appears to be working well
  - See e.g. their 2014 ISMRM Motion Workshop poster
- MP2-Rage version (Alexandru Avram)
  - Available on 3TC

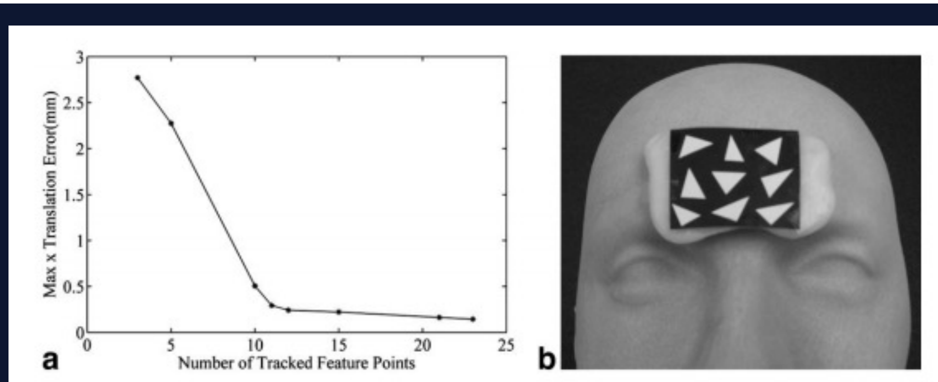
Prospective tracking using stereo optical system

Prospective Head-Movement Correction for High-Resolution MRI Using an In-Bore Optical Tracking System

Lei Qin,[1,2] Peter van Gelderen,[1] John Andrew Derbyshire,[3] Fenghua Jin,[2] Jongho Lee,[1] Jacco A. de Zwart,[1] Yang Tao,[2] and Jeff H. Duyn[1*]

