4D and 5D Motion-Compensated (MoCo) Image Reconstruction

Marc Kachelriess

German Cancer Research Center (DKFZ)
Heidelberg, Germany
www.dkfz.de/ct
Motion Compensation (MoCo)

- Step 1 (difficult): Motion estimation resulting in motion vector fields (MVF)
- Step 2 (simple): Applying the estimated MVFs during image reconstruction to compensate for the motion.
- Depending on the type of algorithm iteratively repeat these steps
4D MoCo
Motion Management for CBCT in IGRT

- Linear Accelerator
- kV Source
- Detector
- Gantry Rotation

(varian)
4D CBCT Scan with Retrospective Gating

Without gating (3D): Motion artifacts
With gating (4D): Sparse-view artifacts

Acquisition angle
Angular spacing of projection bins
Measured projections assigned to one phase bin
A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration
- Has to be repeated for each reconstructed phase
- Streak artifacts from gated reconstructions propagate into sMoCo results

Gated 4D CBCT

sMoCo

The Cyclic Motion Estimation and Compensation Approach (cMoCo)

- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced

Artifact Model-Based MoCo (aMoCo)

3D CBCT

Measured data:

Segmented Image

Virtual rawdata:

Gated 4D CBCT

4D Artifact Images

Patient Data – Results

| 3D CBCT Standard | Gated 4D CBCT Conventional Phase-Correlated | sMoCo Standard Motion Compensation | acMoCo Artifact Model-Based Motion Compensation |

$C = -200 \text{ HU}, \ W = 1400 \text{ HU}$, displayed with 30 rpm.

Patient data provided by Memorial Sloan–Kettering Cancer Center, New York, NY.
Spin-Off Effects?
What about MoCo in MR, in PET/MR, or in MR-guided RT?

- MR acquisition is slow
- 4D MR acquisition is even slower
- Thus: Develop a framework for MR-MoCo
- Use motion vector fields
  - to compensate the motion from clinical sequences
  - to compensate the motion from other modalities
  - for tracking the tumor position
- Using dedicated image reconstruction and registration techniques, allows to cope with highly undersampled data.¹

Joint MoCo-HDTV Algorithm for MR

Cost Function\(^1,2\)

- **Cost function:**

\[
C = \|X_{pc}S f - p\|_2^2 + \mu \|\text{HDTV } f\|_1
\]

- **The first term optimizes the raw data fidelity**
- **The second term improves the image sparsity by optimizing the spatial and temporal total variation**
- **Both terms are optimized in an alternating manner**
- **The cost function is optimized for the complete 4D volume including all motion phases**
- **An optimal weighting \(\mu\) of the raw data fidelity and total variation step is calculated in each iteration\(^1\)**

---


Joint MoCo-HDTV Algorithm for MR

Update Equation

- Modified update equation of the raw data fidelity step for phase $i$:

$$u_{t,(n+1)} = S^{-1}X_{pc,t}^{-1}(X_{pc,t}Sf_{t,(n)} - p_t)$$

$$f_{t,(n+1)} = f_{t,(n)} + \alpha \left((1 - \beta)u_{t,(n+1)} + \beta \frac{1}{N_t} \sum_{t'} T_{t',(n)}u_{t',(n+1)}\right)$$

- $u_{t,(n)}$: update of phase $t$ at iteration $n$
- $f_{t,(n)}$: image of phase $t$ at iteration $n$
- $X_{pc,t}$: phase-correlated forward transform
- $X_{pc,t}^{-1}$: phase-correlated inverse transform
- $p_t$: measured raw data of phase $t$
- $T_{t'}^t$: warping operation mapping volume of motion phase $t'$ to $t$
- $\alpha$: weight
- $\beta$: MoCo update weight

MoCo update weight, $0 \leq \beta \leq 1$
Joint MoCo-HDTV Algorithm for MR

Schematic Overview

Resolution level 1
- Image reconstruction
- Motion estimation

Resolution level 2
- Image reconstruction
- Motion estimation

Resolution level 3
- Image reconstruction
- Motion estimation

Resolution level 3
- Final reconstruction
- Reduced regularization

cMoCo update weight, $0 \leq \beta \leq 1$

4D MR Motion Compensation
Results Volunteer p8

Gated 4D
6 min 51 s

3D
37 s

Gated 4D
37 s

4D joint MoCo-HDTV
37 s

Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
\( R = 20, \Delta r = 10\% \)
4D MR Motion Compensation
Results Patient c24

Gated 4D
5 min 50 s

3D
41 s

Gated 4D
41 s

4D joint MoCo-HDTV
41 s

Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
$R = 20, \Delta r = 10\%$
MoCo PET Image Reconstruction

• MoCo MLEM update equation of motion phase \( i \):

\[
\lambda_{i}^{(n+1)} = \lambda_{i}^{(n)} \frac{1}{\sum_{i'} T_{i'}^{i} M^{T} \frac{1}{a_{i'}}} \sum_{i'} T_{i'}^{i} M^{T} \frac{p_{i'}}{M T_{i}^{i'} \lambda_{i}^{(n)} + a_{i'} (r_{i'} + s_{i'})}
\]

