Automatic Intrinsic Cardiac and Respiratory Gating from Cone-Beam CT Scans of the Thorax Region

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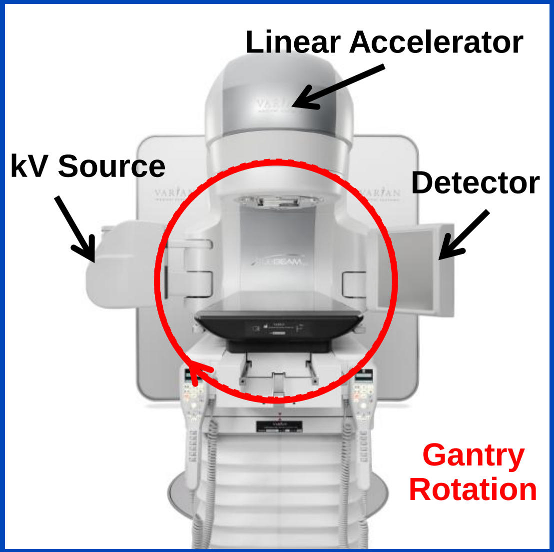
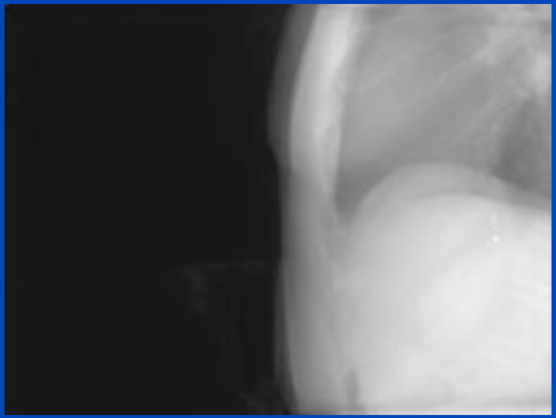
Slowly Rotating CBCT Devices

- Image-guided radiation therapy (IGRT)
  - CBCT imaging unit mounted on gantry of a LINAC treatment system
  - Accurate information about patient motion for precise radiation therapy
- Slow gantry rotation speed of 6° per second (60 s/360°)
  - Much slower than clinical CT devices (0.25 s /360°)
- <u>Breathing</u> about 10 to 30 rpm (respirations per minute) and thus per scan
- <u>Heartbeat</u> about 60-100 bpm (beats per minute)

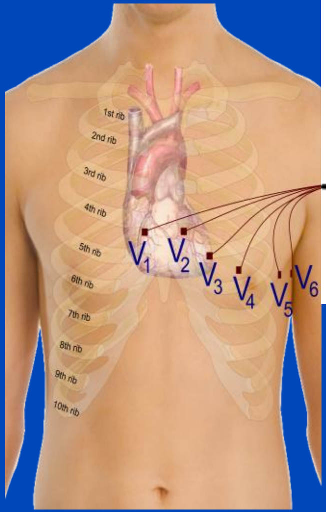


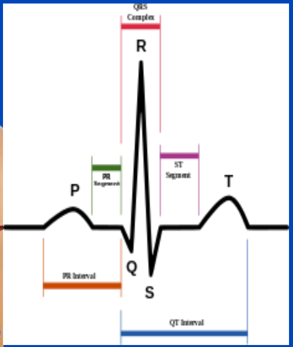


Projections that show cardiac and respiratory motion

External Respiratory/Cardiac Signal Acquisition

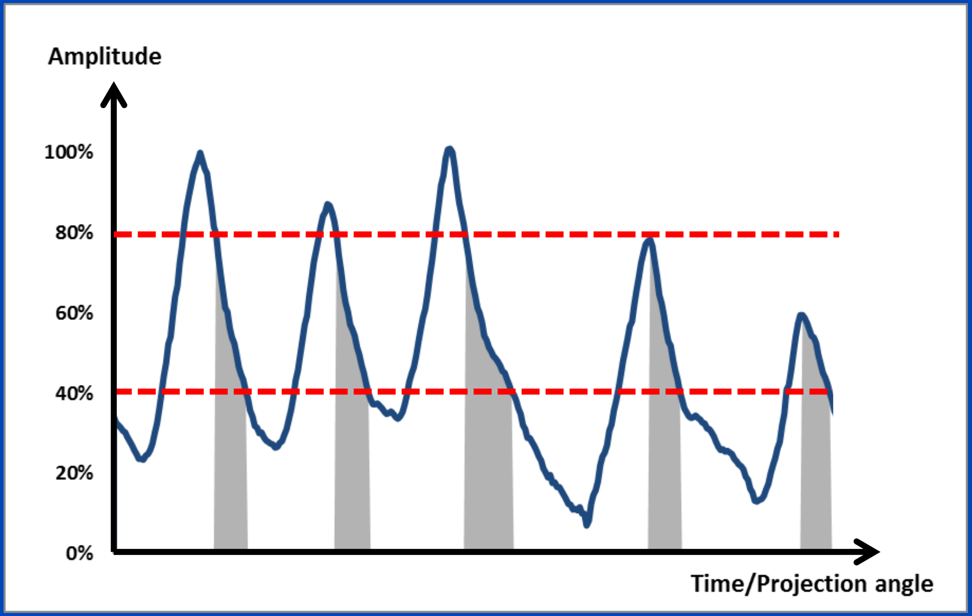
ECG





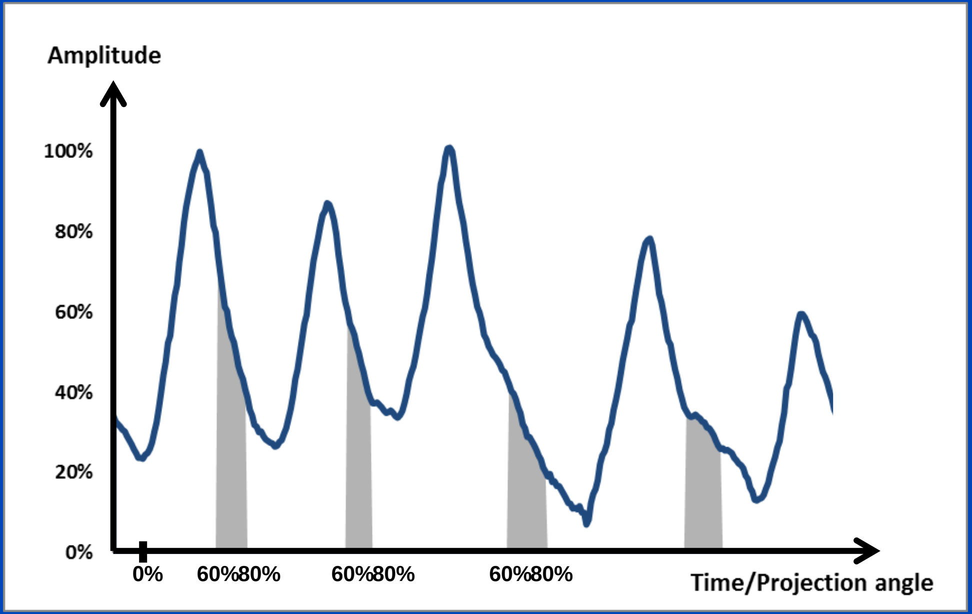
Amplitude Gating

- Motion bins are determined by amplitude
- Assumption:
  - Good correlation between amplitude signal and lung expansion
- Advantages:
  - Amplitude reflects lung expansion
- Disadvantages:
  - Depending on the implementation not all phases may contain the same number of projections