MRM **62**:924:2009



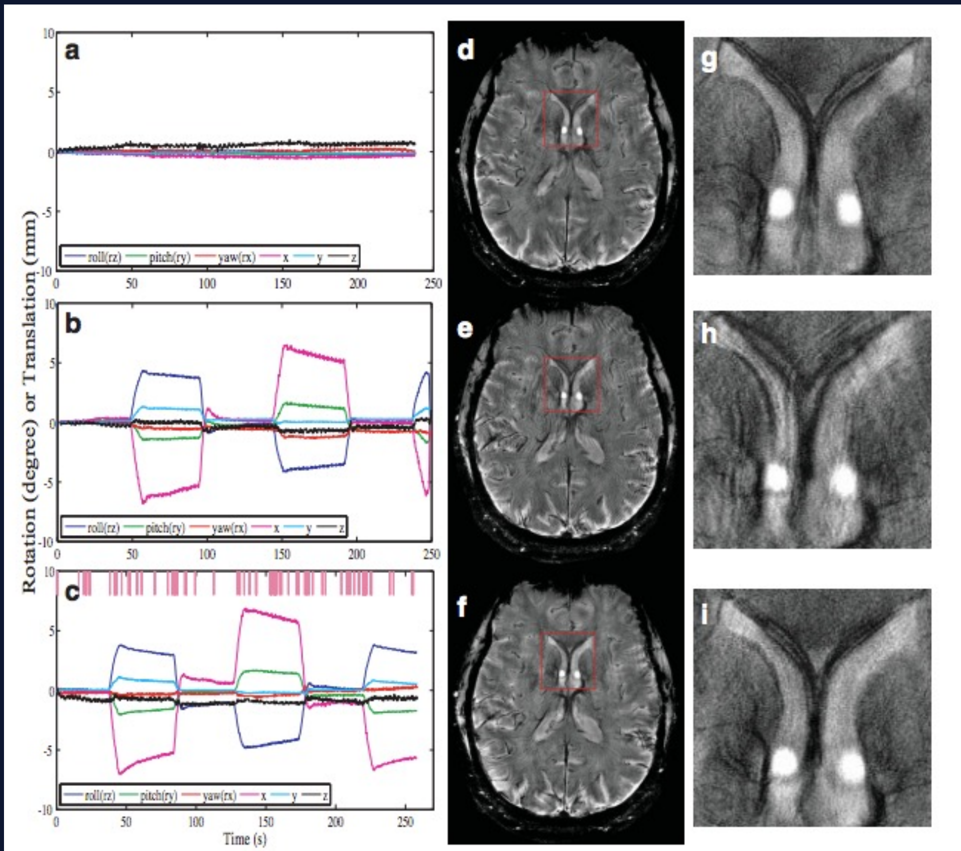


Prospective tracking using stereo optical system

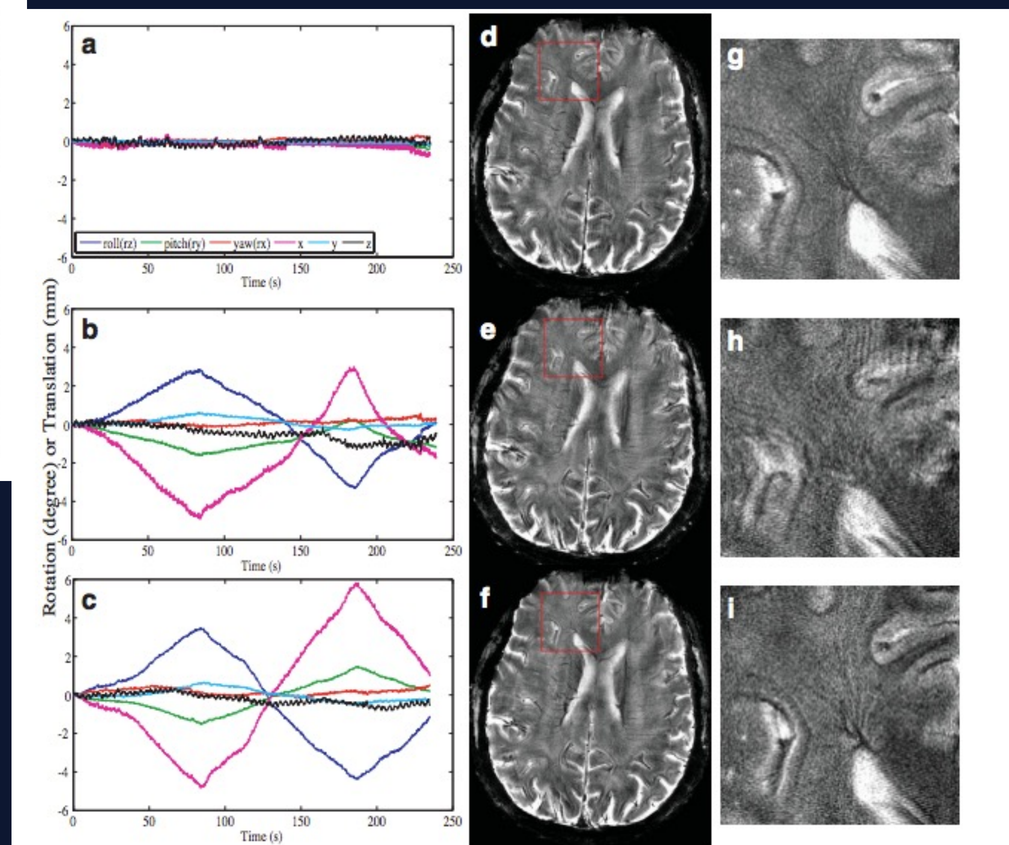
- Additional calibration of camera with MR system required
  - Not required for MR based tracking
- Camera mounted on coil – table motion
- Accuracy:
  - 0.1mm translation
  - 0.15° rotation
- Tracking rate: 10Hz