- \( n \): iteration index
- \( M, M^{T} \): system matrix including forward-/backprojection
- \( a \): attenuation correction factors
- \( p \): measured rawdata (prompts)
- \( r \): estimated randoms
- \( s \): estimated scatter
- \( \lambda^{(n)} \): image estimate at iteration \( n \)
- \( i, \hat{i} \): indices of motion phases
- \( T_{i}^{i'} \): warping operation mapping motion phase \( i \) to \( \hat{i} \)

• To reduce computation time, an ordered subset implementation (OSEM) was used

Due to the high noise level of 4D gated PET, $\text{SUV}_{\text{mean}}$ was systematically overestimated.

4D PET/MR Motion Compensation
PET Results Patient s09

3D Gated 4D 4D cMoCo

MR: 5 min / bed MR: 1 min / bed

\[ \text{SUV}_{\text{mean}} = 5.2 \] \[ \text{SUV}_{\text{mean}} = (8.0) \] \[ \text{SUV}_{\text{mean}} = 6.7 \] \[ \text{SUV}_{\text{mean}} = 6.7 \]

due to the high noise level of 4D gated PET, \( \text{SUV}_{\text{mean}} \) was systematically overestimated
Conclusion and Outlook

• Quasi-periodic motion can be accurately assessed from very sparse data.
• MVFs can continuously be updated, which is important for MR-based RT.
• Non-periodic motion can be compensated using deformable 3D-2D registration\(^1\) (not shown here).

Is There More?
Data displayed as:
Heart: 280 bpm
Lung: 150 rpm

Mouse with 150 rpm and 280 bpm.
Data displayed as:
Heart: 90 bpm
Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.
Data displayed as:
Heart: 0 bpm
Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.
Mouse with 180 rpm and 240 bpm.

Data displayed as:
Heart: 90 bpm
Lung: 0 rpm
5D with Double Gating?

Double gating example:

- Cardiac window width: 20%
- Respiratory window width: 10%
- Only 2% of all projections per reconstructed volume
5D Motion Compensation

5D MR Motion Compensation
Results Patient c11 (Acquisition Time: 2 min)

5D double-gated
72 bpm, 18 rpm

5D MoCo
72 bpm, 18 rpm

5D MoCo
0 bpm, 18 rpm

5D MoCo
72 bpm, 0 rpm

Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
$R = 20$, $\Delta r = 10\%$, $C = 10$, $\Delta c = 20\%$, radial undersampling = 27.9
5D MR Motion Compensation
Results Patient c12

3D reconstruction
motion average

5D reconstruction
resp & card gated
$r = 1, c$-loop

5D reconstruction
resp MoCo & card gated
$r = 1, c$-loop

5D MoCo
resp & card MoCo
$r = 1, c$-loop

total acquisition time: 1 min 55 s, radial undersampling = 36
5D MR Motion Compensation
Results Patient c19

3D reconstruction
motion average

5D MoCo
resp & card MoCo
r = 1, c-loop

5D MoCo
resp & card MoCo
r-loop, c = 1

5D MoCo
resp & card MoCo
r-loop, c-loop

total acquisition time: 1 min 55 s, radial undersampling = 36
## 5D PET/MR Motion Compensation

Results Patient s04

<table>
<thead>
<tr>
<th>3D PET motion average</th>
<th>5D double-gated PET ( r = 1, c\text{-loop} )</th>
<th>5D MoCo PET ( r = 1, c\text{-loop} )</th>
<th>5D MoCo MR ( r = 1, c\text{-loop} )</th>
</tr>
</thead>
</table>

![Images of PET/MR results](image1.png)

![Images of PET/MR results](image2.png)

![Images of PET/MR results](image3.png)

![Images of PET/MR results](image4.png)
5D MR Motion Compensation
Results Patient s10

5D double-gated MR
\( r = 1, \ c\text{-loop} \)

5D MoCo MR
\( r = 1, \ c\text{-loop} \)

5D MoCo MR
\( r\text{-loop, } c = 1 \)

5D MoCo MR
\( r\text{-loop, } c\text{-loop} \)

total acquisition time: 5 min
5D PET/MR Motion Compensation
Results Patient s10

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D PET</td>
<td>motion average</td>
</tr>
<tr>
<td>5D double-gated PET</td>
<td>$r = 1, c$-loop</td>
</tr>
<tr>
<td>5D MoCo PET</td>
<td>$r = 1, c$-loop</td>
</tr>
<tr>
<td>5D MoCo MR</td>
<td>$r = 1, c$-loop</td>
</tr>
</tbody>
</table>

SUV

total acquisition time: 5 min
Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through DKFZ’s international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or directly through Marc Kachelriess (marc.kachelriess@dkfz.de).

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.