An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram

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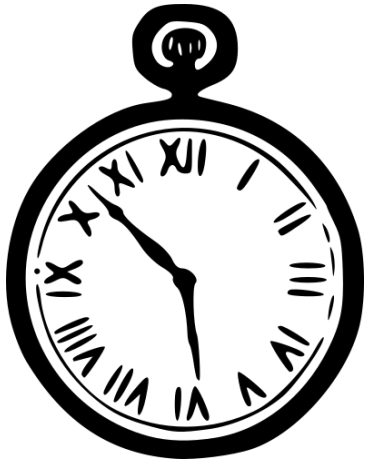
Clinical Need

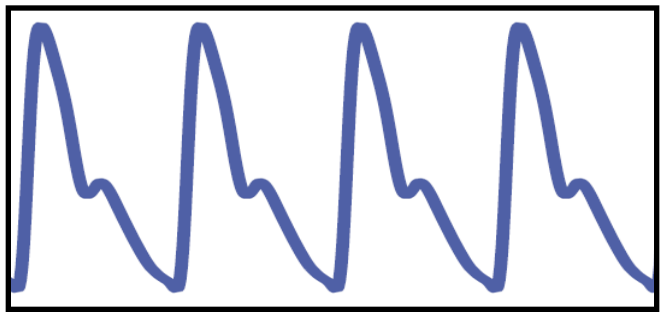
Respiratory Rate

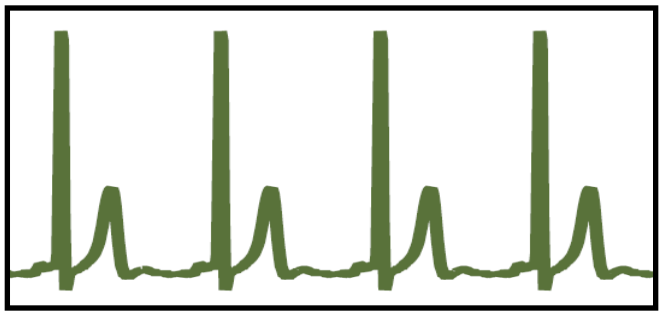
- Physiological state
- Marker of deterioration
- Hospital, home and community



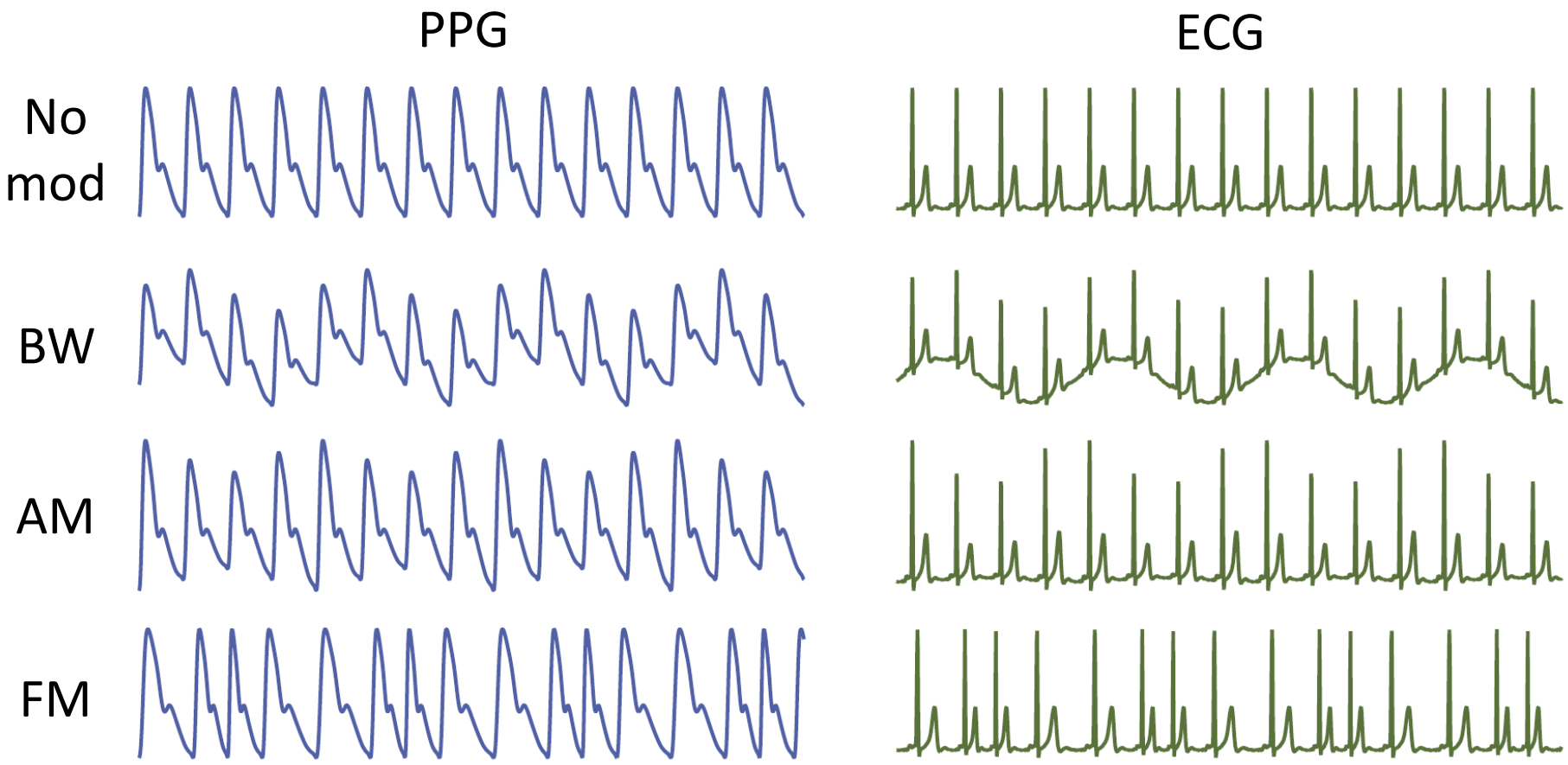
Wearable Sensors

- Few monitor RR
- Chest bands
- Accelerometers
- PPG and ECG





PPG and ECG



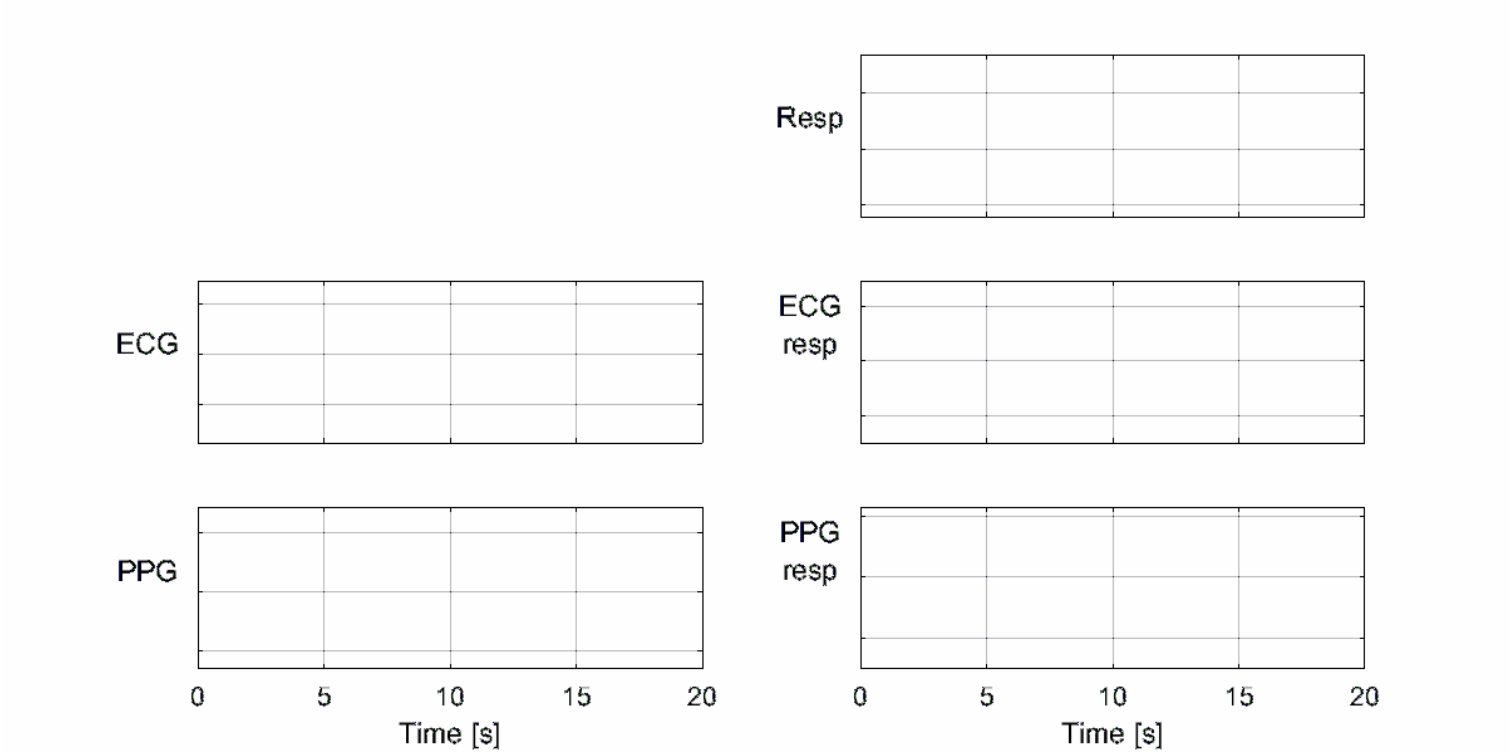
Literature

- Over 100 RR algorithms
- Performances not compared
- Limitations:
  - Different statistical measures
  - Small sample sizes
  - Repeated measures
  - No standard implementations
  - Ventilated subjects
- Which algorithm, if any, is suitable?