Prospective tracking using stereo optical system

7T GE system
0.2mm x 0.2mm x 3mm



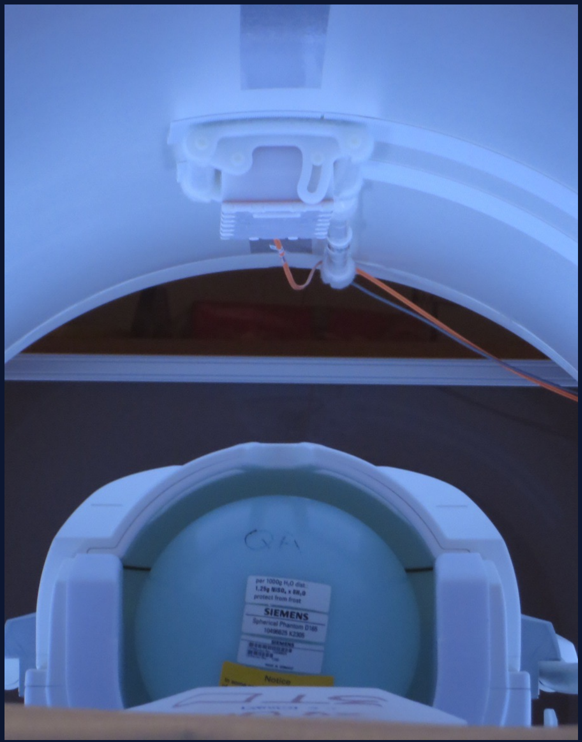
Sudden stepwise motion



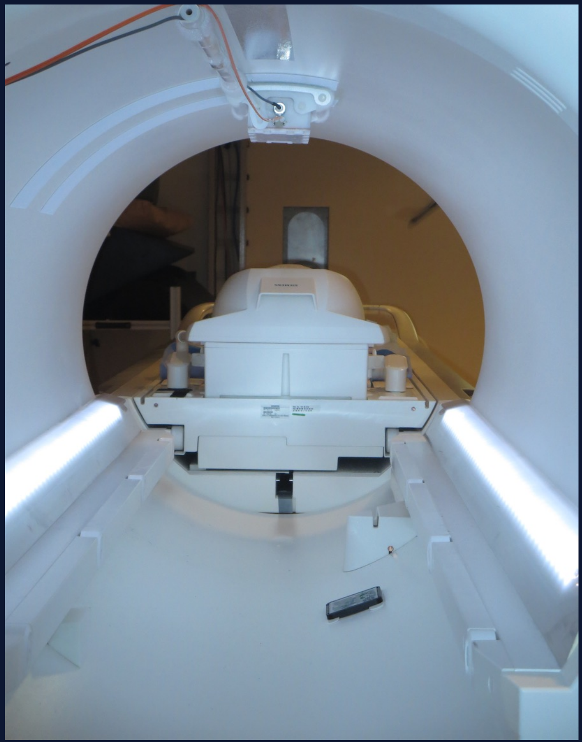
Gradual motion

Kineticor system

- Evaluating system on FMRIF 3TD (Siemens)



