Computer Aided Medical Procedures

Automatic Detection of Non-Biological Artifacts in ECGs Acquired During Cardiac Computed Tomography

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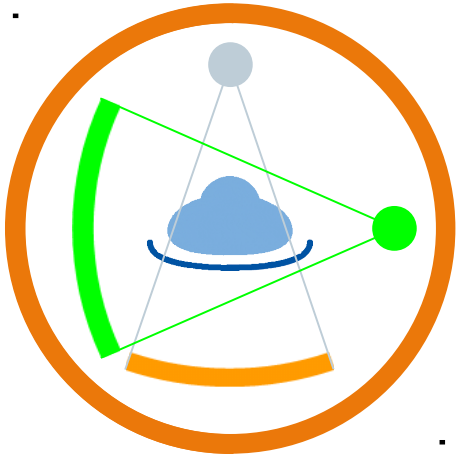
Background: Cardiac CT

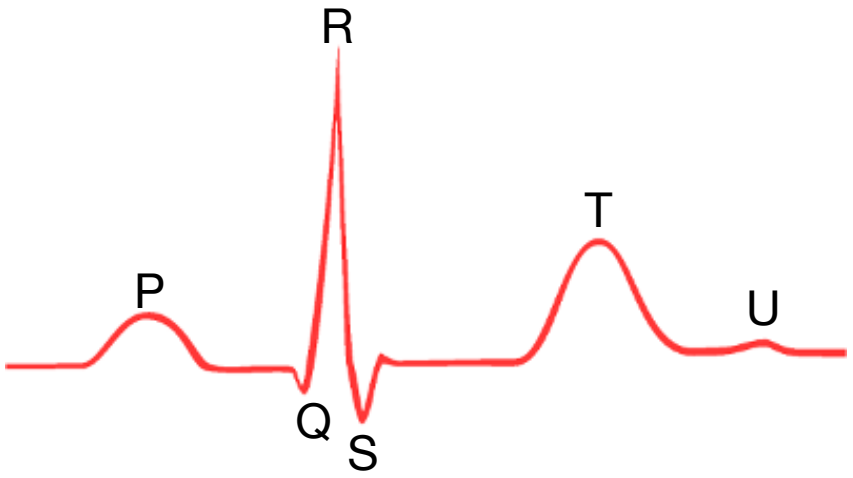
- Cardiac computed tomography (CT) is a non-invasive technique to image the beating heart
- To ensure sharp motion-free images, **multiple X-ray projections** need to be taken **at the same cardiac phase**
- One of the main concerns during the procedure is the **total radiation dose** imposed on the patient
- **Trade-off**: image quality vs. total radiation exposure



Background: Prospective ECG Gating

- Radiation is only applied during the target cardiac phase[1]
- Uses electrocardiogram (ECG) to determine when to activate X-ray
- **Predicts upcoming R peaks**

- The cardiac cycle:



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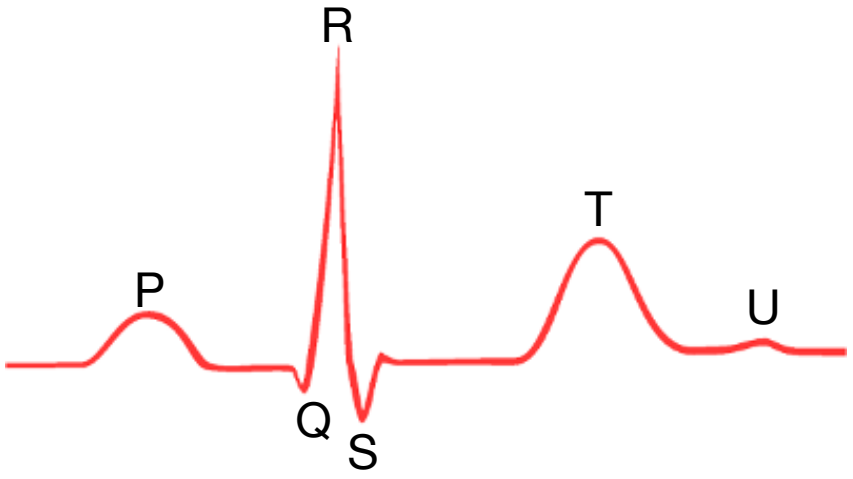

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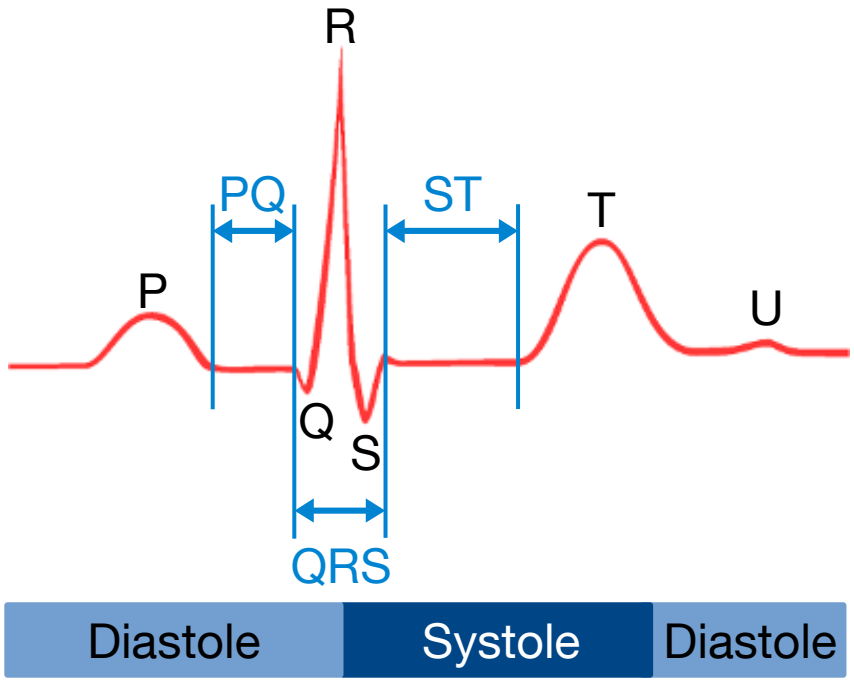