Aims

Primary Aim

Determine how closely algorithms agree with a gold standard reference RR under ideal conditions



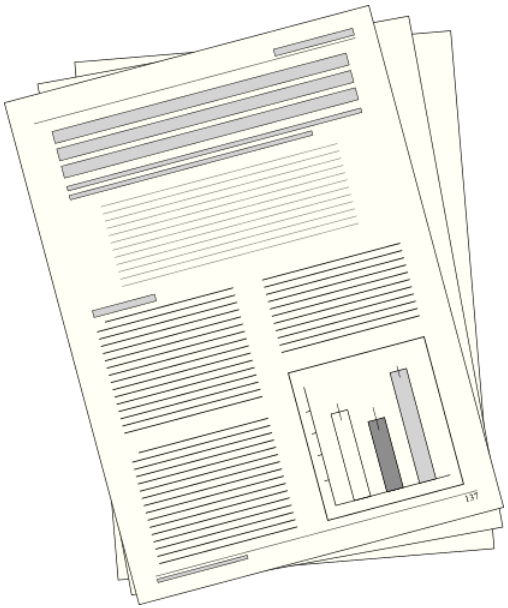
Secondary Aims

Compare performance to impedance pneumography

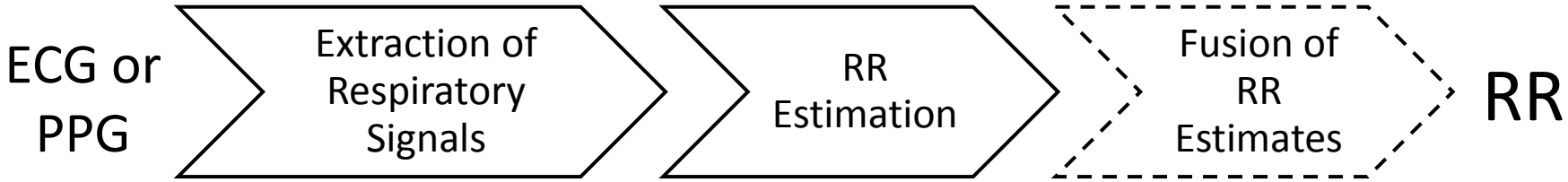
Compare performance when using ECG or PPG