Camera mounted on top side of bore



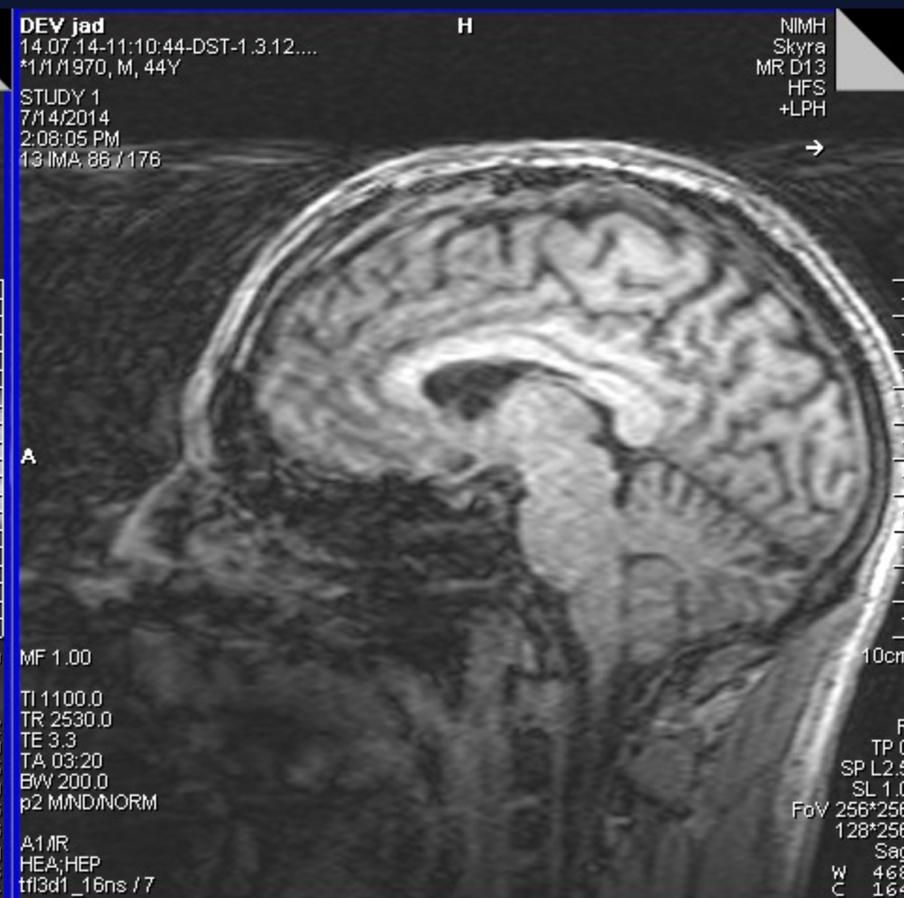
MR system calibration patch mounted on bottom of bore