Phase Gating

- Motion bins are determined by phase, i.e. relative distance between peaks
- Advantages:
  - Only peaks need to be known
  - Depending on the implementation the number of projections per phase may be more or less constant
- Disadvantages:
  - Does not reflect true expansion of the lung/heart



Phase Gating

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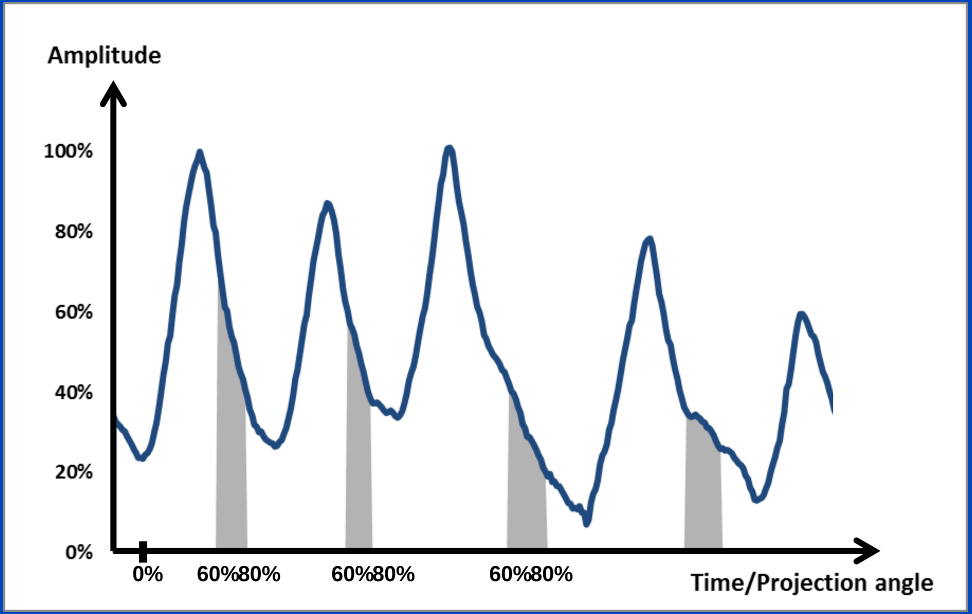
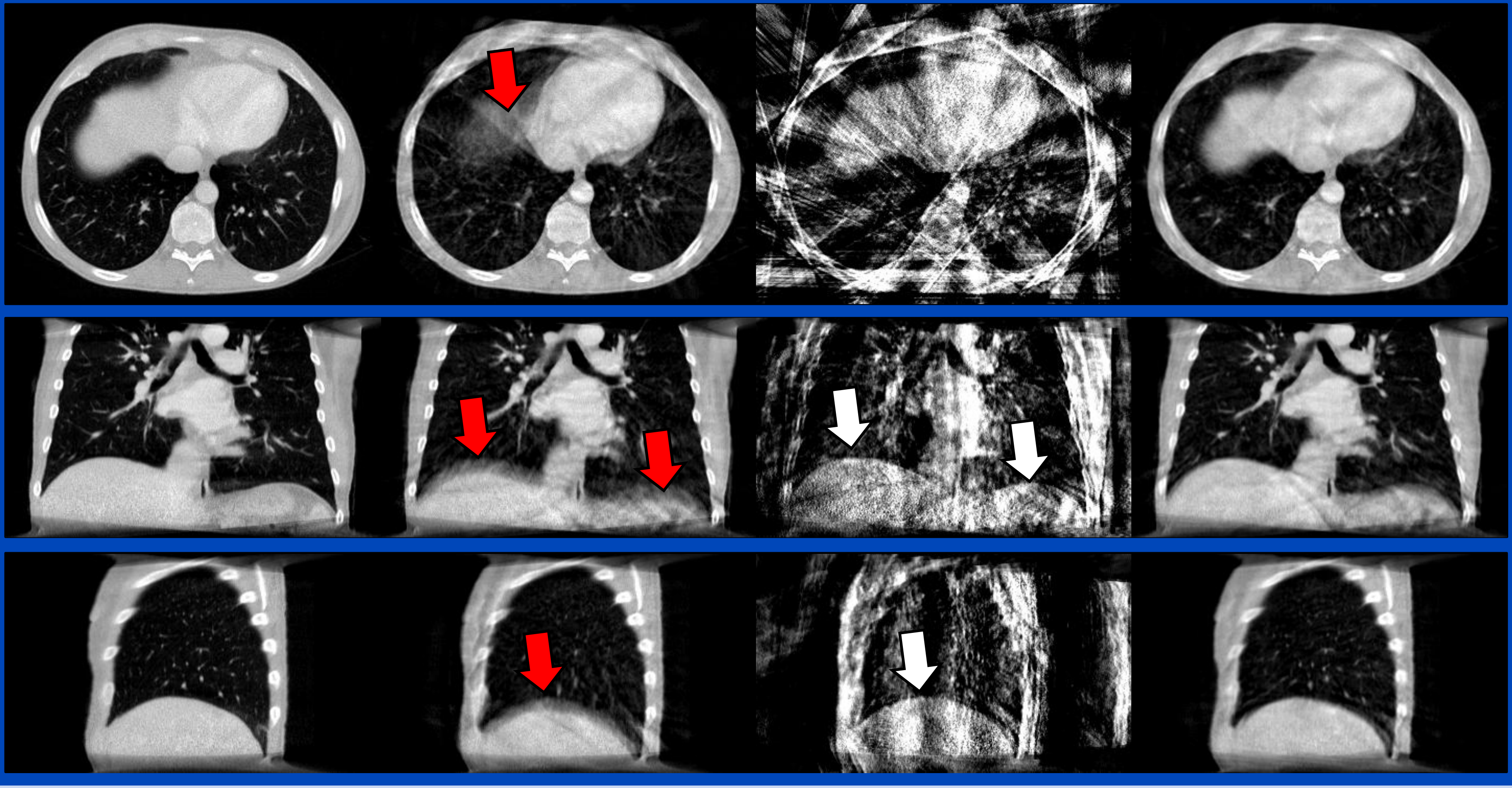


Here we only use phase gating since the algorithm proposed later only determines peaks!

Gated 4D Reconstruction

GT	3D CBCT	Gated 4D CBCT	acMoCo[1]
Ground Truth	Standard	Conventional Phase-Correlated	Artifact Model-Based Motion Compensation



1: M. Brehm, S. Sawall, J. Maier, S. Sauppe, and M. Kachelrieß. Cardiorespiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation. Med. Phys. 42(4):1948-1958, April 2015

C=-200 HU, *W*=1400 HU

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Aim

- Provide intrinsic respiratory and cardiac motion parameters for scans
  - where no external signal is available
  - or where the gating signal is corrupted
- No user input is required.