Provide a toolbox of algorithms and data

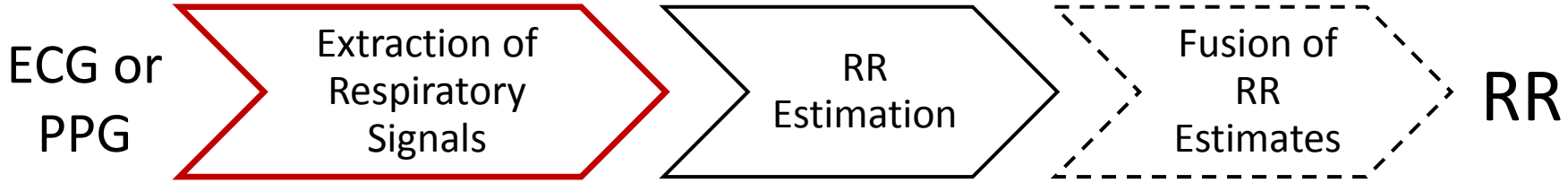
Prior Work

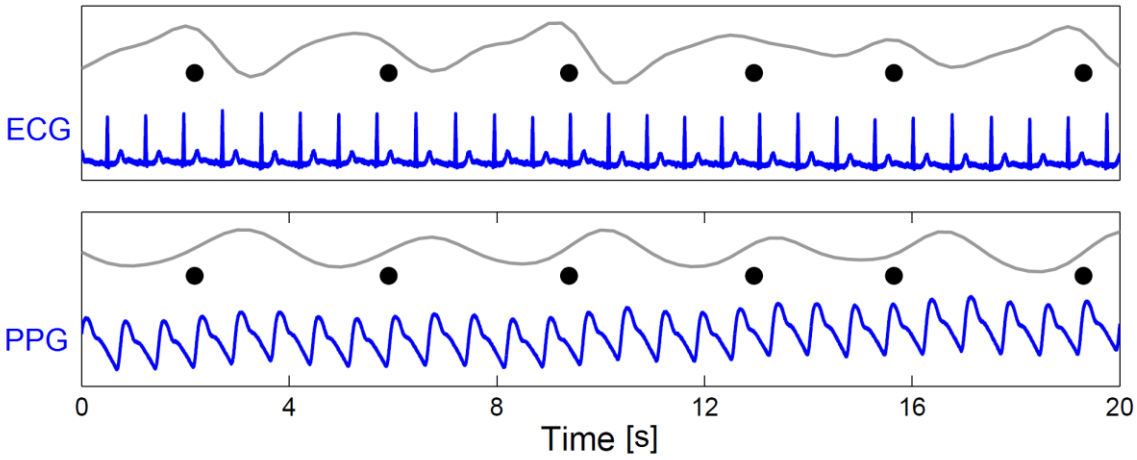


Structure of Algorithms



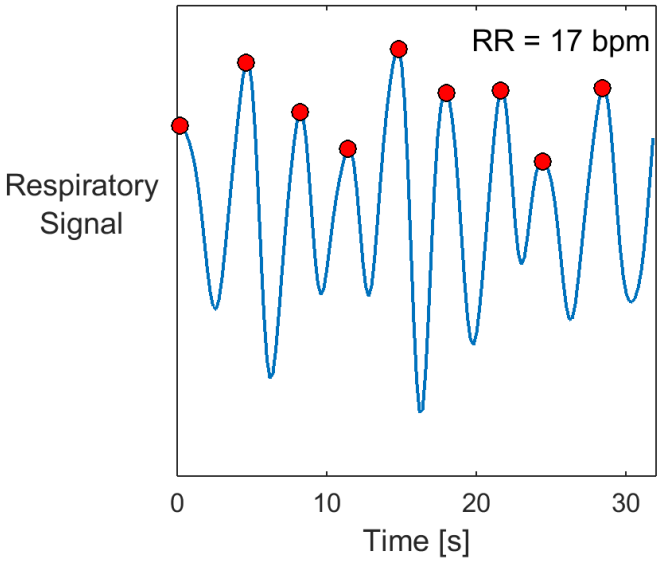
Structure of Algorithms

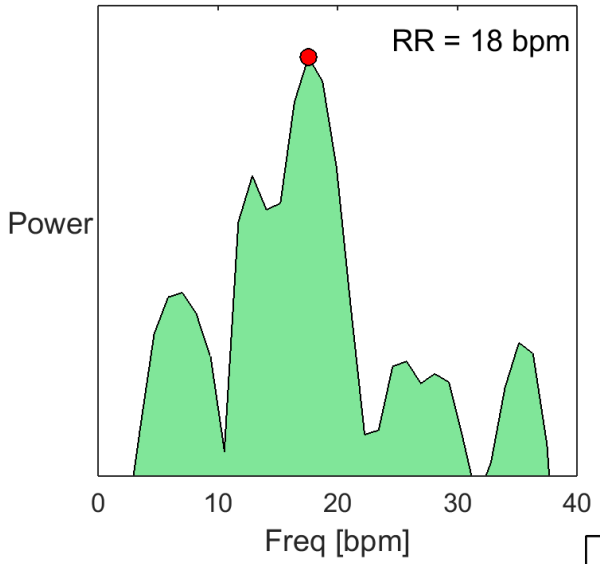




14 techniques implemented

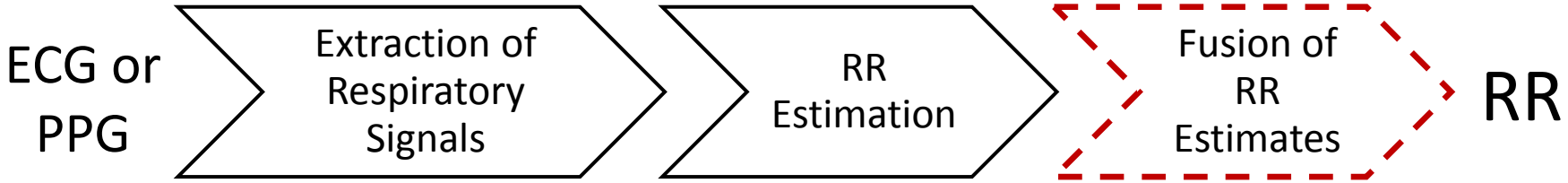
Structure of Algorithms

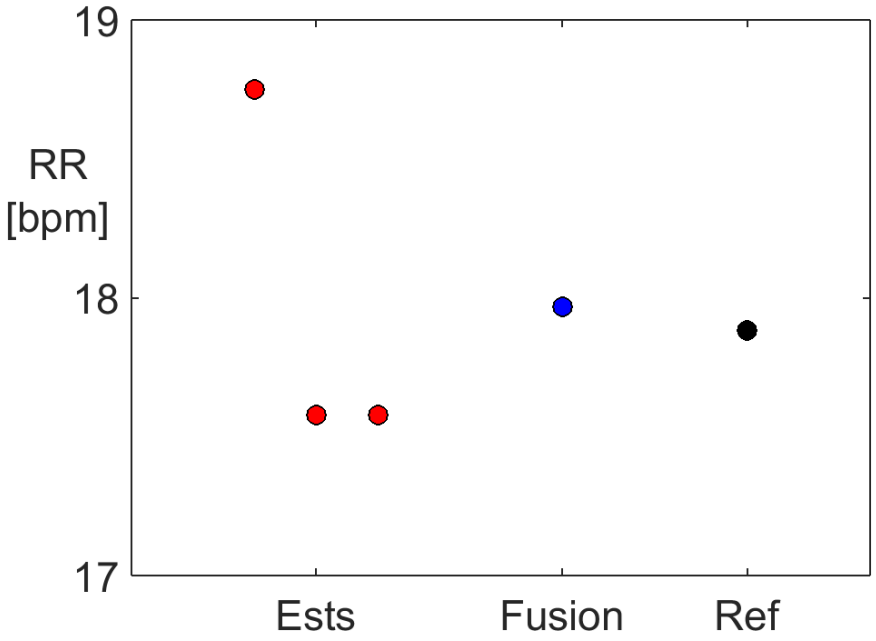




12 techniques implemented

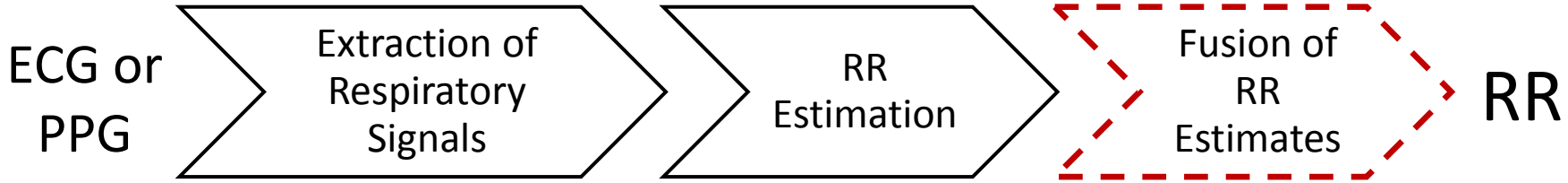
Structure of Algorithms

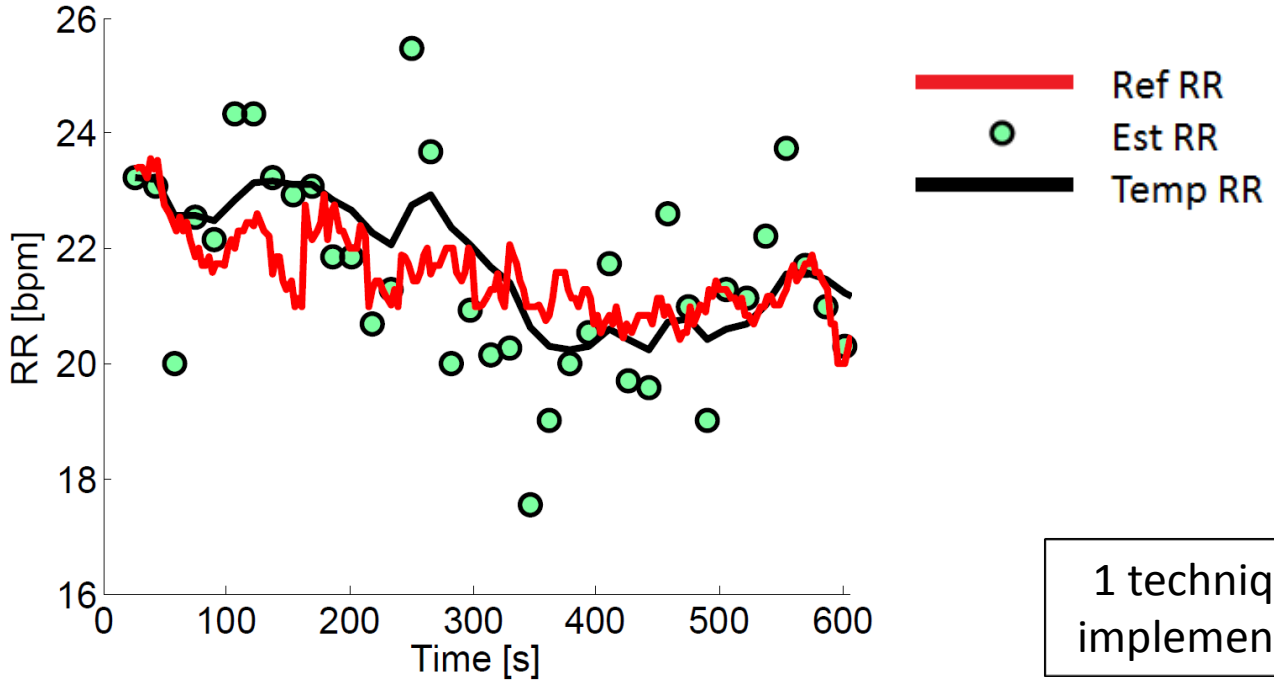