Marker for Moiré phase tracking

Kineticor system

- Evaluating system on FMRIF 3TD (Siemens)
- 3 minute MP-RAGE scan

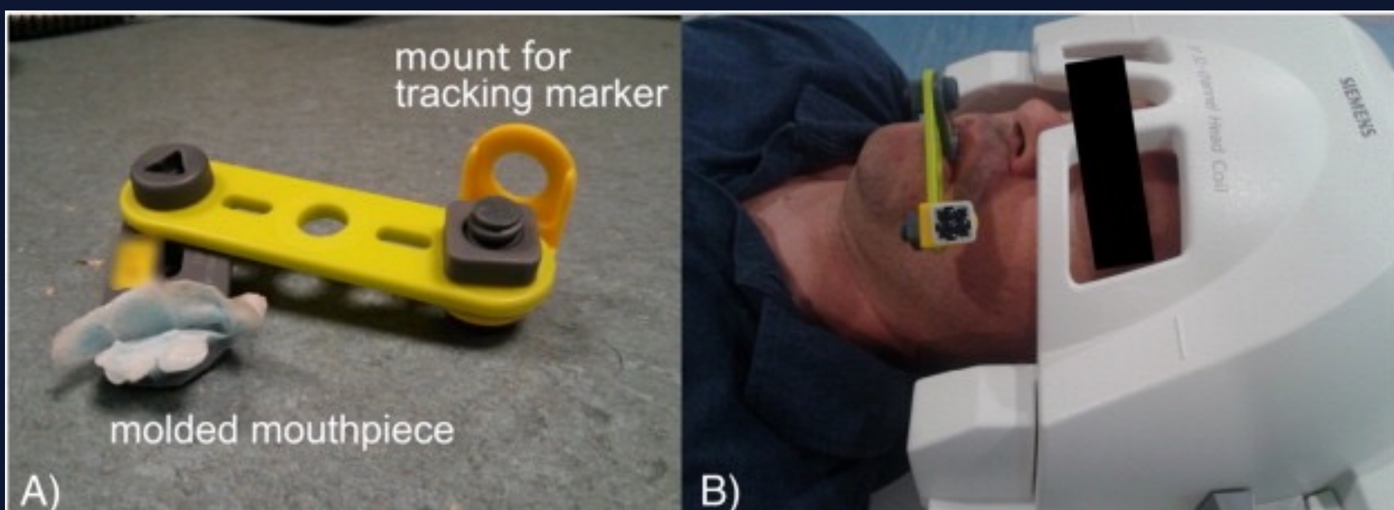
Motion correction on



Motion correction off

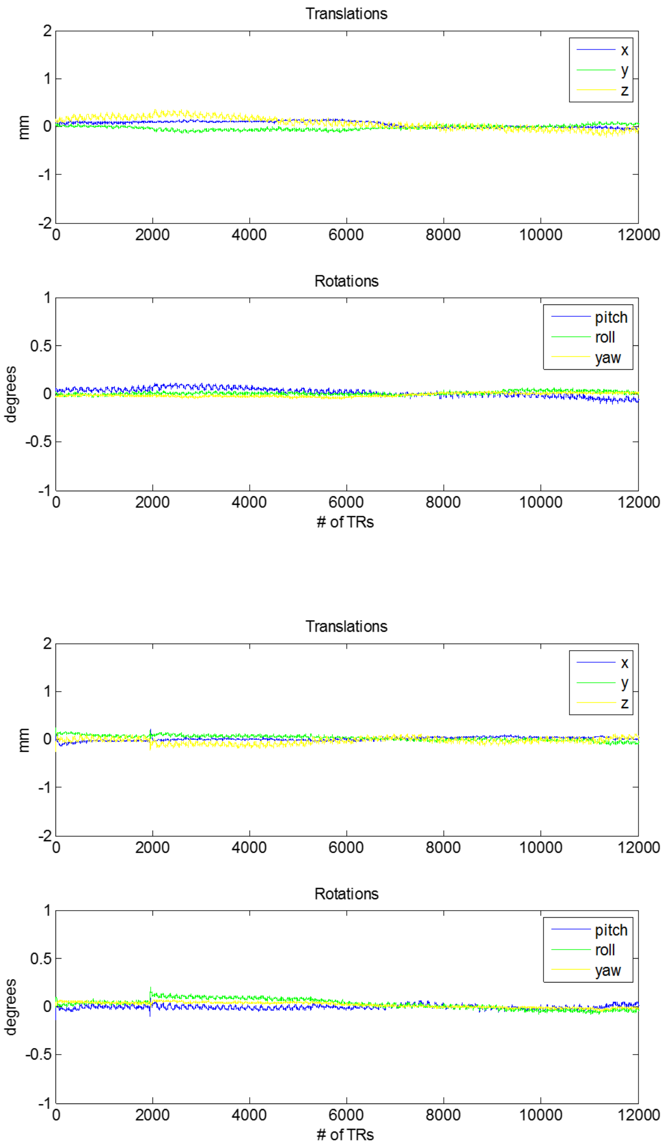
Kineticor system

- The UCL group investigated multiple approaches to marker fixation:
  - Direct-to-skin
  - Nose-clip
  - Glasses
  - Toothclip mounting required
- 32 channel headcoil