Prior Art

	Method	Respiratory Gating	Cardiac Gating	Fully Automatic	CBCT	Spiral CT
[1]	Kymogram detection	X	✓	✓	X	✓
[2]	Intrinsic gating for small animal CT	✓	✓	X	✓	X
[3]	Fully automated gating for small animal CT	✓	✓	✓	✓	X
[4,5,6]	Intrinsic respiratory gating for small animal CT	✓	X	X	✓	X

[1] Marc Kachelrieß, Dirk-Alexander Sennst, Wolfgang Maxlmoser, and Willi A Kalender. *Kymogram Detection and Kymogram-Correlated Image Reconstruction from Subsecond Spiral Computed Tomography Scans of the Heart*, Med. Phys. 29(7): 1489-1503, July 2002

[2] Dinkel J, Bartling SH, Kuntz J, Grasruck M, Kopp-Schneider A, Iwasaki M, Dimmeler S, Gupta R, Semmler W, Kauczor HU, Kiessling F. *Intrinsic gating for small-animal computed tomography: a robust ECG-less paradigm for deriving cardiac phase information and functional imaging*, Circ Cardiovasc Imaging 1(3):235-43, Nov 2008

[3] J Kuntz, J Dinkel, S Zwick, T Bäuerle, M Grasruck, F Kiessling, R Gupta, W Semmler and S H Bartling. *Fully automated intrinsic respiratory and cardiac gating for small animal CT,* PHYSICS IN MEDICINE AND BIOLOGY 55(7):2069-85, April 2010

[4] T. H. Farncombe. *Software-based respiratory gating for small animal cone-beam CT*, Med. Phys. 35, 1785, 2008

[5] Bartling S H, Dinkel J, Stiller W, Grasruck M, Madisch I, Kauczor H U, Semmler W, Gupta R and Kiessling F. *Intrinsic respiratory gating in small-animal CT,* Eur. Radiol. 18 1375-84, 2008

[6] Jicun Hu, Steve T. Haworth, Robert C. Molthen, Christopher A. Dawson. *Dynamic Small Animal Lung Imaging Via a Postacquisition Respiratory Gating Technique using Micro-Cone Beam Computed Tomography*, Academic Radiology Volume 11, Issue 9, Pages 961–970, September 2004

Prior Art

	Method	Respiratory Gating	Cardiac Gating	Fully Automatic	CBCT	Spiral CT
[7,8,9]	Local principal analysis method	✓	X	✓	✓	X
[8]	Amsterdam shroud method	✓	X	✓	✓	X
[9]	Intensity analysis method	✓	X	✓	✓	X
[10]	Fourier-transform-based phase analysis method	✓	X	✓	✓	X
[11]	Local intensity feature tracking	✓	X	✓	✓	X
	Proposed algorithm	✓	✓	✓	✓	X

[7] Zijp L, Sonke J J and Herk M. *Extraction of the Respiratory Signal from Sequential Thorax Cone-Beam x-ray Images*, Int. Conf. on the Use of Computers in Radiation Therapy, pp 507–9, 2004

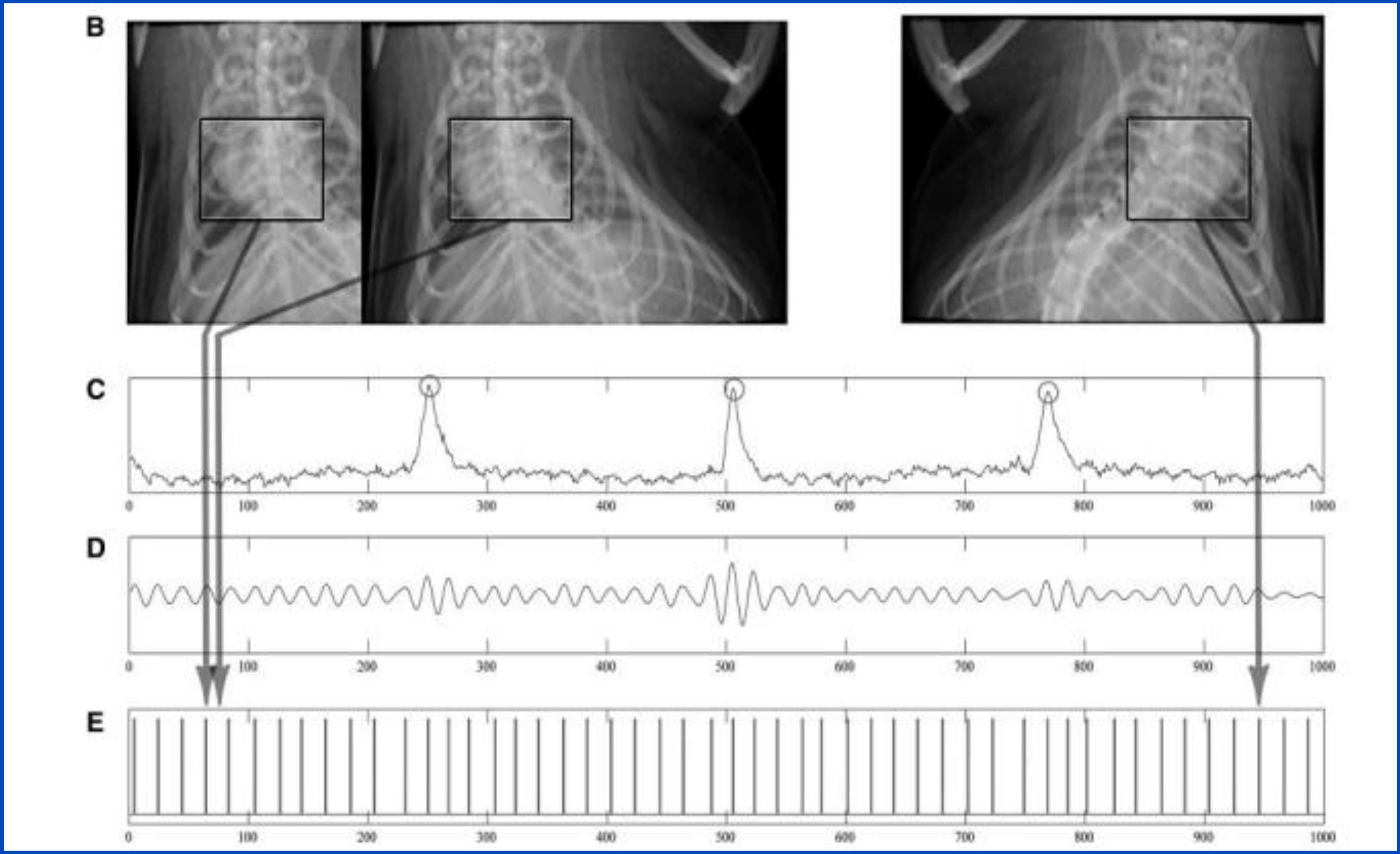
[8] Van Herk M, Zijp L, Remeijer P, Wolthaus J and Sonke J. *On-line 4D Cone Beam CT for Daily Correction of Lung Tumour Position during Hypofractionated Radiotherapy*, Proc. Int. Conf. on the Use of Computers in Radiation Therapy (ICCR 07) p 6241[9], 2007

[9] Kavanagh A, Evans P M, Hansen V N and Webb S. *Obtaining Breathing Patterns from any Sequential Thoracic X-Ray Image Set*, Phys. Med. Biol. 54 4879, 2009

[10] Vergalasova I, Cai J and Yin F. *A Novel Technique for Markerless, Self-Sorted 4D-CBCT: Feasibility Study*, Med. Phys. 39 1442, 2012