4 techniques implemented

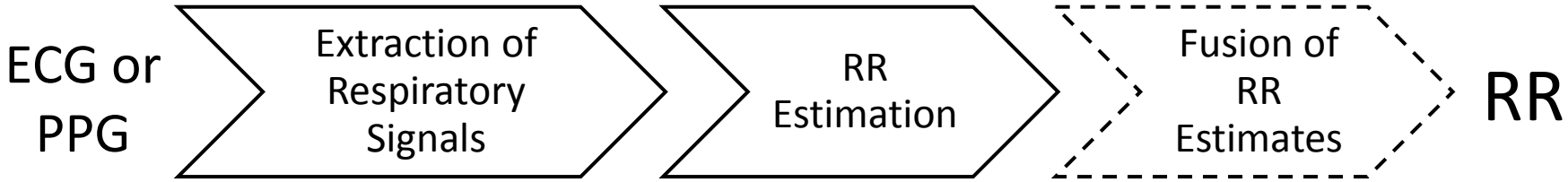
Structure of Algorithms





1 technique implemented

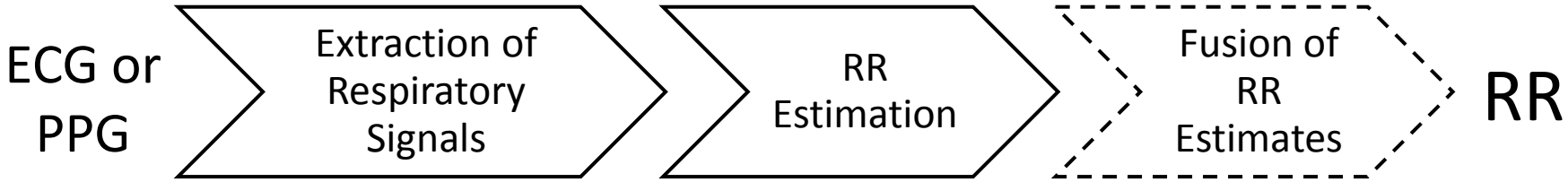
Constructing Algorithms

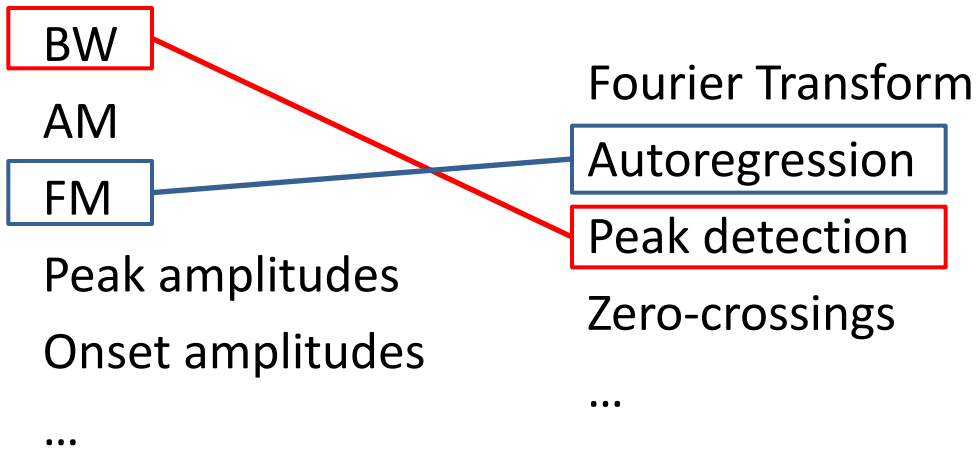


BW
AM
FM
Peak amplitudes
Onset amplitudes
…

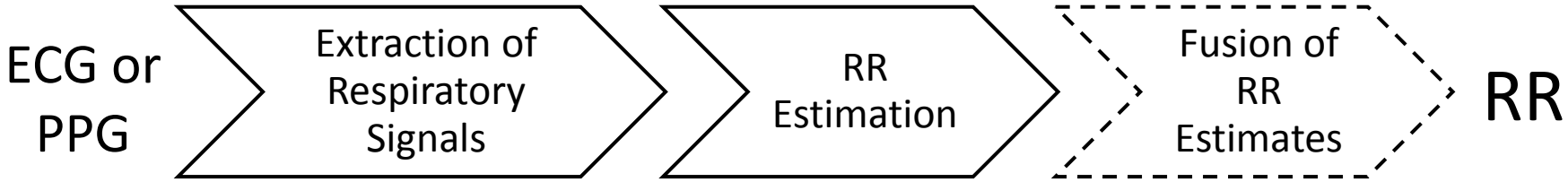
Fourier Transform
Autoregression
Peak detection
Zero-crossings
…

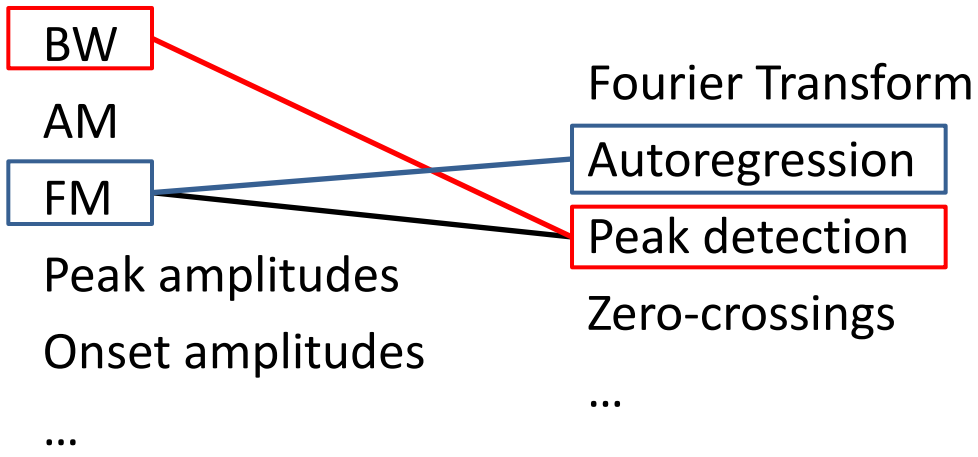
Constructing Algorithms





Constructing Algorithms





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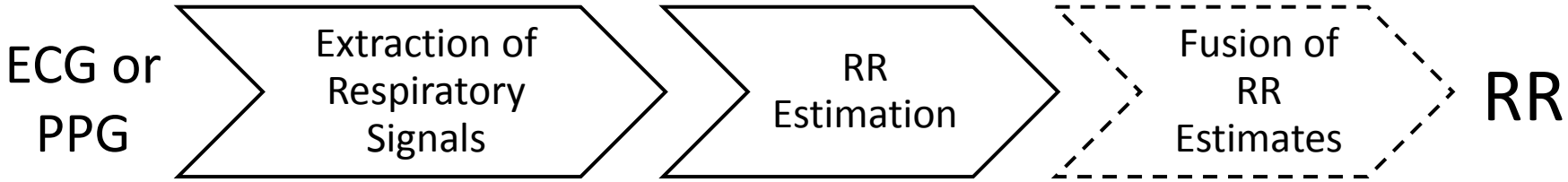

