Motion Vector Field Upsampling with Joint Phase and Amplitude Binning for Motion-Compensated 4D Cone-Beam Beam CT Image Reconstruction

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Slowly Rotating CBCT Devices

- Image-guided radiation therapy (IGRT)
  - Cone-beam CT (CBCT) imaging unit mounted on gantry of a LINAC treatment system
  - Accurate information about patient motion required for radiation therapy
- Slow gantry rotation speed of 3° or 6° per second
  - Much slower than clinical CT devices
- Breathing about 10 to 30 respiration cycles per minute (and thus per scan)
- Heartbeat about 50 to 80 beats per minute
- Acquire breathing signal during acquisition

Account for patient motion!

Motion Compensation (MoCo)

- Use all projection data for each phase to be reconstructed
  - Even those of other respiratory phase bins (100% dose usage)
  - Compensate for motion applying motion vector fields (MVF)
  - In our case MVFs are estimated from conventional gated reconstructions

- Use MVFs during image reconstruction
  - Backproject sparse data along straight lines, then warp with respect to the MVFs
  - Computational efficiency
    - Corresponds to backprojection along deformed lines
Aims

• To provide high fidelity motion-compensated (MoCo) respiratory- or cardiac-correlated volumes from CBCT.
• Reduce motion blurring by switch from phase to amplitude binning.
• To further increase the temporal resolution by motion vector field (MVF) upsampling in temporal dimension.
• Use cases for MoCo (in the field of radiation therapy):
  – Accurate patient positioning
  – Treatment verification
  – Online treatment adaptation
  – …
Motion Compensation (MoCo)
Motion Estimation Based on Phase Gating

- Respiratory gating is done based on motion phase signal.
  - Each respiratory phase contains only a subset of the total number of projections and this leads to sparse view artifacts.
  - Each respiratory bin contains projections that cover the whole scan angular range.
  - This robust binning method ensures a homogeneous rawdata distribution for all respiratory bins. This is important for reliable motion estimation.

- Disadvantage: Depending on the breathing pattern of the patient motion blurring occurs.
Why MVF Resampling?

- Phase binning = nearly homogeneous projection angle distribution
- Amplitude binning = reflects chest motion amplitude
- Idea:
  - Start with phase binning to obtain good initial MVF estimates.
  - Switch to amplitude binning afterwards to consider variations in amplitude.

Amplitude Gating

10 equidistant bins

Phase Gating

10 equidistant bins

10 adaptive bins

Only the exhale bins are shown in the illustration. $C = -100 \text{ HU}$, $W = 1200 \text{ HU}$

Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam.
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- 10 adaptive bins
- 10 equidistant bins

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Step 1: Phase Gating

- The white curve shows a respiratory amplitude signal (external monitor)
- The yellow curve shows the dedicated phase signal (modulo 1)
- The red squares are phase-gated projections (phase and amplitude ordinates)

- Phase gating ensures a nearly uniform projection distribution for all phases
- Phase-gated projections may have a strong variation in their respiratory amplitude. This introduces motion blurring even with perfect MVFs.
Mean Amplitude of Phase Bins

- The white curve shows a respiratory amplitude signal.
- The red line represents the average amplitude of all projections in this phase.
- Motion estimation is done between adjacent phase bins.
- Pragmatic assumption: The MVFs describe the deformation between the mean amplitude of adjacent phase bins.
Step 2: a) Motion Estimation with Cyclic Regularization (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:

Gated 4D CBCT

Virtual rawdata:

Segmented Image

4D Artifact Images

Step 3: Defining the Adaptive Amplitude Bins
(exhale period shown, R=10, K=1)
Step 4: Recalculation of the Mean Amplitudes
Switching From Phase to Amplitude Binning

Phase gating for motion estimation
- Mean amplitude of phase bin n+1
- Mean amplitude of amplitude (sub)bin
- Mean amplitude of phase bin n
- Phase-gated bins

Amplitude gating for deformation & superimposition
- MVF from phase n to n+1
- Scaled MVF from bin to n+1
- Amplitude-gated bins with resampling
- Amplitude-gated bins with upsampling

Amplitude Gating for Deformation & Superimposition

Motion Compensated Images

Respiratory Gating
- Estimate Motion Vector Fields (MVF)

Measured Rawdata

Motion

COMPENSATED
IMAGES

Motion

补偿后的图像
Patient I
Motion Compensation R=10, 20% Bin Width
Scan Velocity 2 °/s with 7 fps, 21 rpm

Feldkamp (FDK)  Phase-Correlated Feldkamp (PCF)  acMoCo  acMoCo with Resampling  acMoCo with Re- and Upsampling

Transversal

Coronal

Sagittal

C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam
Patient II
Motion Compensation R=10, 20% Bin Width
Scan Velocity 3 °/s with 7 fps, 19 rpm

Feldkamp (FDK)  Phase-Correlated Feldkamp (PCF)  acMoCo  acMoCo with Resampling  acMoCo with Re- and Upsampling

C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam
Patient II
Motion Compensation R=10, 20% Bin Width
Scan Velocity 3 °/s with 7 fps, 19 rpm

acMoCo

acMoCo with Resampling

Transversal

C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam
• Sharpness metric $G(\mu)$ (image 3D gradient) was improved by switching from phase to amplitude gating by 8% and with additional upsampling up to 10%.

$$G'(\mu) = \sum_{j} \nabla_x (\mu_j)^2 + \nabla_y (\mu_j)^2 + \nabla_z (\mu_j)^2$$
Edge Profile
Patient Data II, End Inhale Phase
Summary

- MVF resampling allows to robustly switch from phase to amplitude binning.
- Especially for irregular breathing pattern motion blurring was reduced.
- Motion blurring was reduced in all motion bins.
- MVF resampling does not increase computation time.
- The additional upsampling may not be necessary.
Thank You!

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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).