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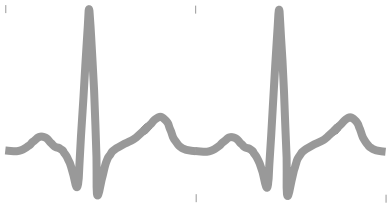

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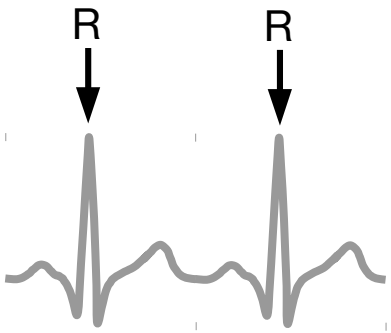

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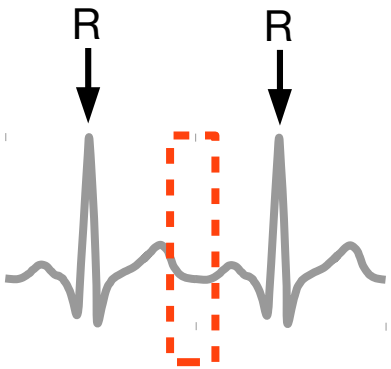

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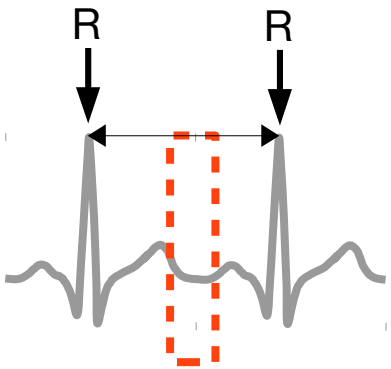

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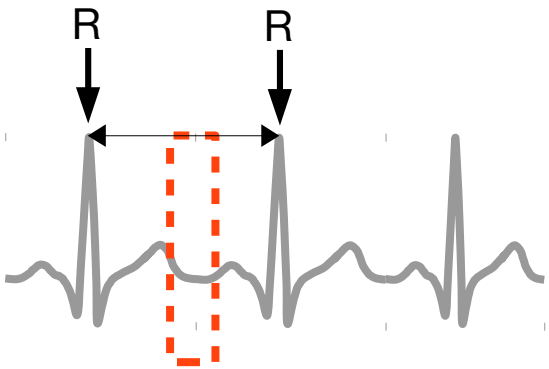

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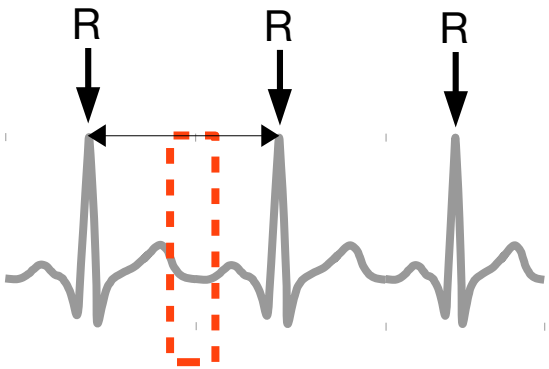

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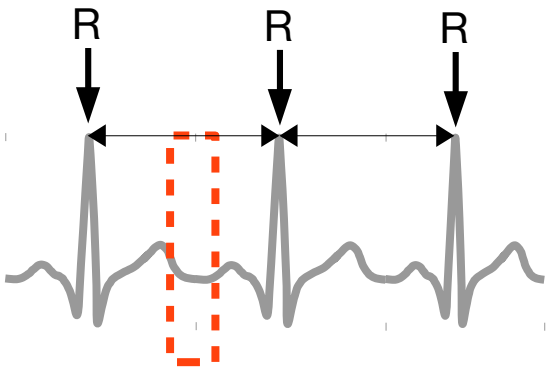

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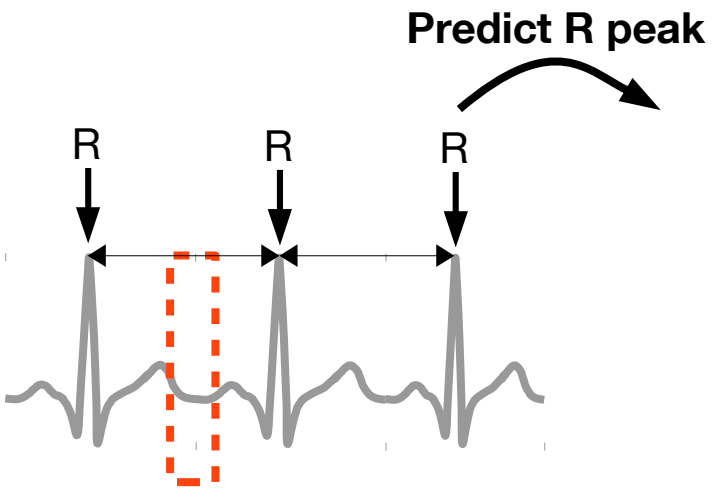