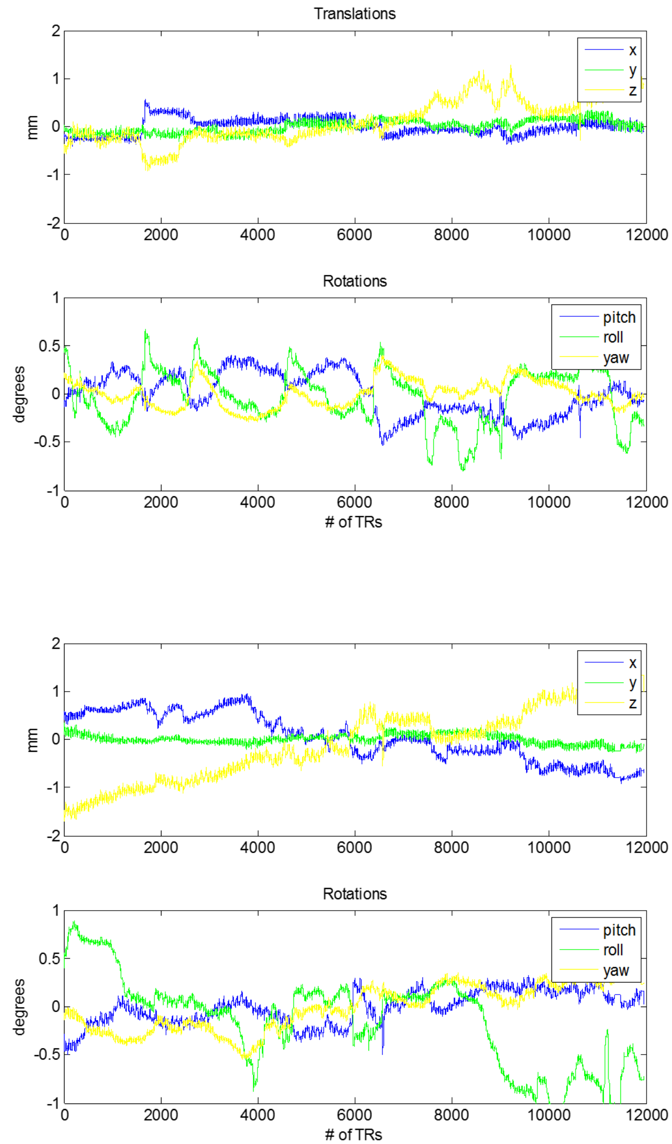


Callaghan, Todd: UCL group

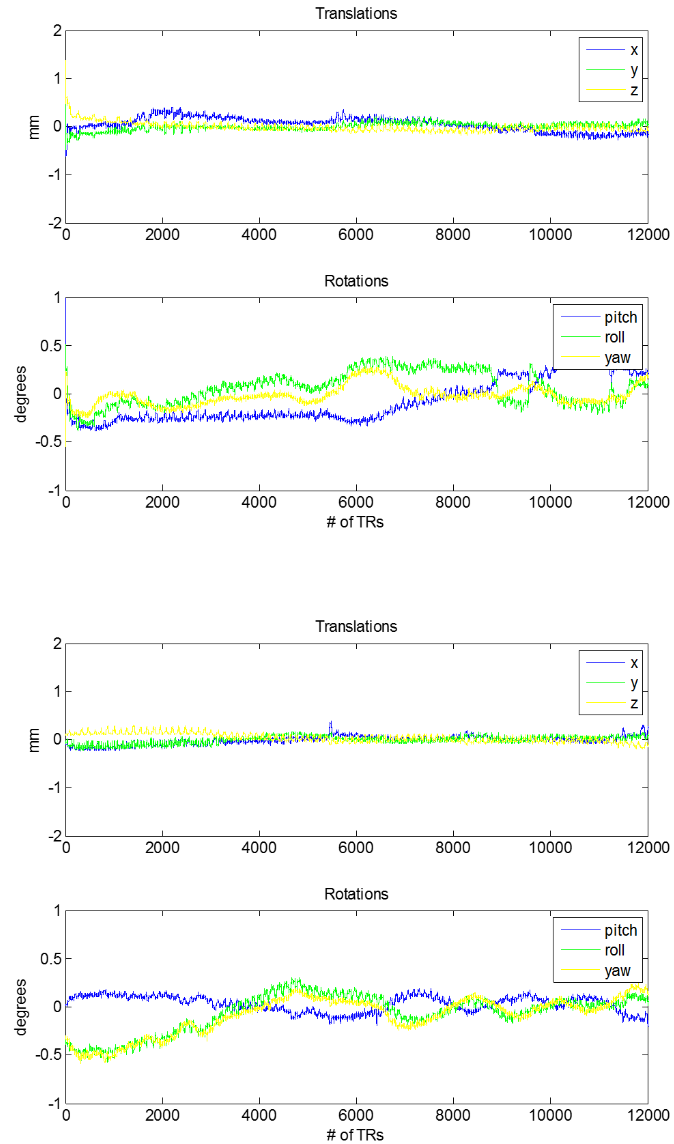
Mini Bite-bar



Facial Attachment A



Facial Attachment B

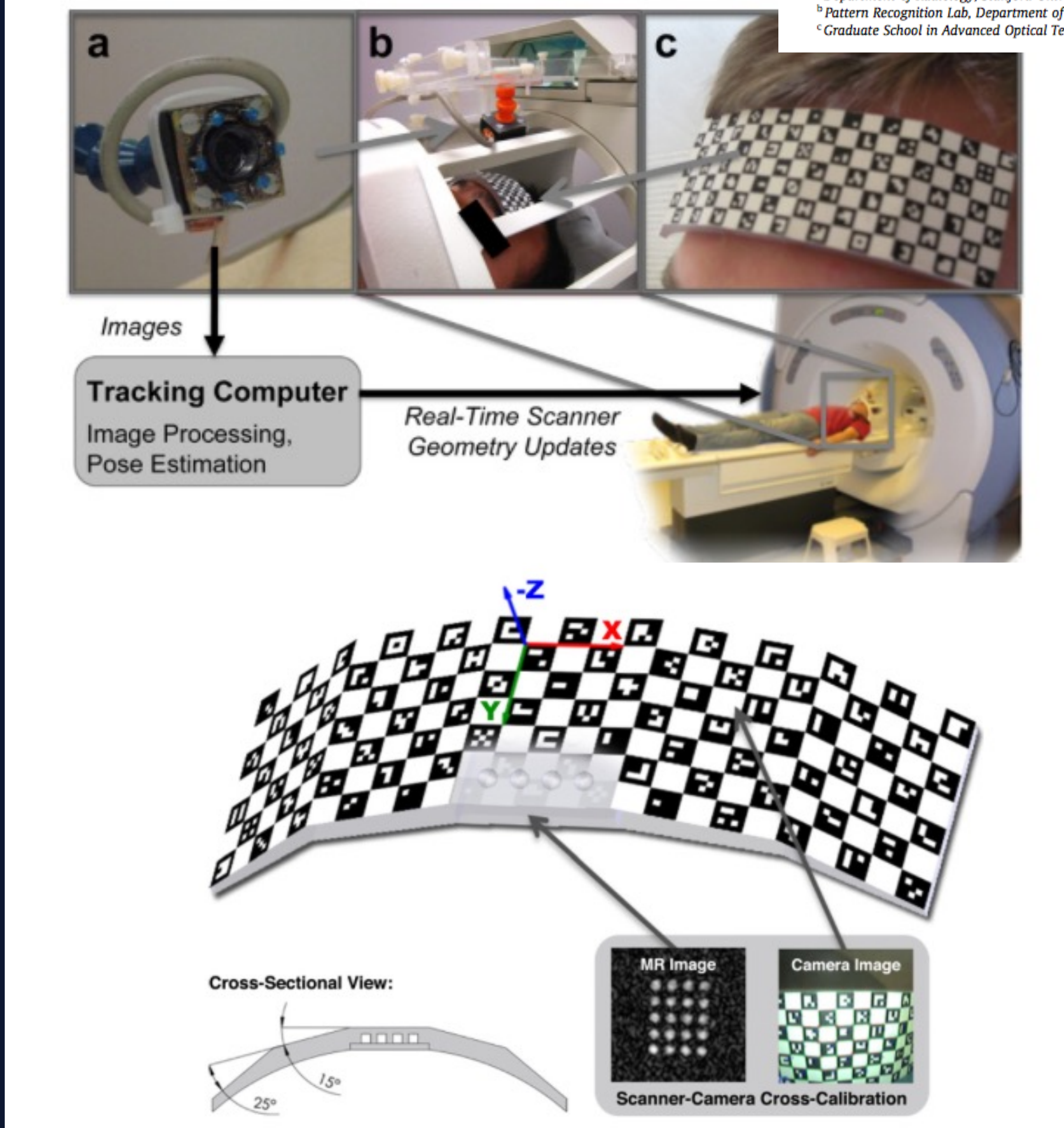


Other systems

Self-encoded marker for optical prospective head motion correction in MRI

Christoph Forman [a,b,c,*], Murat Aksoy [a], Joachim Hornegger [b,c], Roland Bammer [a]

[a] Department of Radiology, Stanford University, Stanford, CA, USA
[b] Pattern Recognition Lab, Department of Computer Science, Friedrich-Alexander-University, Erlangen-Nuremberg, Martensstrasse 3, 91058 Erlangen, Germany
[c] Graduate School in Advanced Optical Technologies (SAOT), Erlangen, Germany



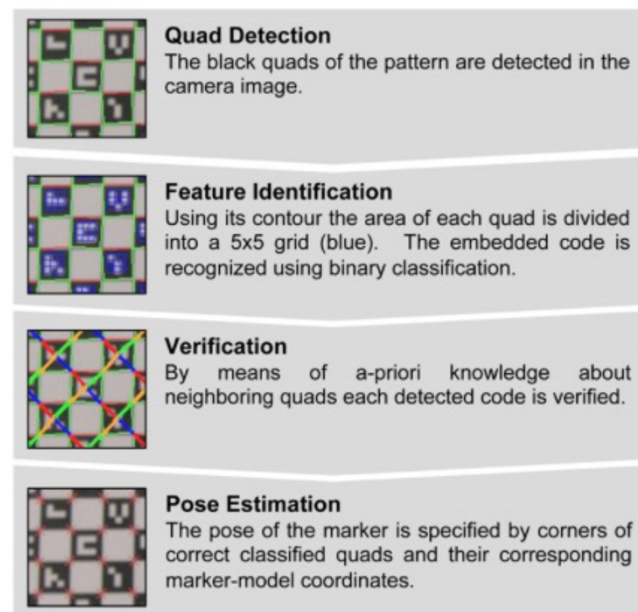