[11] Salam Dhou, Yuichi Motai, and Geoffrey D. Hugo. *Local Intensity Feature Tracking and Motion Modeling for Respiratory Signal Extraction in Cone Beam CT Projections*, IEEE Transactions on (Volume:60 , Issue: 2) Page(s): 332 – 342, 2012

Prior Art
Intrinsic Gating for Small-Animal CT[1]



1: Dinkel J, Bartling SH, Kuntz J, Grasruck M, Kopp-Schneider A, Iwasaki M, Dimmeler S, Gupta R, Semmler W, Kauczor HU, Kiessling F. *Intrinsic gating for small-animal computed tomography: a robust ECG-less paradigm for deriving cardiac phase information and functional imaging*, Circ Cardiovasc Imaging 1(3):235-43, Nov 2008

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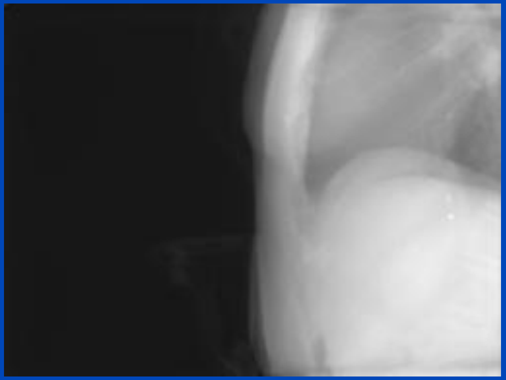
Automatic Intrinsic Gating



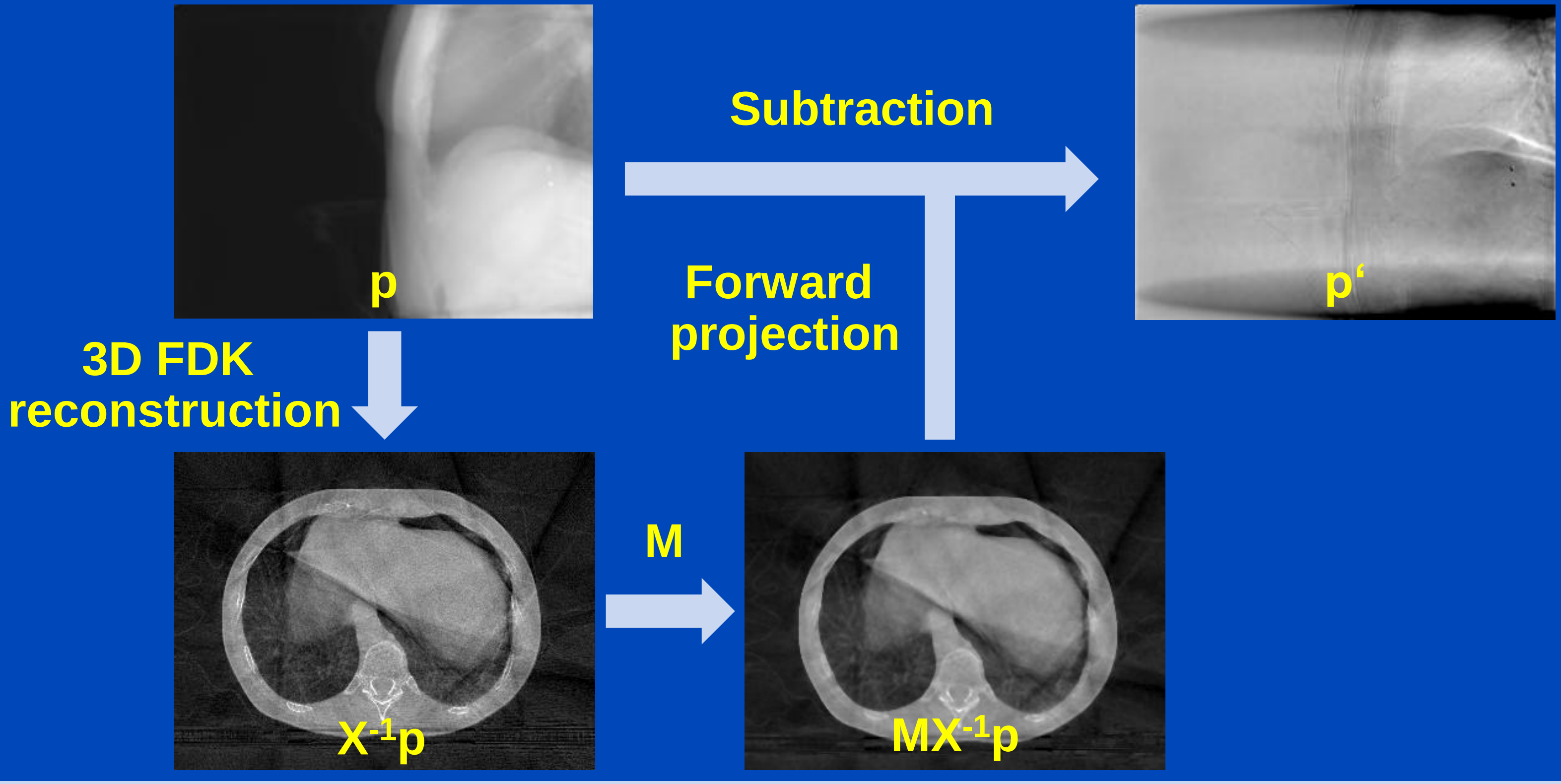
- **Idea:**
  - Rawdata-based motion estimation
  - Subtract static background to improve estimation.
  - Identify optimal ROI in projections that hold the motion information (i.e. diaphragm for respiratory phase and edge of the heart for cardiac phase).
- **Static background:**
  - Standard 3D volume still contains motion information.
  - Reduce this information by applying a 3D median filter M.
  - Forward projection of modified 3D volume contains less motion information.

Static Background

- **Rawdata used for motion estimation:**

$$p' = p - \mathsf{XMX}^{-1}p$$

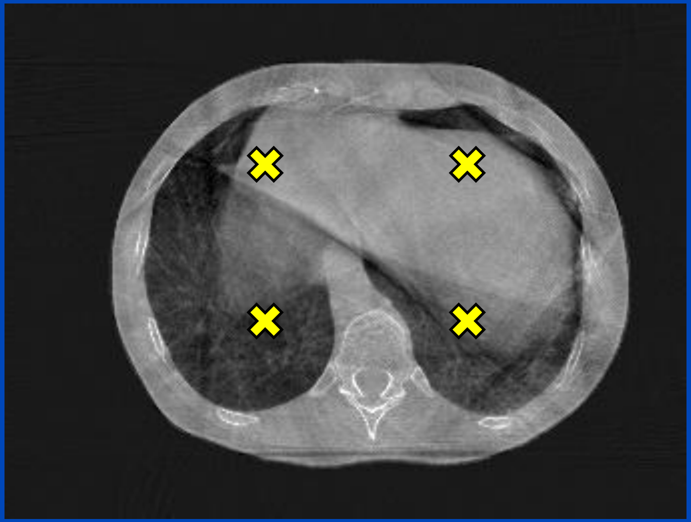
- X **is the forward projection,** X^{-1} **the backprojection,** M **the Median filter.**