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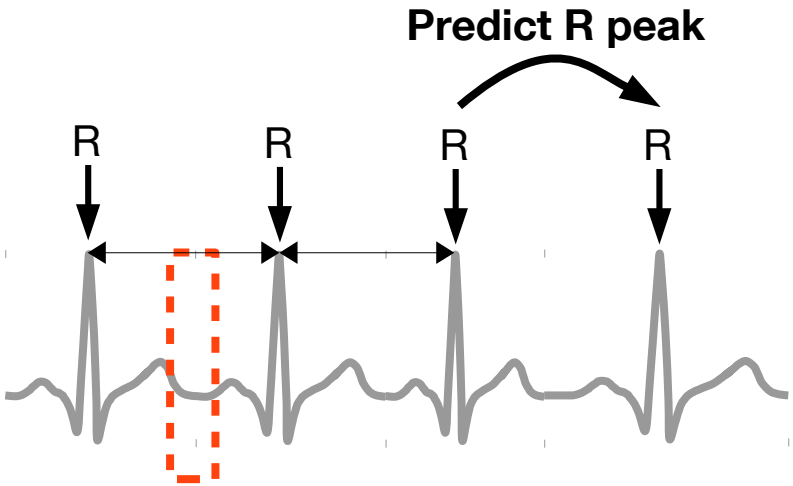

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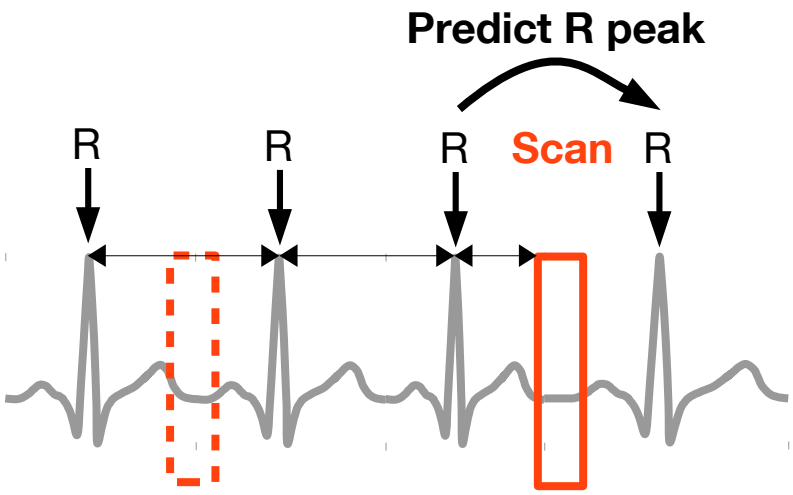

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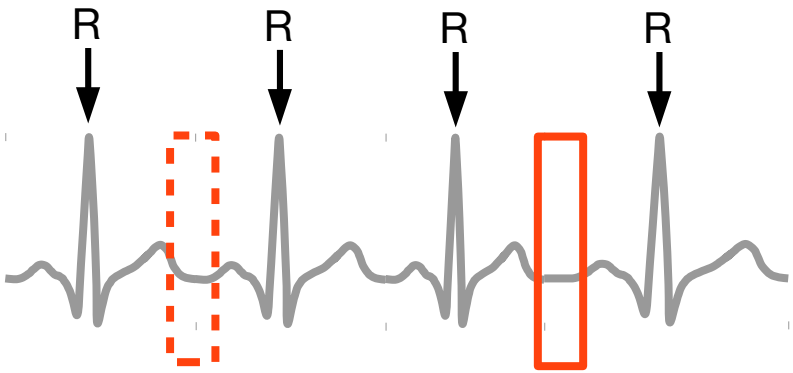

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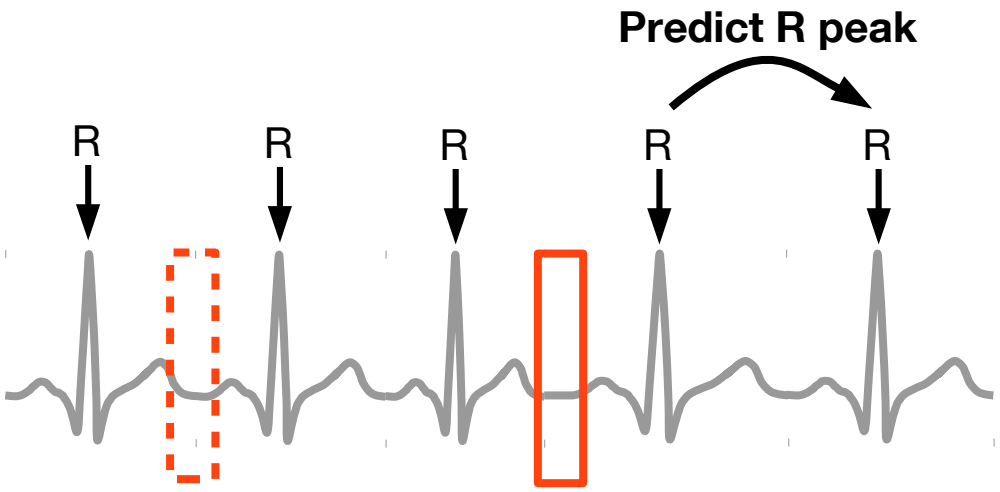