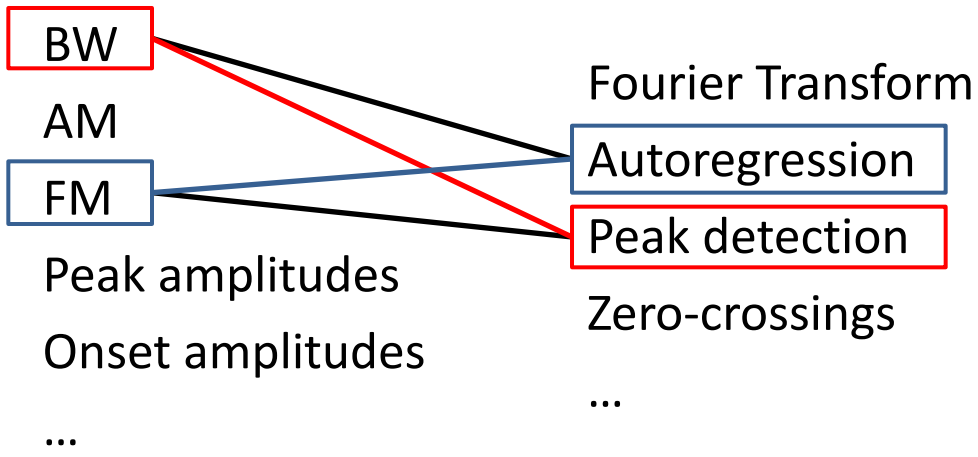

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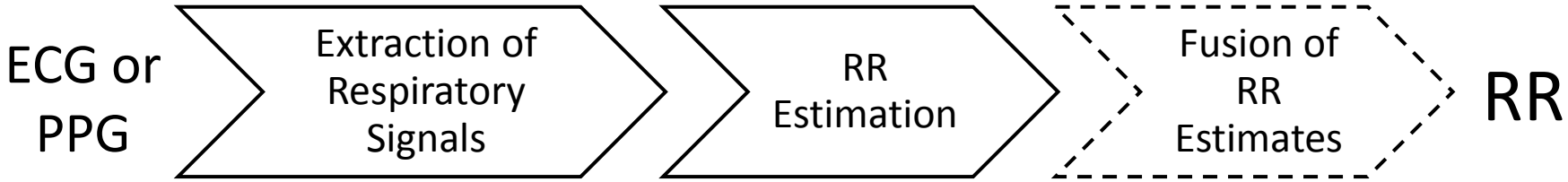
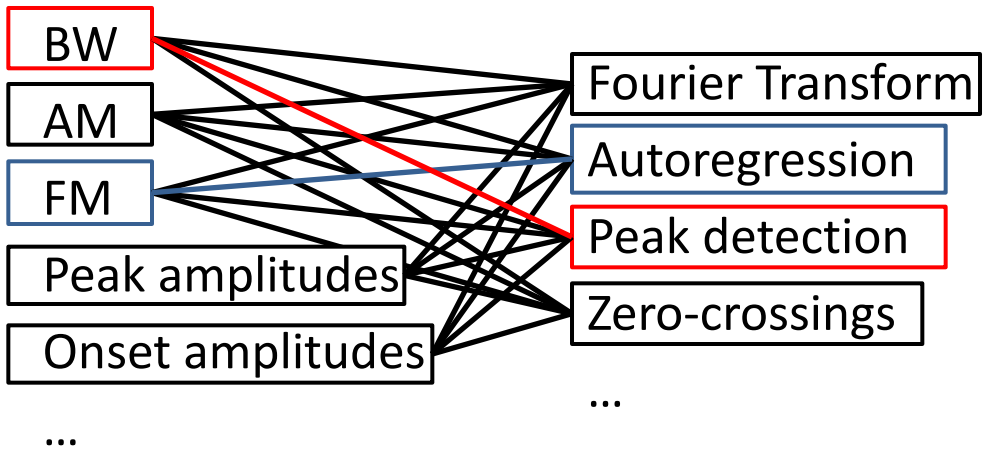
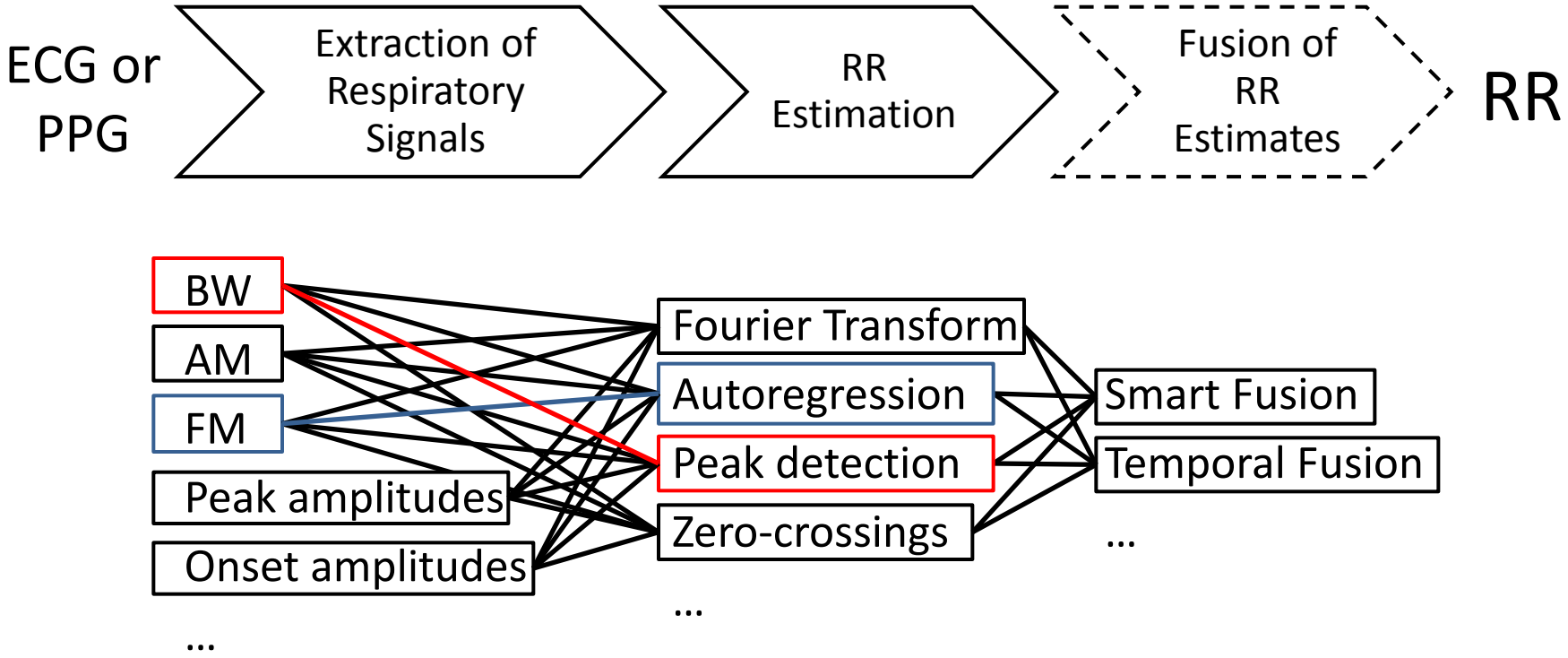




Constructing Algorithms

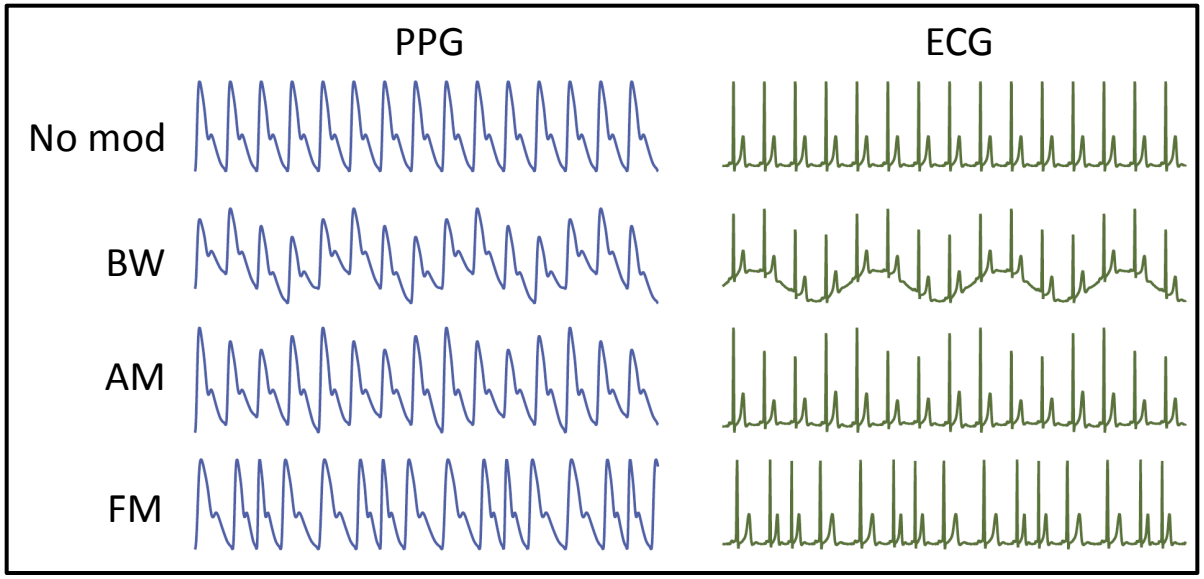


370 algorithms implemented

Methods

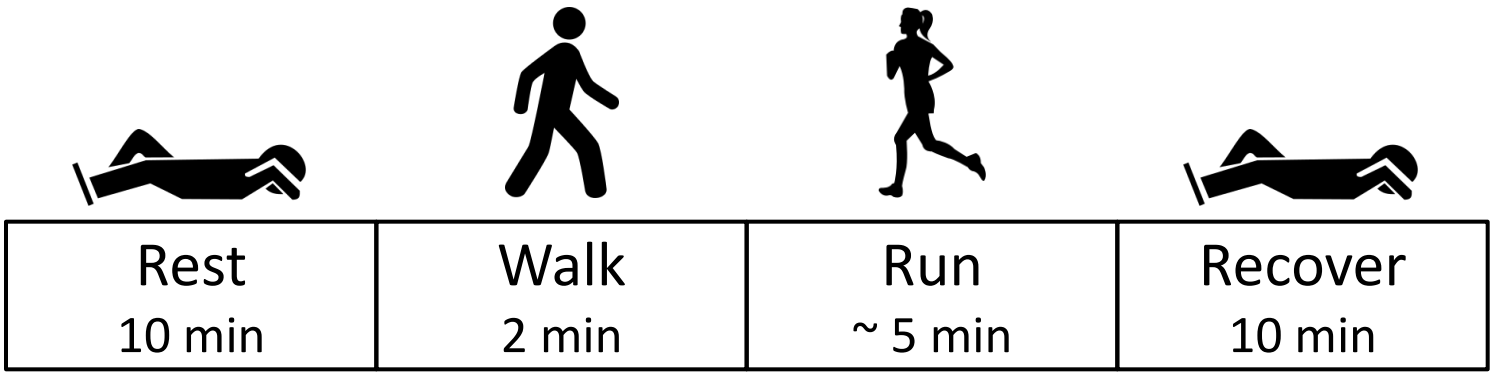
Verification of Implementations

- Simulated data
- RR = 18 bpm, HR = 30:5:200 bpm
- HR = 80 bpm, RR = 4:2:60 bpm
- 314 (85%) of algorithms accurate, two techniques removed



Participants

- 18 ≥ age < 40
- Healthy
- Exclusions:
  - Co-morbidities or medications that affect cardiac, respiratory or autonomic nervous systems