Images: ***C*****=0;** ***W*****=1**

Optimal ROI Identification

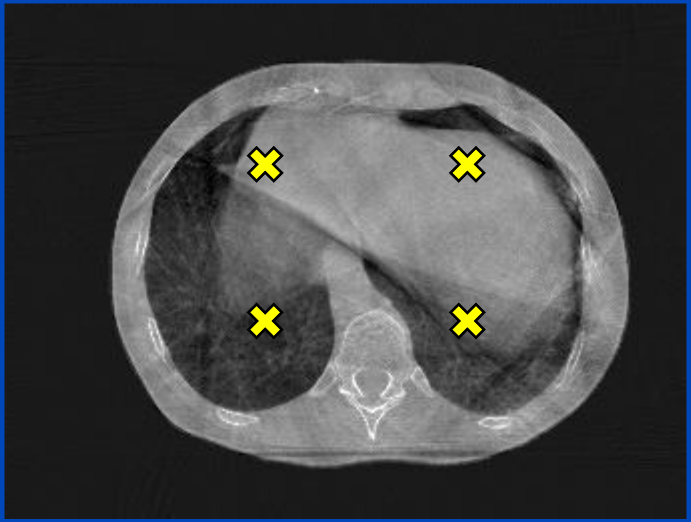
1. Define $(N_x \times N_y \times N_z)$ grid points in volume. Here: $2 \times 2 \times 2$



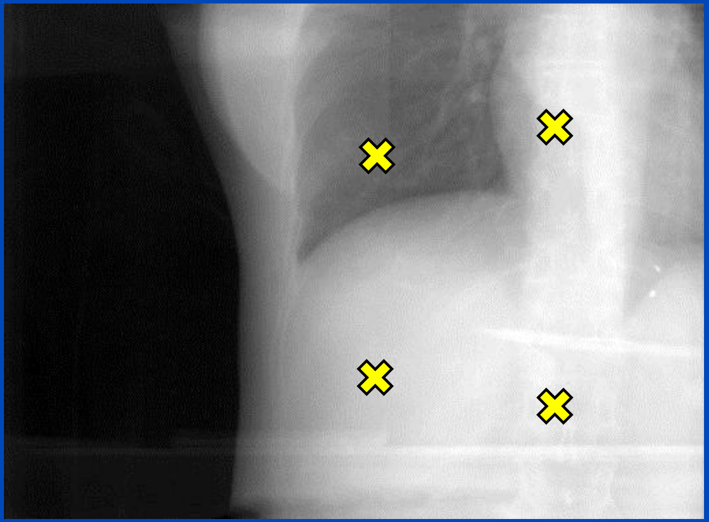
Images: *C*=0 HU; *W*=2500 HU

Optimal ROI Identification

1. Define ($N_x \times N_y \times N_z$) grid points in volume. Here: $2 \times 2 \times 2$
2. Each grid point can be traced in the rawdata after forward projection.



Forward projection



Images: *C*=0 HU; *W*=2500 HU

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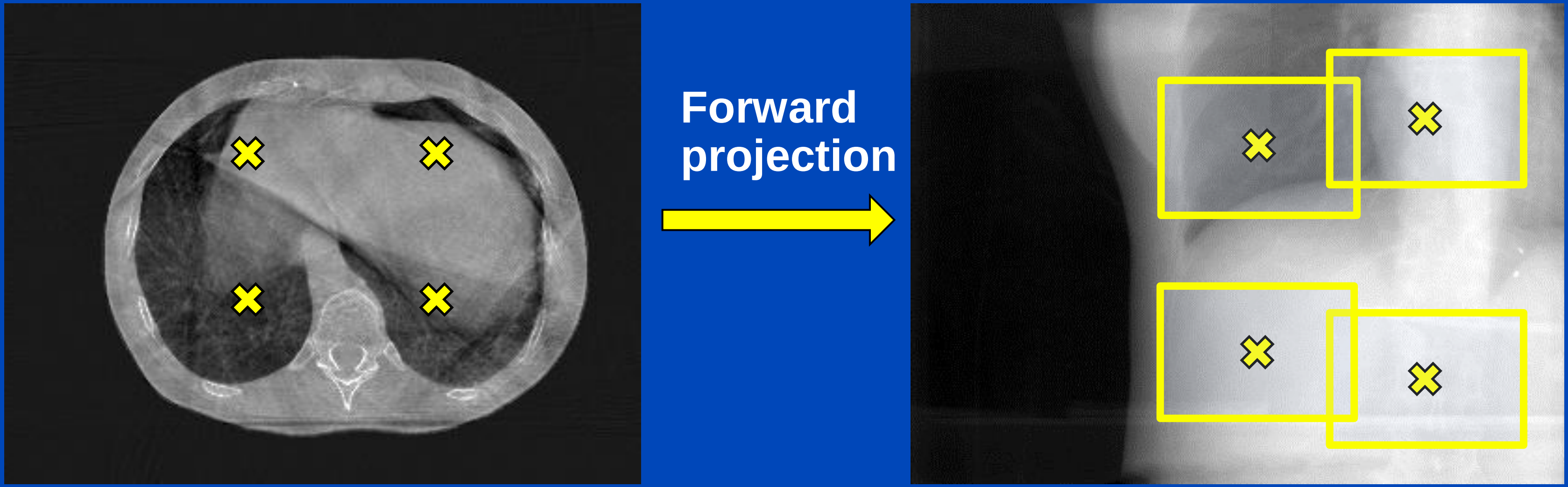
Optimal ROI Identification

1. Define ($N_x \times N_y \times N_z$) grid points in volume. Here: $2 \times 2 \times 2$
2. Each grid point can be traced in the rawdata after forward projection.
3. Create rectangular ROI around grid point in projections. ROIs for the respiratory signal have to be larger since the respiratory motion is stronger than the cardiac motion.