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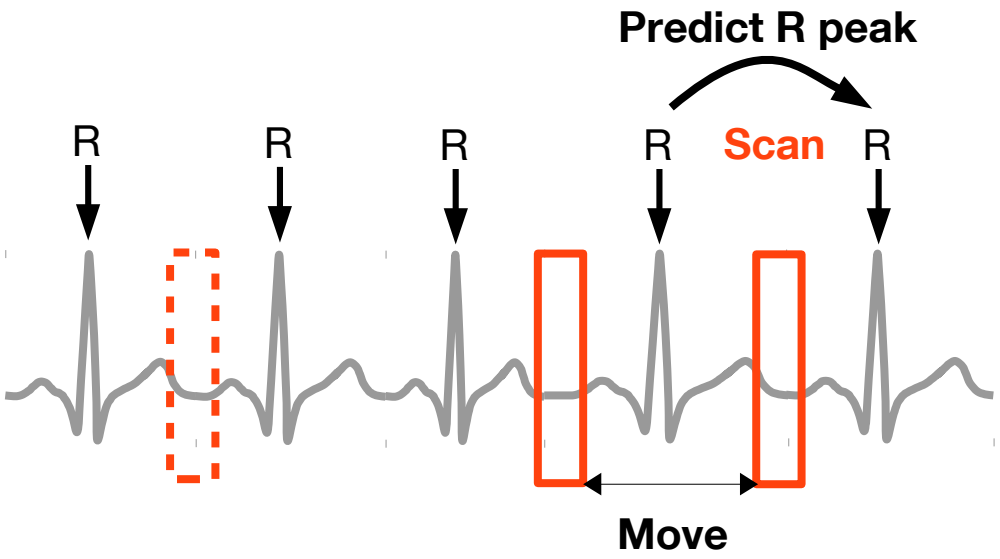

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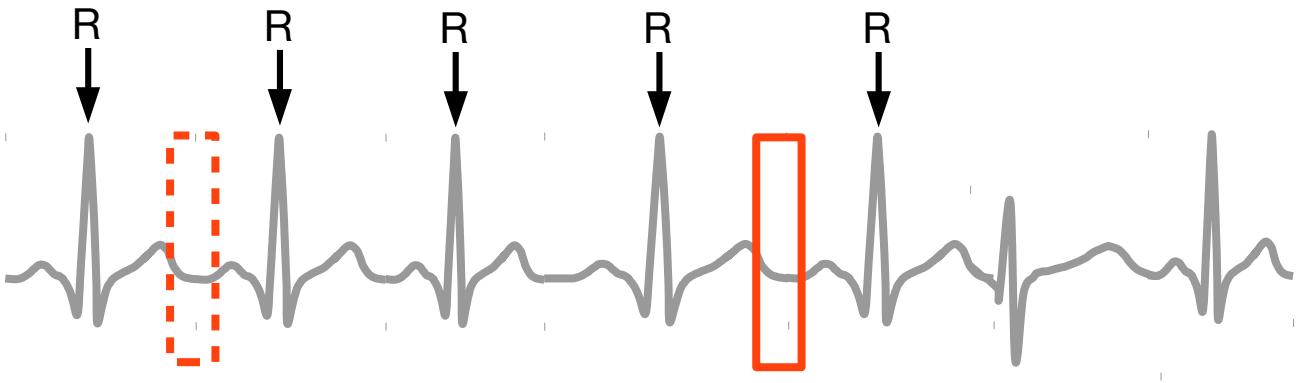

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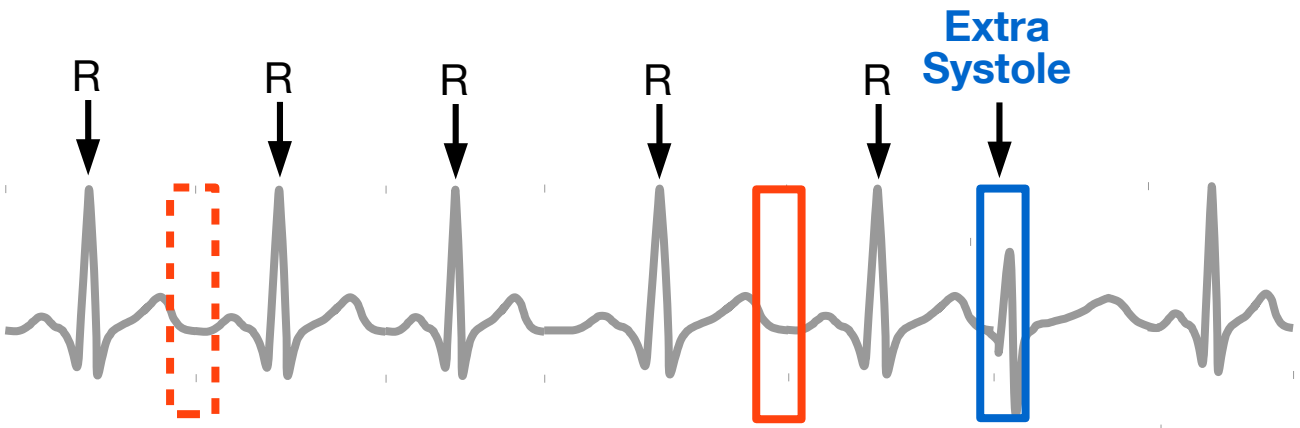