National Clinical Trial 01472133

Participants

- 18 ≥ age < 40
- Healthy
- Exclusions:
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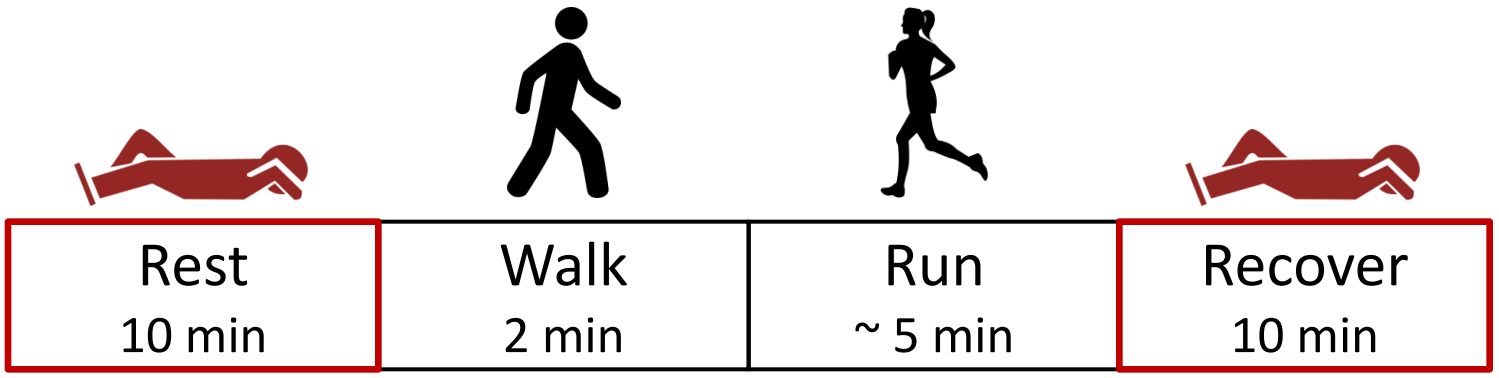
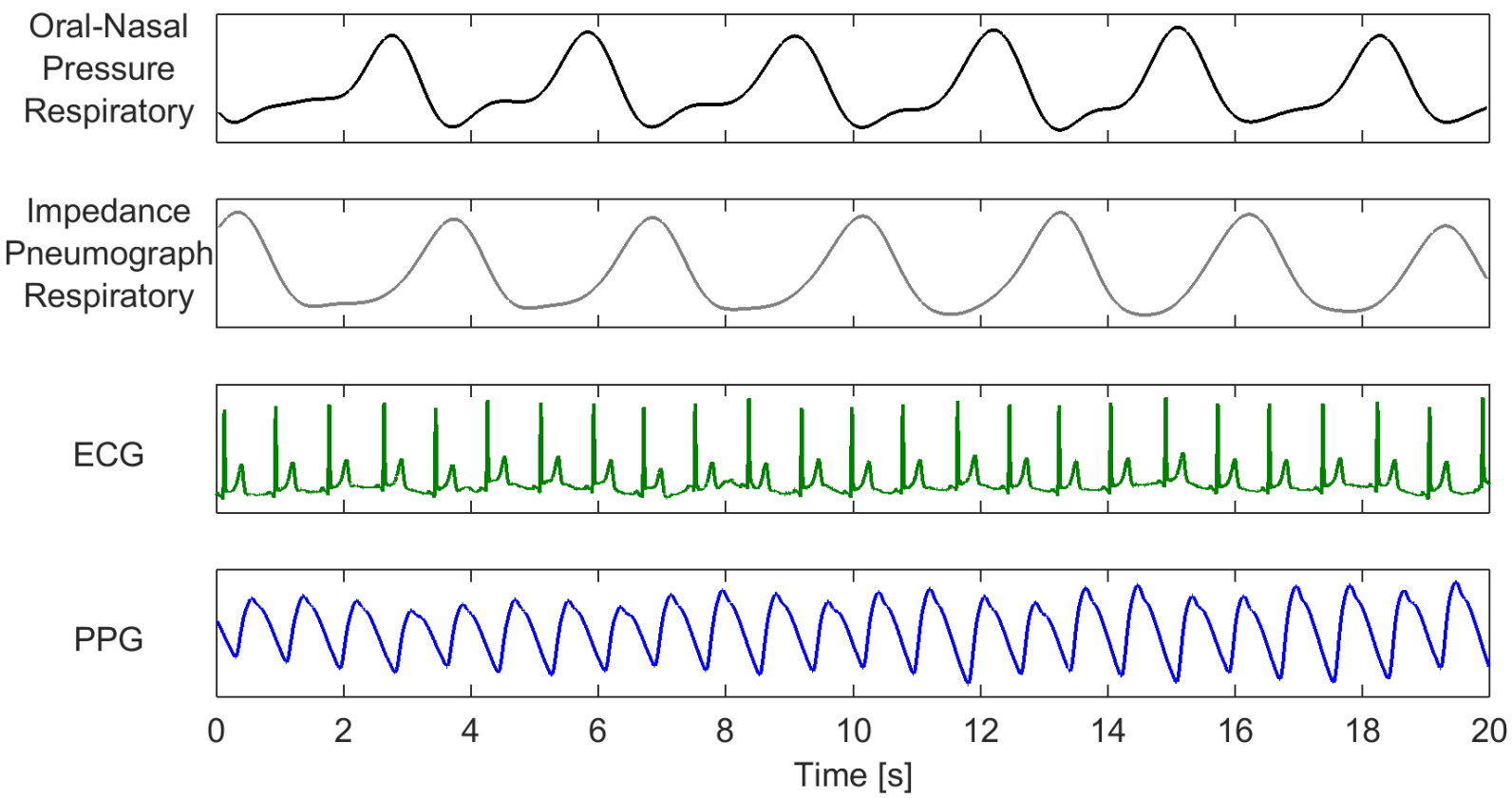


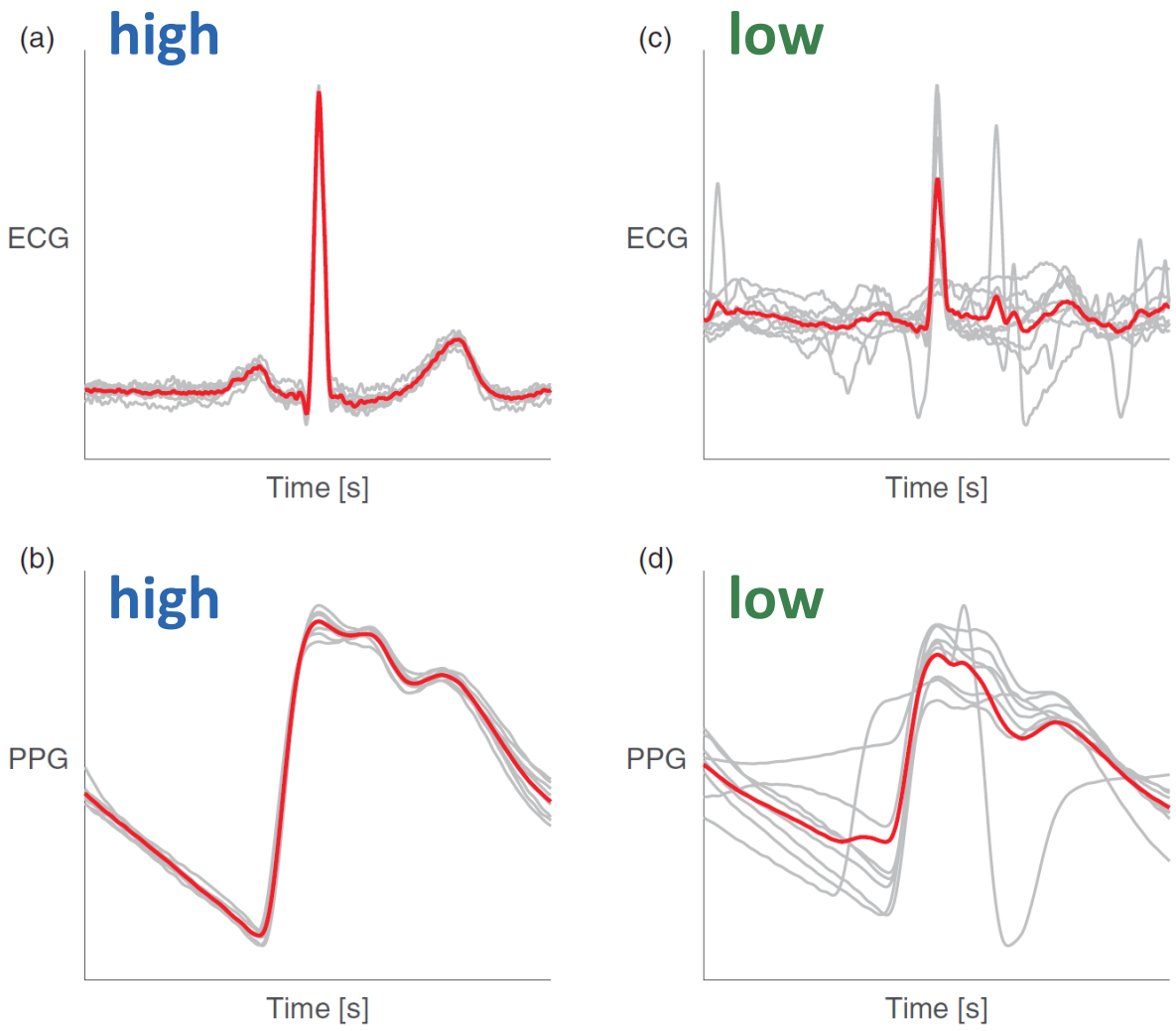
National Clinical Trial 01472133

Signals

Signals


Oral-Nasal
Pressure
Respiratory
Impedance
Pneumograph
Respiratory
ECG
PPG
0
2
4
6
8
10
12
14
16
18
20
Time [s]