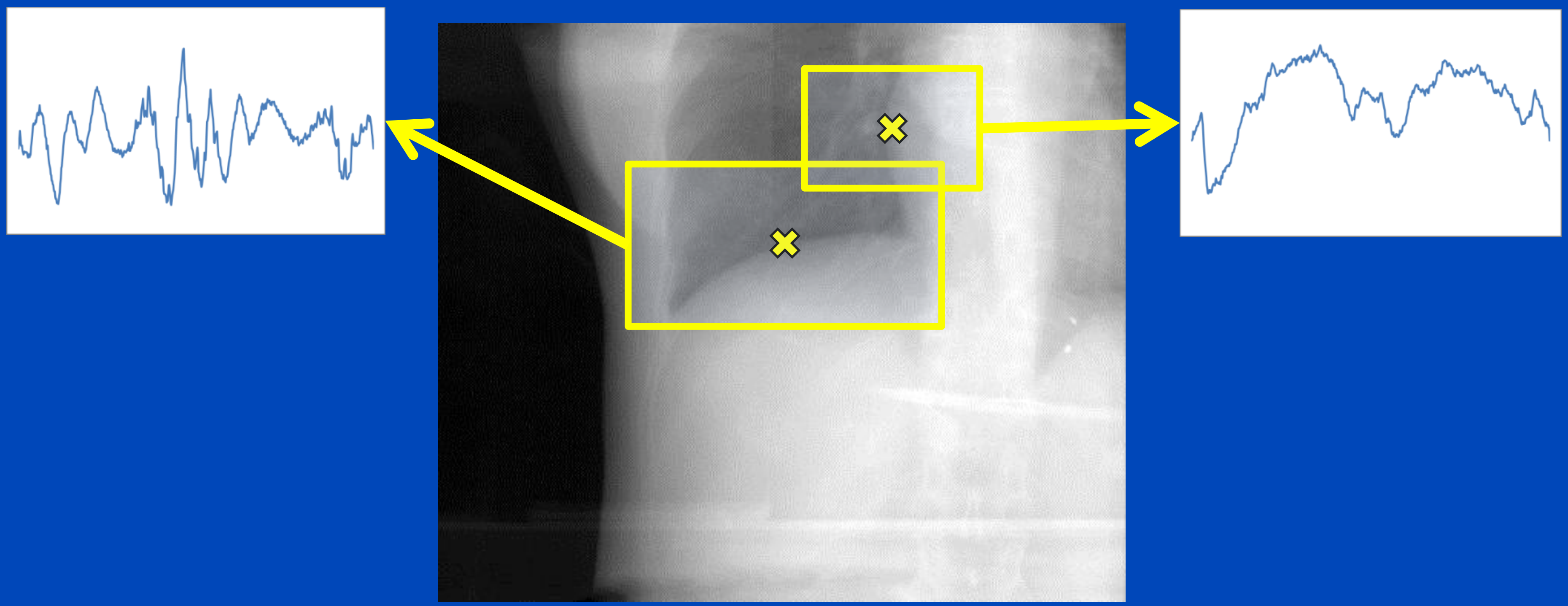


Images: *C*=0 HU; *W*=2500 HU

ROI Evaluation

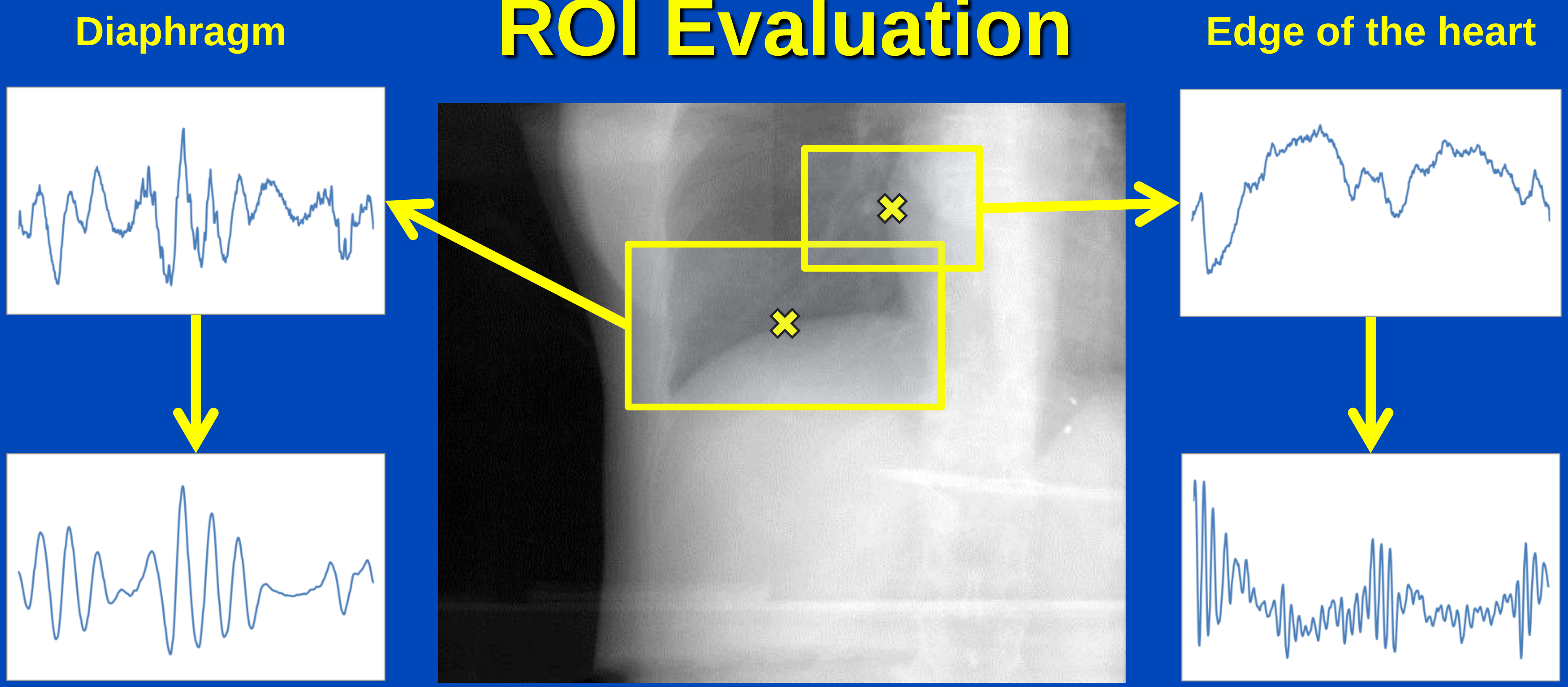
Diaphragm

Edge of the heart



1. Medium gray value in every ROI gives potential motion signal for every projection.

ROI Evaluation

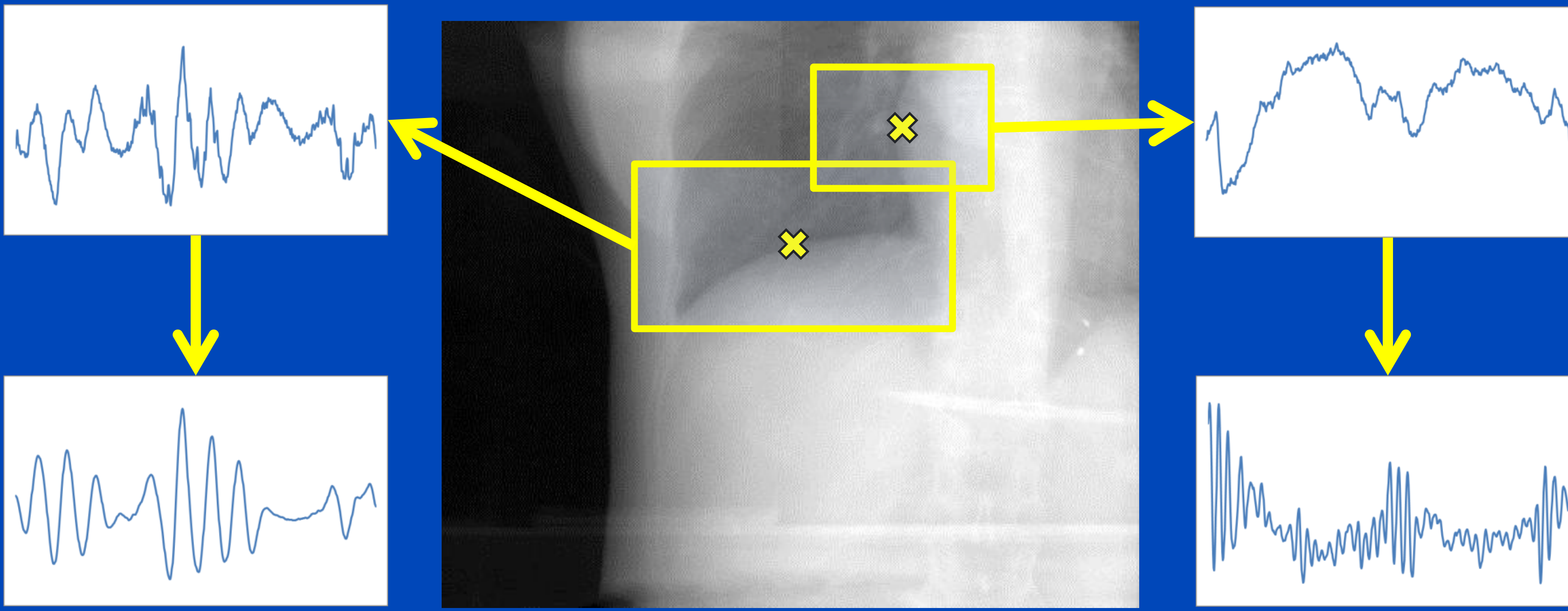


1. Medium gray value in every ROI gives potential motion signal for every projection.
2. Bandpass filter that allows between 10 and 30 rpm for respiratory or 40-120 bpm for cardiac gating.