Fig. 3. Workflow diagram of the detection algorithm for the self-encoded marker. This algorithm can be divided into quad detection, feature identification, verification, and pose estimation.

Discussion

- Rigid body motion model
  - difficult to generalize to more complex motions types
  - Unable to correct local motion (e.g. tongue, eyes, etc.)
- Latency of scan-plane feedback
  - Tracking calculation
  - Sequence update (MRI pulse sequence frame length)
- Requires specially modified pulse sequence
  - to handle real-time imaging parameter feedback
  - vendors may develop an API to support these concepts
- Fixation of external markers for MR or optical tracking
  - markers on skin can move
  - limited visual FOV of camera with 32-channel head coil etc.
- MR tracking systems usually reduce scanning efficiency
- Optical systems need additional camera/MR calibration
- Verification
  - *PMC* changes the acquisition – non-corrected image is not acquired
  - PMC failure often makes the images much worse!

Prospective Motion Correction

- *Is it better?*

  Maybe – at least for applications where it is reasonable to assume rigid body motion

- Given the demands of high (i.e better than 0.5mm isotropic) resolution, we will probably need to use all the available tricks in our MR toolbox.

- A very active area of research at the moment:
  - MRM review article 2012
  - MRM virtual issue
  - ISMRM workshop, 2014

Thanks for your attention