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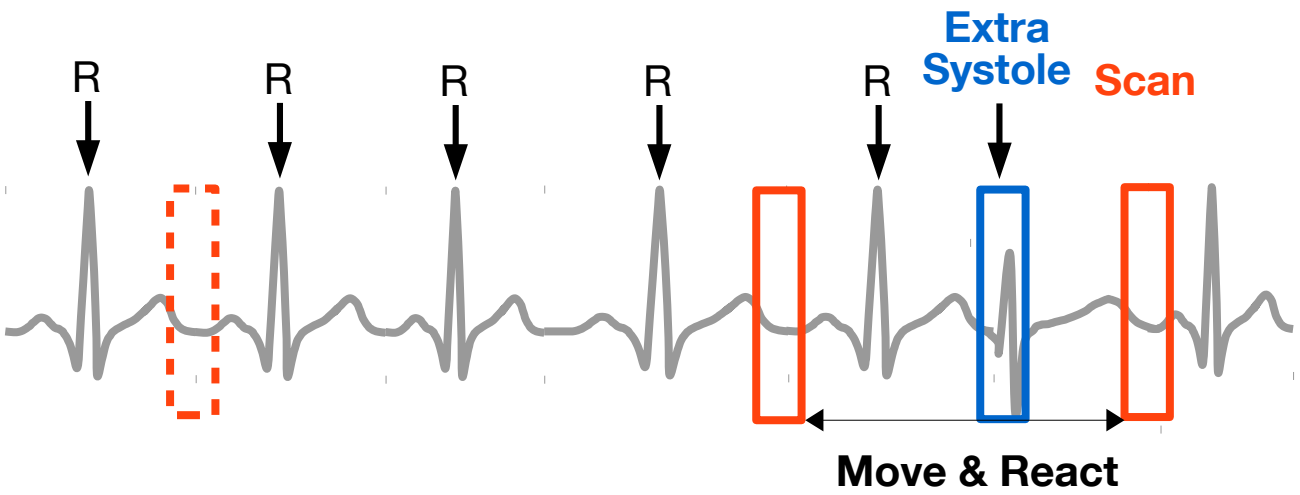

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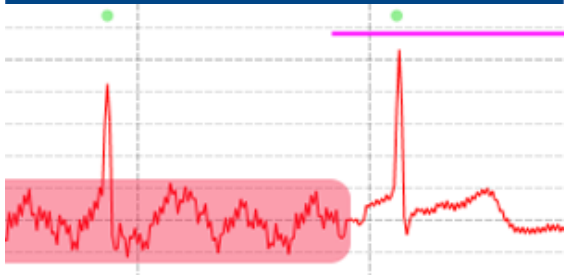
Problem Statement

- Prospective ECG gating relies on correct detection of R peaks
- Noise or **non-biological artifacts** in the ECG signal may **result in false positive R peaks**
- May desynchronize the whole workflow and result in a **low quality image** and the need for a **repeat scan**
- ECG signals are highly heterogeneous:
  - 1 lead in contrast to 12 leads commonly used for clinical diagnosis
  - Different equipment used
  - Different physicians performing the scan
  - Different technical and professional standards among countries
  - Patients with different medical conditions

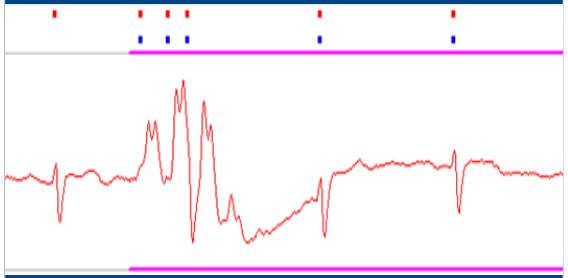
Non-Biological Artifacts in ECG (1)

Rotational Noise



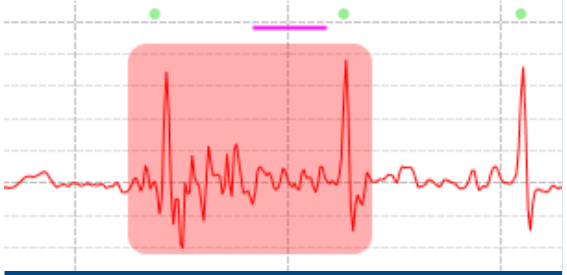
- Electrostatic charges close to the patient generate a fake signal due to the gantry rotation
- Noise is eliminated once the X-ray source is activated

X-ray



- Usually due to an X-ray beam hitting a piece of metal (e.g. if electrodes have been moved inside the scan area)

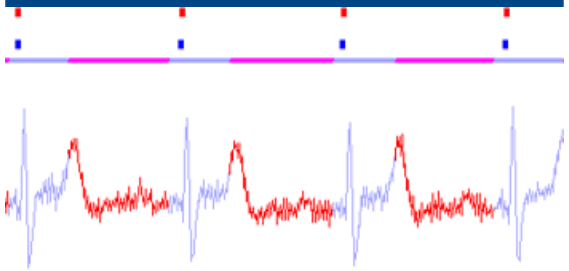
Table Motion



- High-frequency disturbances after the table starts moving due to patient movement or improper wiring of the electrodes