ROI Evaluation

Diaphragm

Edge of the heart

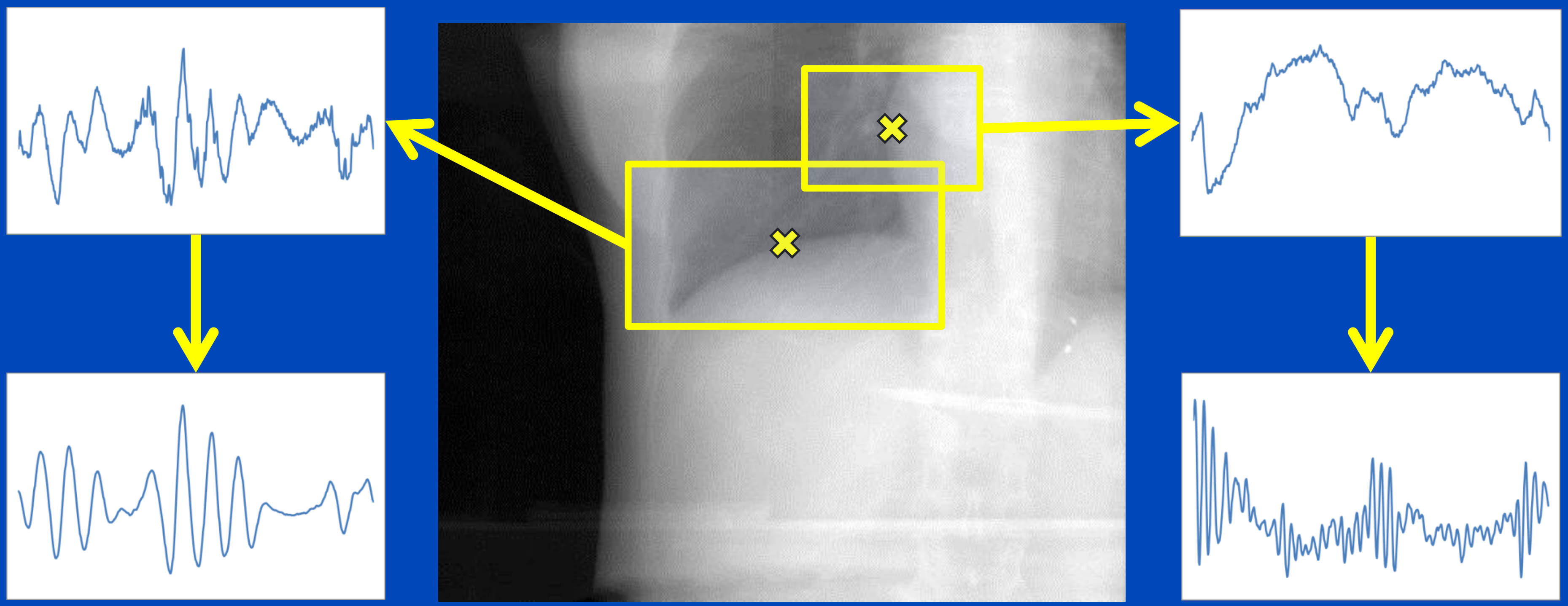


1. Medium gray value in every ROI gives potential motion signal for every projection.
2. Bandpass filter that allows between 10 and 30 rpm for respiratory or 40-120 bpm for cardiac gating.
3. Peaks are determined automatically.

ROI Evaluation

Diaphragm

Edge of the heart

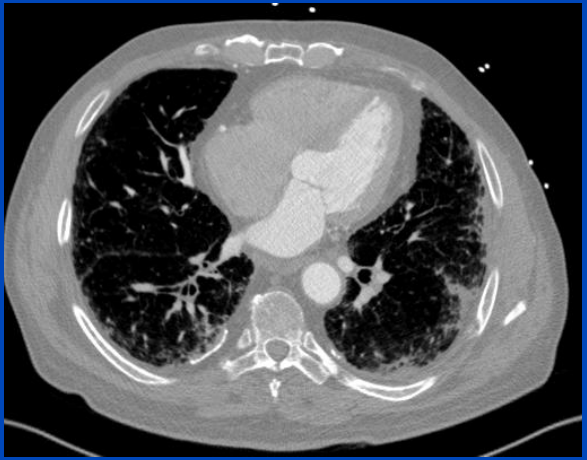


1. Medium gray value in every ROI gives potential motion signal for every projection.
2. Bandpass filter that allows between 10 and 30 rpm for respiratory or 40-120 bpm for cardiac gating.
3. Peaks are determined automatically.
4. ROI with most regular peaks distance is chosen as resulting signal.

RESULTS

Cardiac Simulation
Setup

- **Ground truth:**
  - **Thorax volume for 20 different, overlapping heart phases scanned with Siemens SOMATOM Force**
  - **Artifical phase signal for 60/90/120 bpm**
  - **Rawdata: Forward projection of respective volume**
  - **650 projections → 90.90 ms per projection**
  - **Detector: 1024 × 768 pixels**
- **Grid points to find best ROI: 12 × 12 × 10**
- **Contrast agent**



***C*=-100 HU, *W*=1500 HU**

Cardiac Simulation
Results

- **Difference *Δp* of intrinsically determined phase signal p_{intr} and the ground truth p_{GT} is calculated.**

$$\Delta p = \sum_{n=1}^{N} \left(p_{\text{GT}}(n) - p_{\text{intr}}(n)\right)$$

- **Standard deviation *σ* of *Δp* is a measure of the error of the result.**
- **The error can also be expressed as a temporal error $t = \sigma / f_H$ or a number of projections $N = t$ / (90.90 ms).**

Cardiac Simulation
Results

- Comparison to intrinsic gating for small animal CT[1].
- Both algorithms managed to find all peaks for 60 and 90 bpm.
- New algorithm yields better results. And it is fully automatic. And it can find respiratory and cardiac motion.

	f_H	f_{intr}	Error in σ	Error in t	Error in Projections
Proposed algorithm	60 bpm	60 bpm	3.66 %	36.63 ms	0.40
Small animal gating	60 bpm	60 bpm	4.95 %	49.50 ms	0.54
Proposed algorithm	90 bpm	90 bpm	5.83 %	38.89 ms	0.42
Small animal gating	90 bpm	90 bpm	6.41 %	42.73 ms	0.47
Proposed algorithm	120 bpm	120 bpm	7.20 %	36.00 ms	0.39
Small animal gating	120 bpm	118 bpm	10.13 %	50.65 ms	0.56