Signal Quality



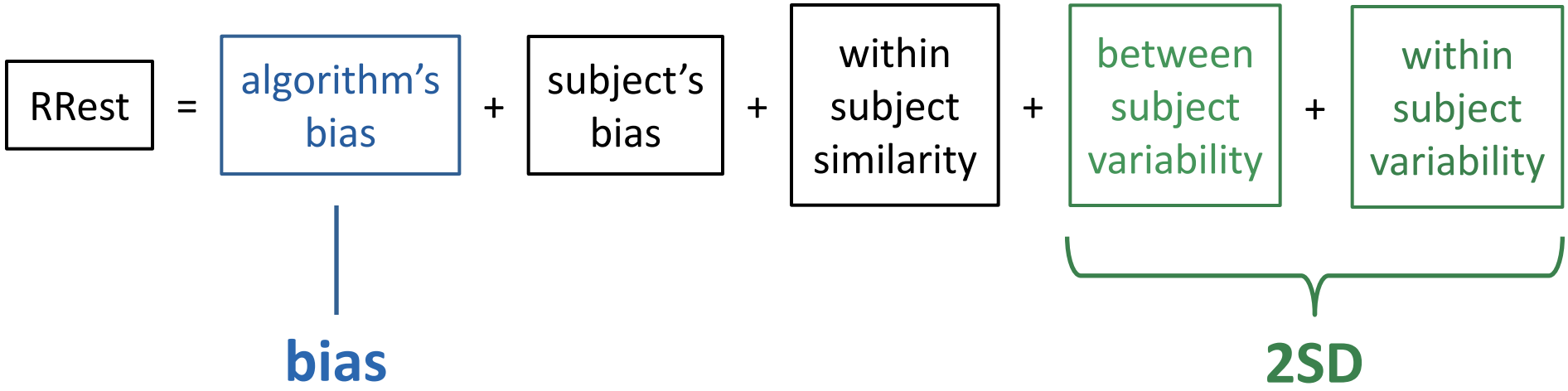
Reference RRs

- Oral-nasal pressure
- Positive-gradient crossings
- Threshold determined using annotated breaths
- Performance:
  - Bias: 0.0 bpm
  - 2SD: 1.3 bpm

i.e. 95% of errors in reference RRs would be expected to be smaller than 0.0 ± 1.3 bpm

Statistics

- Limits of agreement: (i) **bias**, (ii) **2SD** (95% CIs)
- Random effects model:



- Coverage probability: proportion of errors < 2 bpm
- Ranked algorithms by 2SD, followed by bias.

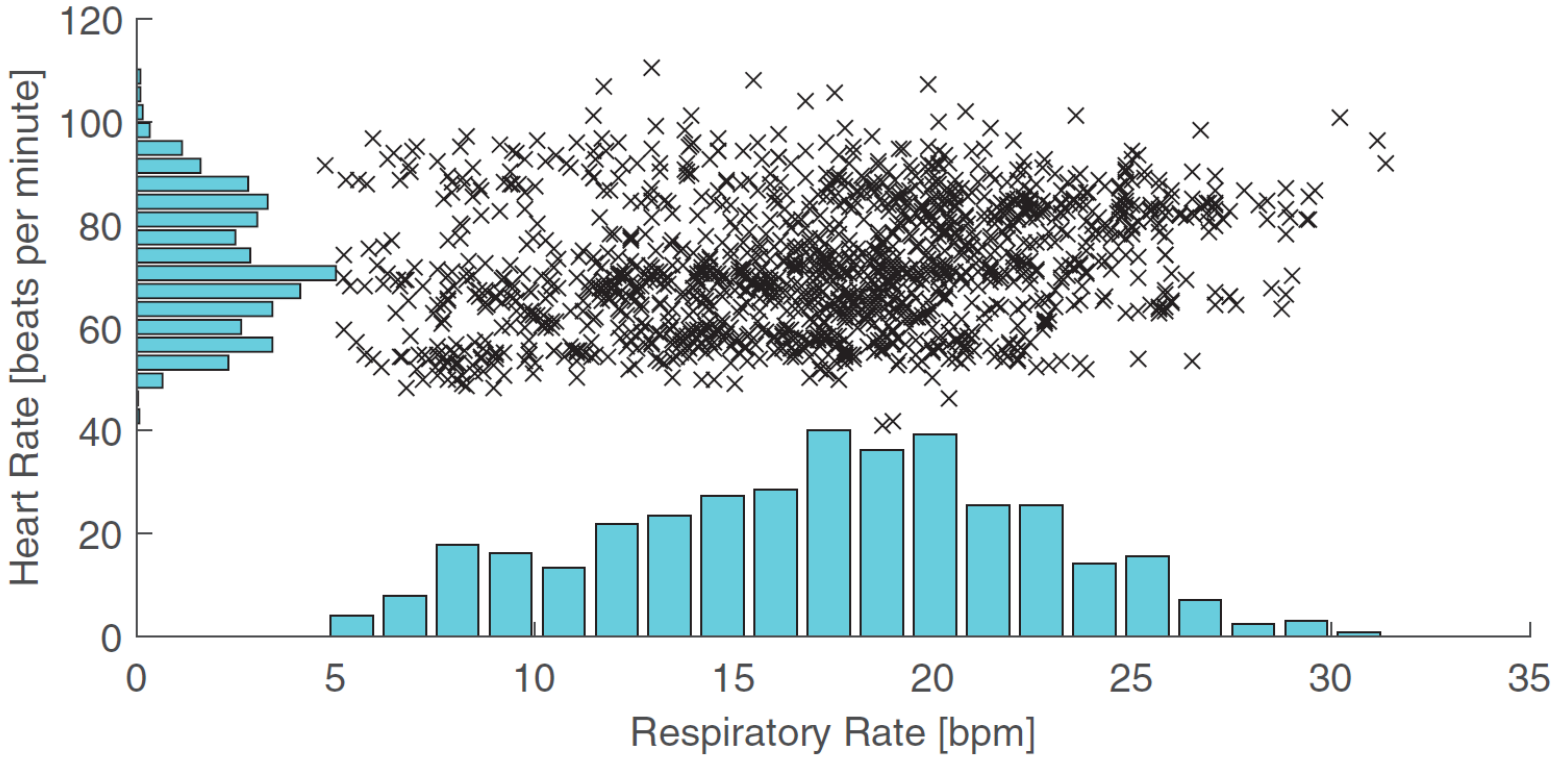
Results

Dataset

- 39 subjects included
  - Age: 29 (26, 32)
  - BMI: 23 (21, 26)
  - 54% female

- Number of 32 s windows analysed:
  - ECG: 37 (34,40)
  - PPG: 36 (34,39)

