Motion Correction in MRI

General Overview - Solutions

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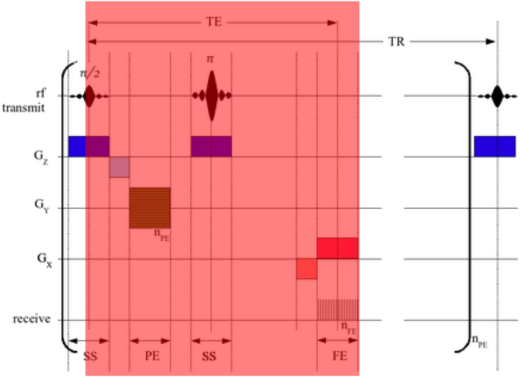
Inhalt

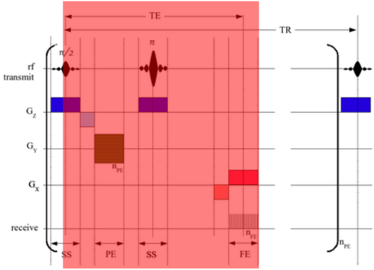
intrashot-motion



Intrashot-Motion-Regime

- motion present during acquisition blocks
- effects: determined by presence of field gradients → additional signal phase; corrupted excitation profile

intrashot-motion

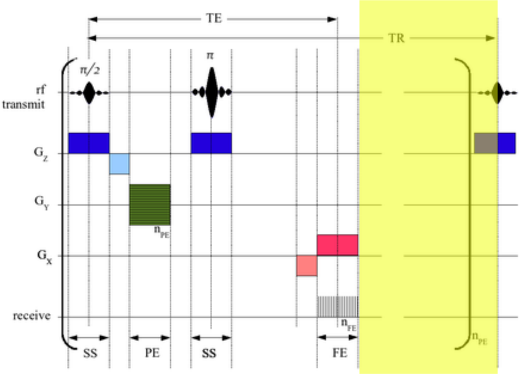


Intrashot-Motion-Regime

$$
\begin{aligned}
s(t) &= \int \rho(x) e^{i\theta(t)} \\
\theta(t) &= \gamma \int G(t) x(t) dt \\
x(t) &= x_0 + v_0 t + (a_0/2) t^2 + \ldots
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\theta(t) &= \gamma \int G(t) x_0 dt + \gamma \int G(t) v_0 dt + \gamma \int G(t) t^2 a_0/2 dt + \ldots \\
&= k_x x_0 + \gamma M_1 v_0 + \gamma M_2 (a_0/2) + \ldots
\end{aligned}
\tag{2}
$$

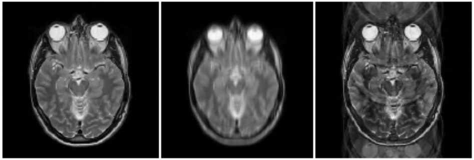
intershot-motion



Intershot-Motion-Regime

- motion present between acquisition blocks
- approximation: motion state changes only with the phase encoding (Cartesian sampling)

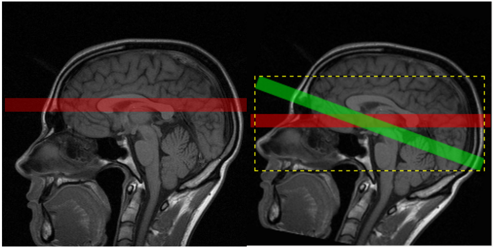
rigid/non-rigid motion



(a) (b) (c)

1. **rigid-motion**
   - translation: fourier-shift-theorem
     $\rho(x - x_0, y - y_0) \leftrightarrow F(k_x, k_y)e^{-2\pi i(k_x x_0 + k_y y_0)}$
   - rotation: fourier-rotation theorem
     $\rho(\hat{R}(x, y)) \leftrightarrow F(\hat{R}(k_x, k_y))$
   - rigid motion manifests itself in blurring and ghosting
   - head-motion, arm-motion, leg-motion
2. **non-rigid-motion**
   - hard to determine, cardiac-motion, respiration, gastrointesinal peristalsis, pulsatile brain-motion