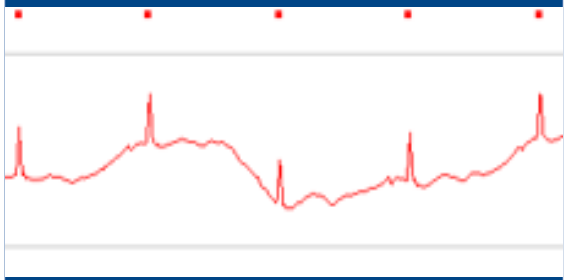
Non-Biological Artifacts in ECG (2)

Powerline



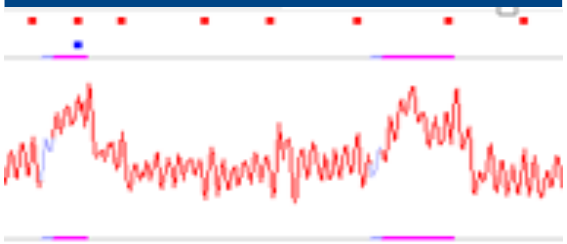
- Interference in the 50/60Hz frequency band due to an external power supply

Baseline Wandering



- Respiratory noise
- Movement artifacts
- Unreliable electrode connection
- …

Other



- Noise of unknown origin

Objective

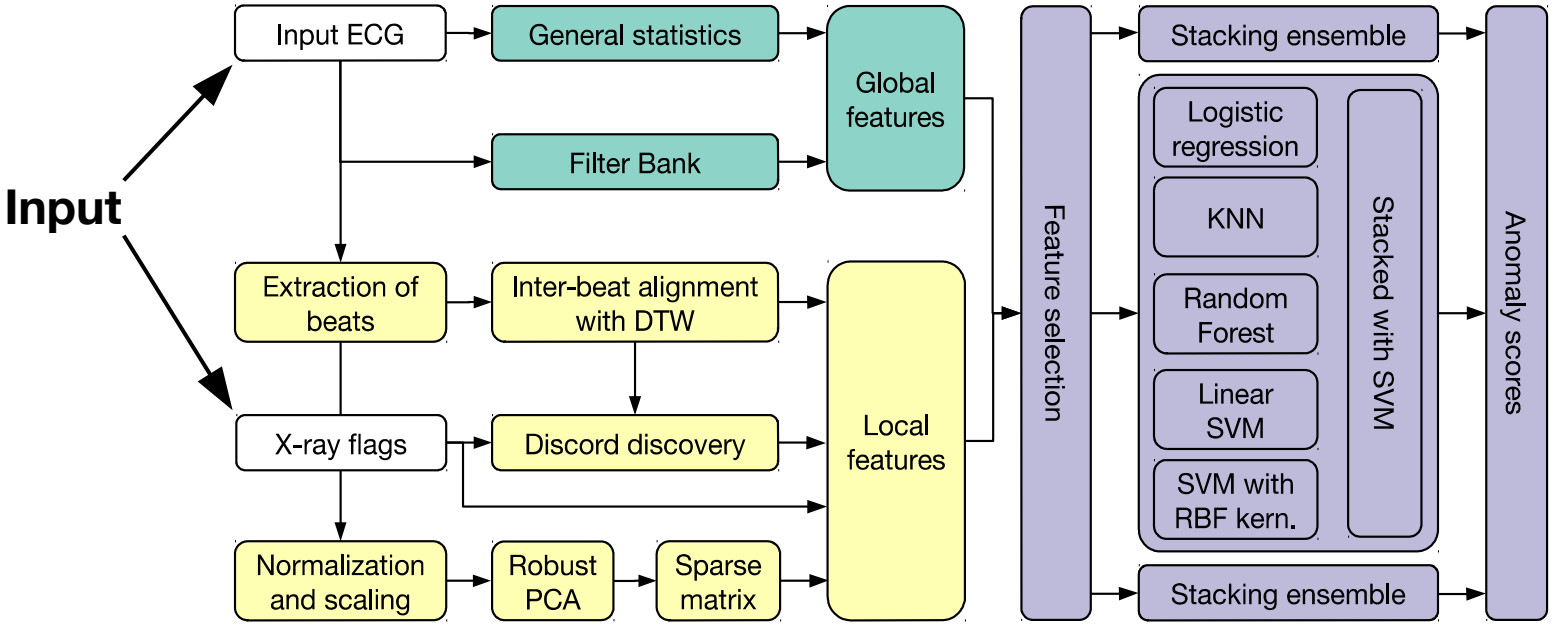
Identify cardiac CT scanners producing a high amount of anomalous **ECG traces containing non-biological artifacts**

Traditional ECG Analysis

- **Traditional ECG analysis** relies on standard ECG features (PQ and ST segment, QRS complex, …), e.g. for
  - clinical diagnosis: robustness w.r.t. the natural variability of ECG waveforms and heart rhythms
  - human identification: robustness w.r.t. variations across multiple measurements
- **Here**: The source of **noise patterns** is almost always **independent from the individual** and his/her heartbeat characteristics:

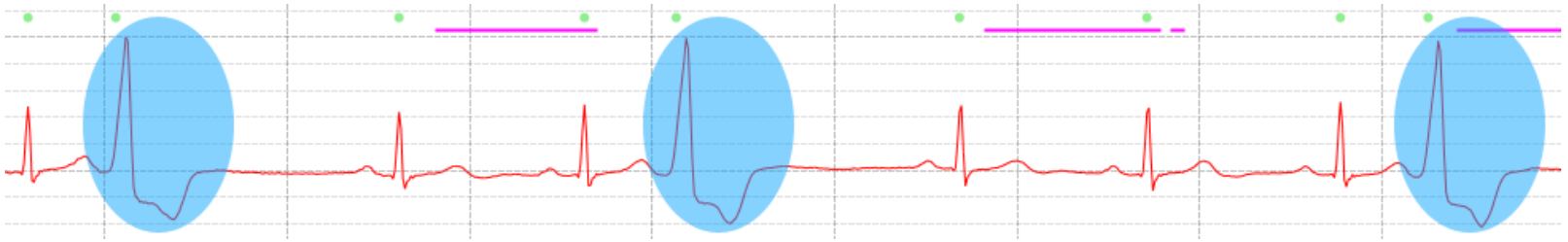
  robustness to variations across CT scanners, imaging protocols, and individuals and their diseases

Overview



- **Localized noise patterns**: Affect the ECG signal only within certain, relatively short, time intervals
- **Global noise patterns**: Tend to contaminate the whole signal (*not discussed in this talk*)

Localized Noise Patterns



- **Artifacts of biological origin** usually occur during specific cardiac phases and **repeat themselves over time**
- A **technological anomaly** occurs **independent of** a **specific cardiac phase,** and **rarely more than once** in the same ECG trace, i.e., it is an outlier
- In severe cases, if R peak detection fails, we observe two consecutive beats with an unusual morphology

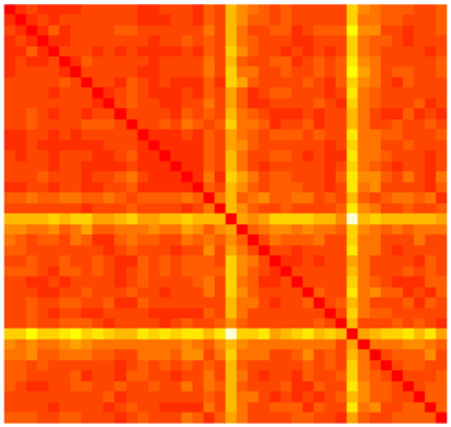
Solution: Localized Noise Patterns

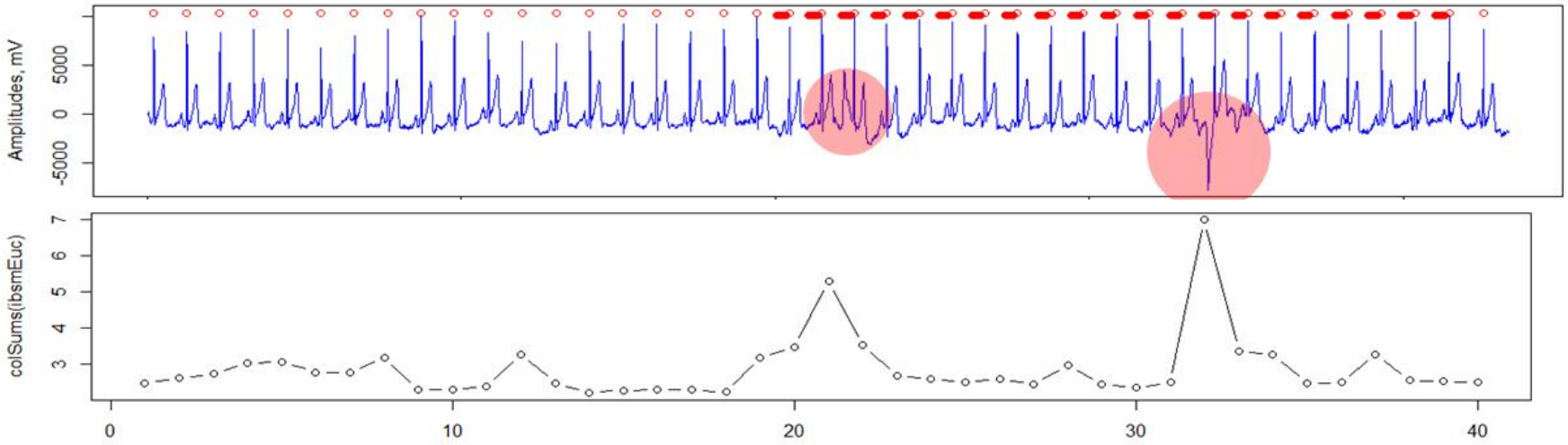
- **Discord beat discovery**:[2]
  - Finds the most unusual cardiac cycle within an ECG signal
- **Robust PCA**:[3]
  - Very precise localization of an anomaly at the sub-beat level
  - Allows extracting anomalous structures and reconstructing the “true”, noise-free signal

2. Keogh et al.: Hot SAX: Efficiently finding the most unusual time series subsequence. In: 5th IEEE Int Conf Data Min. pp. 226–233. (2005)
3. Candes et al.: Robust principal component analysis? Journal of the ACM 58(3) (2011)

Discord Beat Discovery

- Split ECG signal into distinct cardiac cycles and compare ECG waveforms using dynamic time warping[4]