1: Dinkel J, Bartling SH, Kuntz J, Grasruck M, Kopp-Schneider A, Iwasaki M, Dimmeler S, Gupta R, Semmler W, Kauczor HU, Kiessling F. *Intrinsic gating for small-animal computed tomography: a robust ECG-less paradigm for deriving cardiac phase information and functional imaging*, Circ Cardiovasc Imaging 1(3):235-43, Nov 2008

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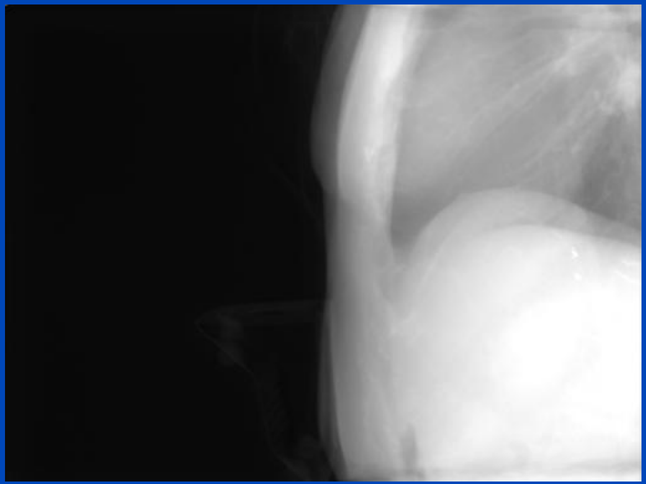
Patient Data

- 60 s scan time with Varian TrueBeam
- 650 projections
- Detector: 1024 $\times$ 768 pixels
- No contrast agent
- Ground truth:
  - External respiration signal available
  - Cardiac signal from manual evaluation of projections
- Grid points to find best ROI : 4 $\times$ 4 $\times$ 4 and 12 $\times$ 12 $\times$ 10 for respiratory and cardiac gating respectively



C=3.5, *W*=7

Patient Data
Results

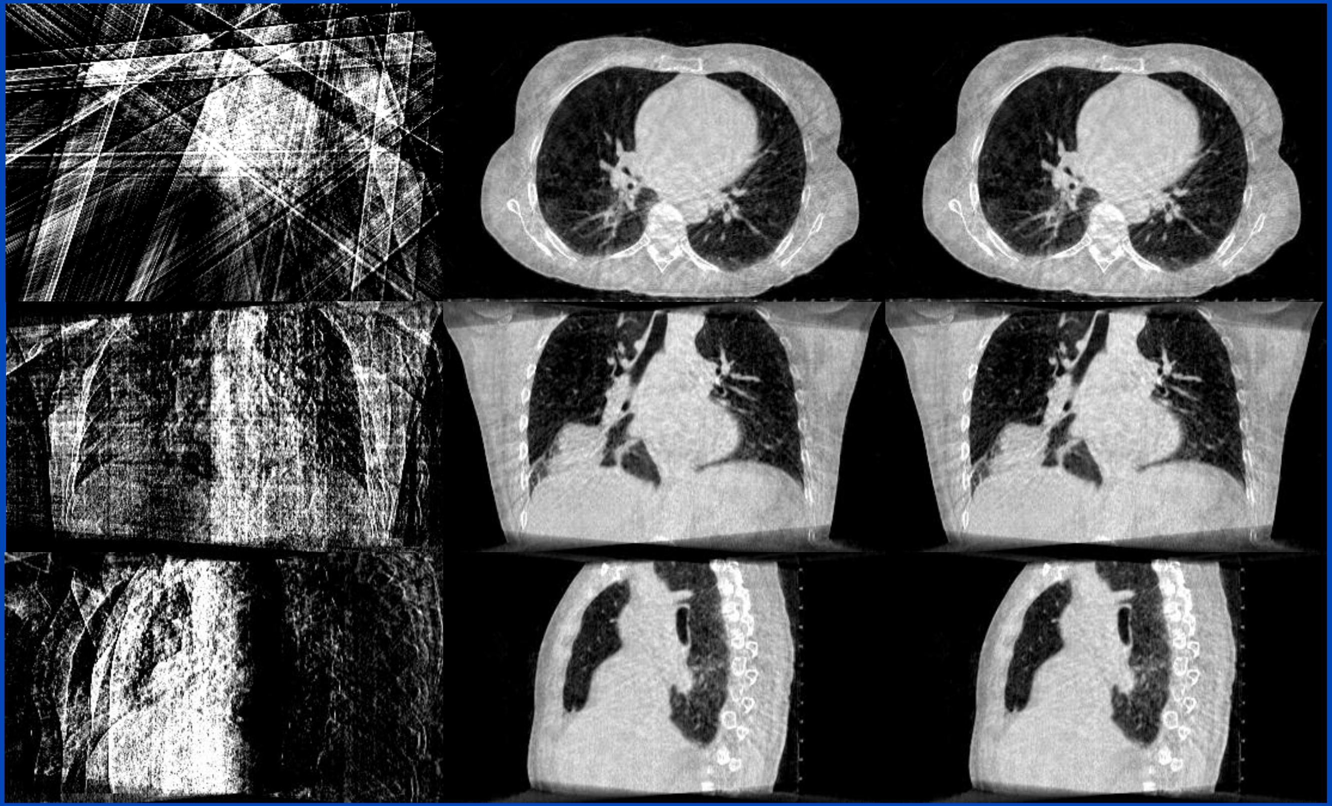
- **New algorithm performs better for both respiratory and cardiac gating. And it is fully automatic.**

	f_R or f_H	f_{intr}	Error in σ	Error in t	Error in Projections
Proposed algorithm	11 rpm	11 rpm	3.30 %	180.36 ms	1.98
Small animal gating	11 rpm	11 rpm	3.60 %	196.36 ms	2.13
Proposed algorithm	51 bpm	51 bpm	11.20 %	131.76 ms	1.43
Small animal gating	51 bpm	57 bpm	25.49 %	299.88 ms	3.30

5D MoCo Results[1]

20 respiratory phases of 10% width, 10 cardiac phases of 20% width

5D Reconstruction Respiratory & Cardiac Gated	**5D MoCo** Respiratory & Cardiac Compensated	**5D MoCo** Respiratory & Cardiac Compensated
r **= 0%,** ***c*****-loop**	***r*** **= 0%,** ***c*****-loop**	**r-loop,** ***c*** **= 0%**



2% dose usage	**100% dose usage**	**100% dose usage**

1: Sebastian Sauppe, Andreas Hahn, Marcus Brehm, Pascal Paysan, Dieter Seghers, and Marc Kachelrieß. Respiratory and Cardiac Motion-Compensated 5D Cone-Beam CT of the Thorax Region, SPIE Medical Imaging 2016

C = -250 HU, *W* = 1400 HU

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Conclusions

- The algorithm is suited to obtain a respiratory and cardiac phase signal where no external signal is given.
- It is fully automatical.
- More patients have to be evaluated to assess the robustness of the algorithm.

Thank You!

This presentation will soon be available at www.dkfz.de/ct. **The study was supported by the Deutsche Forschungsgesellschaft (DFG) under grant No. KA-1678/13-1. Parts of the simulation and reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.**