2D / 3D excitation



(a) 1st excitation (b) 2nd excitation

- for sequences based on slice (2D) excitation it must be assured that motion is in-plane

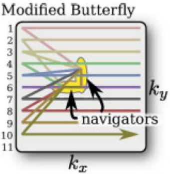
Correction Approaches

1. **Prospective Motion Correction:**
   e.g. PROMO, real-time gradient adjustment, gating, triggering
2. **Retrospective Motion Correction:**
   mathematical approaches focusing on data consistency
3. **Data Acquisition Strategies:**
   e.g. PROPELLER sequence, radial/spiral sampling, fast-imaging techniques

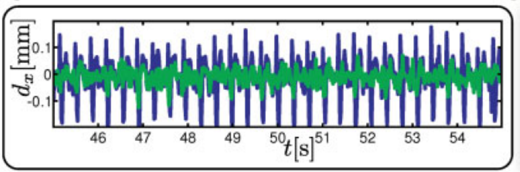
Motion Detection

1. **External Sensors**

2. **Internal Navigator Echoes**



(c)



(d)

Summary

Motion Type		
intershot/intrashot	rigid/non-rigid	2D/3D/4D
		(2D) inplane/troughplane

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prospective	retrospective	data-acquisition

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internal / external

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internal / external

Body Part
neuro, cardiac, abdominal, ...

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SE,GE,FSE,EPI,SSFP,...

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Spin Preparation

DWI/DTI, PC-MRA, Elastography, ...

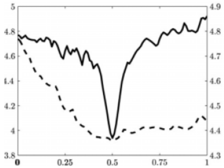
1) General Matrix Description[1]

$$\rho = \left(\sum_{t=0}^{n_s-1} \mathbf{F^H A_t F U_t} \right) \rho_\mathbf{0} = \mathbf{E} \rho_\mathbf{0} \tag{3}$$

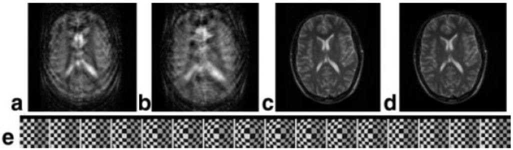
- linear inverse problem: assume motion-operator U_t at time t to be known; A_t: sampling operator; ρ: motion corrupted image; ρ_0: ideal object image
- Assumes **intershot** arbitrary motion
- Assessment of image quality with artifact metric (joint-entropy)
- In-vivo data: 16-echo TSE 256x256

1) General Matrix Description

Motion Model



(e) joint-entropy as function of maximal radial deformation; solid line: LSQR inversion; dashed line: empirical inverse



(f) Nonrigid example (simulation), which simulates a pulsation in 16 shots. (a) The motion-corrupted image; (b) the correction by empirical inverse ; (c) the correction by the LSQR algorithm; (d) the goldstandard image. (e) The deformation at each of the 16 shots on a square checkerboard image

2) Generalized Reconstruction Framework[3]

$$s(\vec{k}) = \int_{\Omega} K(\vec{k}, \vec{r_0}) \rho_0(\vec{r_0}) d\vec{r_0}$$
$$K(\vec{k}, \vec{r_0}) = d(\vec{k}) \sigma(\vec{k}, \Phi(\vec{r_0})) e^{-i\vec{k}\Phi_k(\vec{r_0})} |J_{\Phi_k(\vec{r_0})}| \tag{4}$$

$$s = E\rho_0 \tag{5}$$

- reconstruction problem is equivalent to solving a Fredholm equation of the first kind with a generalized kernel comprising Fourier and **coil sensitivity encoding**, modified by physiological motion information
- $d(\vec{k})$: sampling operator; $\sigma(\vec{k}, \vec{r})$: **static** coil sensitivity; $\Phi_k : \vec{r_0} \mapsto \vec{r}$