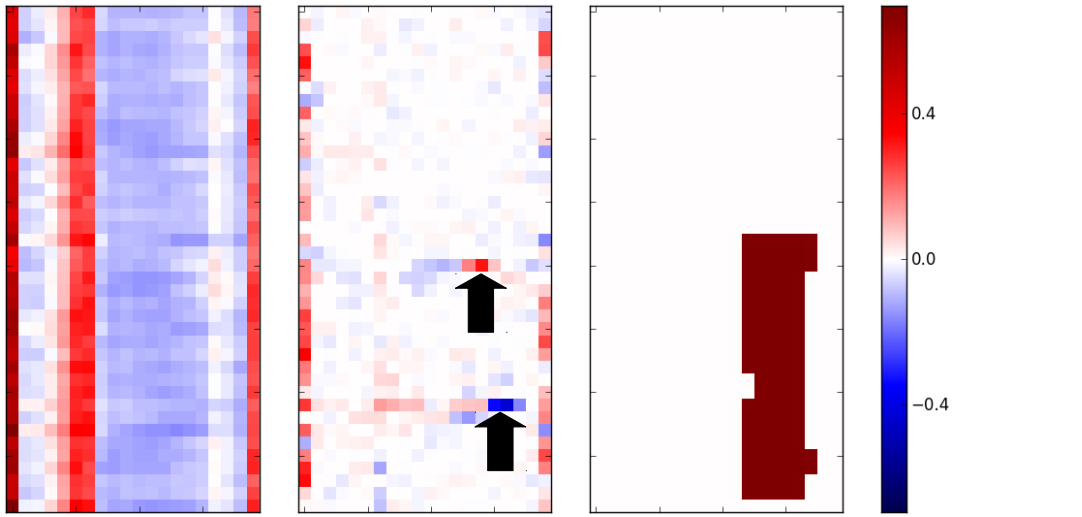




4. Vintsyuk: Speech discrimination by dynamic programming. Cybern Syst Anal 4(1), 52–57 (1968)

Robust PCA

- Particularly useful to detect X-ray artifacts
- Construct matrix *X*, where each row corresponds to a cardiac cycle in the same ECG trace
- Solve $\min_{L,S} \quad \|L\|_* + \lambda\|S\|_1 \qquad \text{subject to} \quad L + S = X$



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Ensemble of Classifiers

- After feature extraction, we obtain 181 features describing local and global noise patterns
- Remove redundant and irrelevant features based on feature importance retrieved from a random forest[7]
- Aggregate predictions of multiple classifiers via *stacking* to reduce the bias of the overall system[8]
- Ensemble ought to quantify the overall extent of noise in a given ECG trace

7. Breiman: Random forests. Mach Learn 45(1), 5–32 (2001)
8. Wolpert, D.: Stacked generalization. Neural Netw 5(2), 241–260 (1992)

10-fold Cross-Validation Results

- Data consisted of 2,581 cardiac CT scans (501 with global noise, 391 with localized noise) from 60 medical centers from 18 countries
- Many corrupted ECG signals are subject to multiple artifacts
- A corrupted ECG should not be missed: prefer higher recall over precision

Metric	SVM	RF	Ensemble
mean AUROC	0.996	**0.997**	**0.997**
mean AUPRC	0.993	0.994	**0.996**
mean accuracy	0.973	0.978	**0.983**
mean precision	0.964	0.979	**0.985**
mean recall	0.952	0.954	**0.964**

Acc., prec., and recall have been computed at a threshold of 0.6

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External Validation (1)

- Train system on 2,581 ECG signal used for cross-validation
- Two domain experts independently annotated 150 unseen ECG signals
- Annotations on 5 level Likert scale (1: no artifact, 5: extremely corrupted)
- Inter-expert agreement was high (Kendall's coefficient of concordance $W = 0.938$)

		Expert 1				
		1	**2**	**3**	**4**	**5**
Expert 2	**1**	32	21			
	2		23	11	3	
	3		4	23	6	
	4			3	12	
	5				5	7

External Validation (2)

	Expert 1	Expert 2	Combined
AUPRC	0.875	0.905	
AUROC	0.898	0.942	
Kendall's W	0.859	0.896	0.863

AUPRC and AUROC have been computed at a threshold of 0.6, where levels 3-5 of experts' annotations were considered as positive class

External Validation (3)

		Expert 1					Expert 2				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Predicted	**1**	27	32	6	1		45	19	2		
	2	3	5	7			5	5	5		
	3		5	4				6	3		
	4		2	3	5			5	3	1	1
	5	2	4	17	20	7	3	2	20	14	11

Predicted probabilities have been discretized into 5 equal-sized bins.

External Validation (3)

		Expert 1					Expert 2				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Predicted	**1**	27	32	6	1		45	19	2		
	2	3	5	7			5	5	5		
	3		5	4				6	3		
	4		2	3	5			5	3	1	1
	5	2	4	17	20	7	3	2	20	14	11

Probabilities are badly calibrated

Predicted probabilities have been discretized into 5 equal-sized bins.

Conclusion

- We presented a system to automatically detect various non-biological anomalies in ECG signals acquired during cardiac CT
- The results demonstrate that our system is highly discriminatory and allows processing thousands of ECGs with minimal human interaction
- Our system is currently deployed at Siemens Healthcare, where it continuously analyzes cardiac CT scans collected from various medical centers all around the world

Thanks for your attention!

Questions?