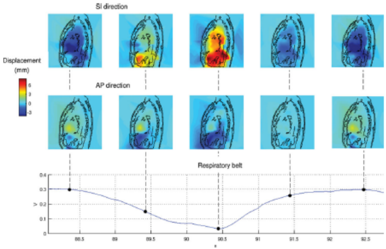
2) Generalized Reconstruction Framework

Numerical Resolution

$$
\begin{aligned}
A &= E^T E \\
A &= \sum_{t=0}^{n_s-1} U_t^H \left(\sum_{c=1}^{N_c} \sigma_c^H F^H A_t^H A_t F \sigma_c \right) U_t
\end{aligned} \tag{6}
$$

- Generalized Matrix Description for multiple coils
- Also assumes **intershot** motion

2) Generalized Reconstruction Framework



Motion Model

$$\hat{u}(r,t) = \alpha(r)S(t) = \sum_{k=1}^{K} \alpha_k(r)S_k(t) \tag{7}$$

- Elastic motion is represented by **displacement values** at certain control points, defined by a Cartesian grid
- predictive motion model: simultaneous acquisition of image and sensor data (pneumatic belts, ECG data, ...) $S(t)$ allows to construct - based on a **regression method** - a linear model described by the coefficients $\alpha_k(r)$.
- the model is able to estimate the displacement fields $\hat{u}(r,t)$ $\rightarrow$ input to generalized reconstruction

3) Localized Linear Translations, Autofocusing[2]

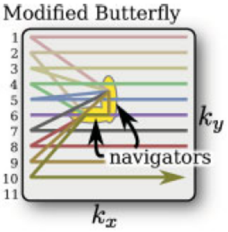
Start movie

- sufficient small spatial and temporal scale $\rightarrow$ elastic motion can be approximated as simple **linear translations**
- formulation of **autofocusing** algorithm that locally minimizes a given **motion metric** (gradient entropy)
- possible motion paths are limited to the motion measured from **multichannel navigator** data

3) Localized Linear Translations, Autofocusing

Motion Model

$$s_n[l] = C[n]s_0[l]e^{2\pi i\vec{k}[l]\vec{d}[n]}$$
$$C[n] = c_r[n]e^{2\pi i c_\Phi[n]} \quad (8)$$



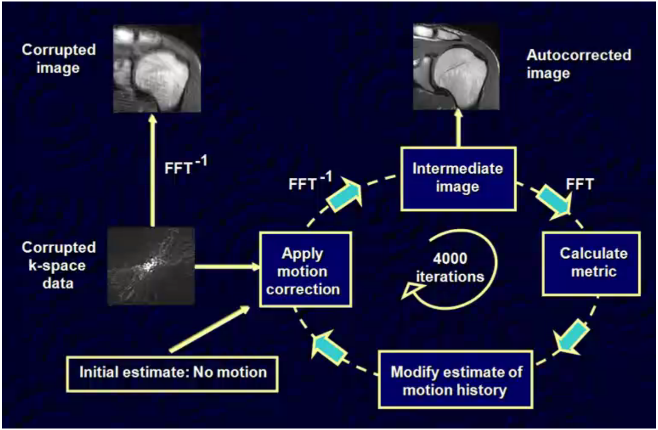
- $l \in \{0, ..., L\}$: navigator consists of the first L samples in readout; $s_n[l]$: l-th navigator-signal of n-th shot for each coil; $\vec{d}[n]$: linear translation modeled as linear-phase modulation applied to reference navigator signal s_0
- $C[n]$ accounts for bulk magnitude and phase fluctuations

$\rightarrow$ solved with weighted Gauss-Newton motion estimate

$$\min_{d_x, c_\Phi} \sum_l w^2[l] |s_0[l] - s[l]e^{-2\pi i k_x[l] d_x + c_\Phi}|^2$$

3) Localized Linear Translations, Autofocusing

Autofocusing



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