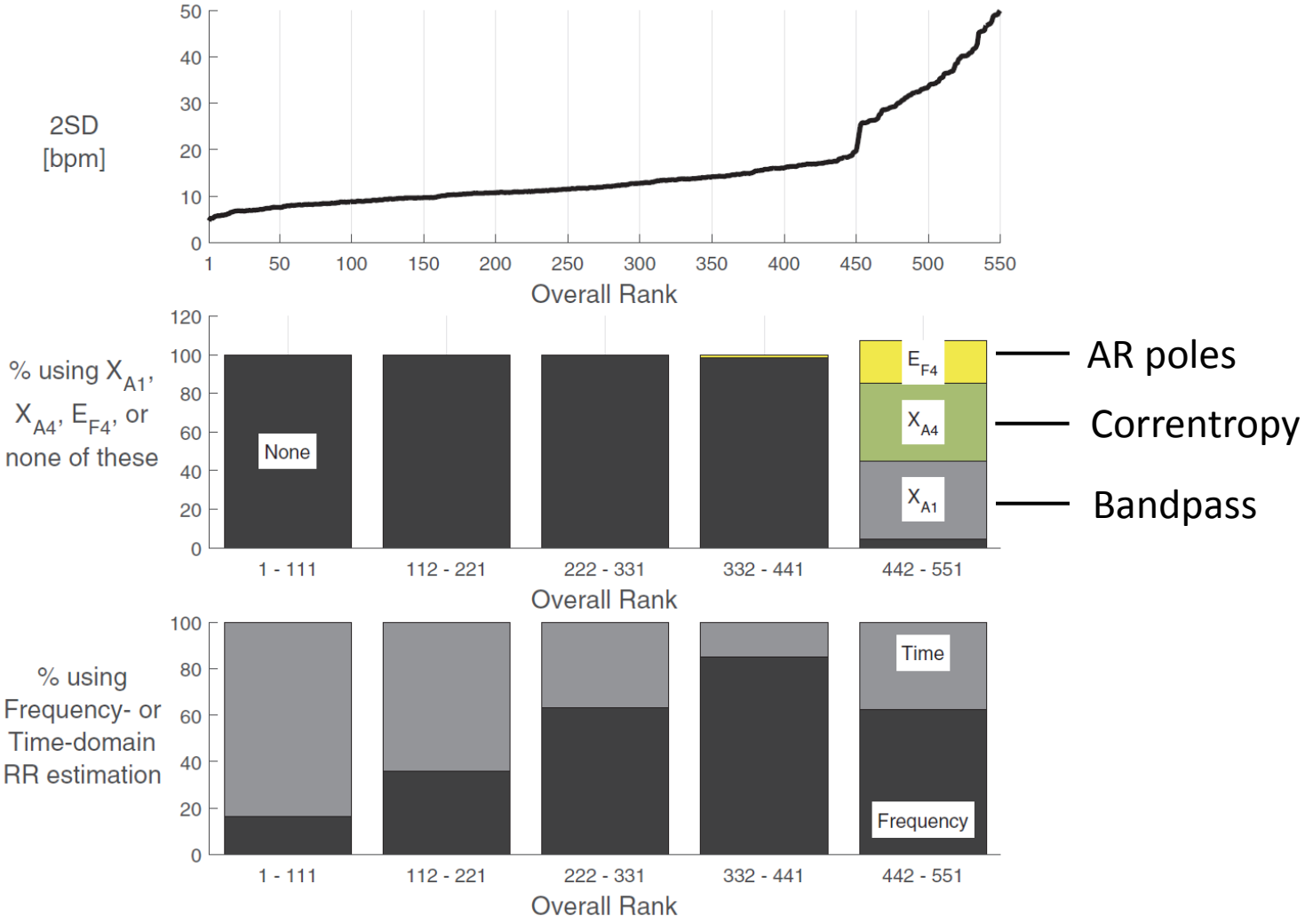
Dataset



RR: 5-32 bpm

HR: 41 – 111 bpm

Performance of Algorithms



Performance of Algorithms

Signal	Algorithm	Overall Rank	2SD [bpm]	Bias [bpm]	95% LOA [bpm]	Proportion of windows with RR estimate [%]	CP_2 [%]
IP	Clinical Monitor	5	5.4	-0.2	-5.6 – 5.2	100.0	76.0
ECG	$X_{B1,2,3}E_{T4}F_{M1}$	1	4.7	0.0	-4.7 – 4.7	73.8	80.5
	$X_{B1,2,3}E_{T2}F_{M1}$	2	5.2	1.4	-3.8 – 6.4	72.3	72.6
	$X_{B1,2,3}E_{T5}F_{M1}$	3	5.2	2.0	-3.3 – 7.2	75.4	69.1
	$X_{B1,2,3}E_{T3}F_{M1}$	4	5.3	1.4	-3.8 – 6.7	72.5	73.0
	$X_{B2}E_{T2}$	6	5.6	-0.2	-5.8 – 5.4	100.0	75.2
	$X_{B2}E_{T3}$	7	5.7	-0.2	-5.9 – 5.4	100.0	74.3
	$X_{B2}E_{T2}F_{T1}$	8	5.7	-0.2	-6 – 5.5	100.0	69.3
	$X_{B2}E_{T5}$	9	5.7	0.5	-5.2 – 6.3	100.0	74.9
	$X_{B2}E_{T3}F_{T1}$	10	5.8	-0.2	-6.0 – 5.6	100.0	69.8
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	11	5.9	0.0	-5.9 – 6.0	100.0	66.6
PPG	$X_{B1,2,3}E_{T4}F_{M1}$	15	6.2	1.0	-5.1 – 7.2	54.2	71.5
	$X_{B1,2,3}E_{T1}F_{M1}$	17	6.5	-1.0	-7.5 – 5.5	62.1	62.1
	$X_{B1,2,3}E_{T1}F_{M1}F_{T1}$	35	7.0	-1.3	-8.3 – 5.7	100.0	54.2
	$X_{B2}E_{T5}F_{T1}$	46	7.5	3.0	-4.5 – 10.5	100.0	44.3
	$X_{B5}E_{T1}F_{T1}$	48	7.6	0.7	-6.9 – 8.3	100.0	57.0
	$X_{B2}E_{T2}F_{T1}$	53	7.6	2.7	-4.9 – 10.3	100.0	47.2
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	54	7.8	1.1	-6.8 – 8.9	97.3	57.2
	$X_{B1,2,3}E_{T5}F_{M1}$	55	7.8	3.8	-4.0 - 11.5	70.9	49.8
	$X_{B2}E_{T4}F_{T1}$	56	7.9	0.3	-7.7 – 8.2	100.0	60.5
	$X_{B1,2,3}E_{T2}F_{M1}F_{T1}$	58	7.9	3.7	-4.2 – 11.5	100.0	60.5

Performance of Algorithms

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ECG	$X_{B1,2,3}E_{T4}F_{M1}$	1	4.7	0.0	-4.7 – 4.7	73.8	80.5
	$X_{B1,2,3}E_{T2}F_{M1}$	2	5.2	1.4	-3.8 – 6.4	72.3	72.6
	$X_{B1,2,3}E_{T5}F_{M1}$	3	5.2	2.0	-3.3 – 7.2	75.4	69.1
	$X_{B1,2,3}E_{T3}F_{M1}$	4	5.3	1.4	-3.8 – 6.7	72.5	73.0
	$X_{B2}E_{T2}$	6	5.6	-0.2	-5.8 – 5.4	100.0	75.2
	$X_{B2}E_{T3}$	7	5.7	-0.2	-5.9 – 5.4	100.0	74.3
	$X_{B2}E_{T2}F_{T1}$	8	5.7	-0.2	-6 – 5.5	100.0	69.3
	$X_{B2}E_{T5}$	9	5.7	0.5	-5.2 – 6.3	100.0	74.9
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	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	11	5.9	0.0	-5.9 – 6.0	100.0	66.6
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	$X_{B1,2,3}E_{T1}F_{M1}F_{T1}$	35	7.0	-1.3	-8.3 – 5.7	100.0	54.2
	$X_{B2}E_{T5}F_{T1}$	46	7.5	3.0	-4.5 – 10.5	100.0	44.3
	$X_{B5}E_{T1}F_{T1}$	48	7.6	0.7	-6.9 – 8.3	100.0	57.0
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	$X_{B1,2,3}E_{T2}F_{M1}$	2	5.2	1.4	-3.8 – 6.4	72.3	72.6
	$X_{B1,2,3}E_{T5}F_{M1}$	3	5.2	2.0	-3.3 – 7.2	75.4	69.1
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	$X_{B1,2,3}E_{T1}F_{M1}$	17	6.5	-1.0	-7.5 – 5.5	62.1	62.1
	$X_{B1,2,3}E_{T1}F_{M1}F_{T1}$	35	7.0	-1.3	-8.3 – 5.7	100.0	54.2
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	$X_{B5}E_{T1}F_{T1}$	48	7.6	0.7	-6.9 – 8.3	100.0	57.0
	$X_{B2}E_{T2}F_{T1}$	53	7.6	2.7	-4.9 – 10.3	100.0	47.2
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	54	7.8	1.1	-6.8 – 8.9	97.3	57.2
	$X_{B1,2,3}E_{T5}F_{M1}$	55	7.8	3.8	-4.0 - 11.5	70.9	49.8
	$X_{B2}E_{T4}F_{T1}$	56	7.9	0.3	-7.7 – 8.2	100.0	60.5
	$X_{B1,2,3}E_{T2}F_{M1}F_{T1}$	58	7.9	3.7	-4.2 – 11.5	100.0	60.5

Performance of Algorithms

Signal	Algorithm	Overall Rank	2SD [bpm]	Bias [bpm]	95% LOA [bpm]	Proportion of windows with RR estimate [%]	CP_2 [%]
IP	Clinical Monitor	5	5.4	-0.2	-5.6 – 5.2	100.0	76.0
ECG	$X_{B1,2,3}E_{T4}F_{M1}$	1	4.7	0.0	-4.7 – 4.7	73.8	80.5
	$X_{B1,2,3}E_{T2}F_{M1}$	2	5.2	1.4	-3.8 – 6.4	72.3	72.6
	$X_{B1,2,3}E_{T5}F_{M1}$	3	5.2	2.0	-3.3 – 7.2	75.4	69.1
	$X_{B1,2,3}E_{T3}F_{M1}$	4	5.3	1.4	-3.8 – 6.7	72.5	73.0
	$X_{B2}E_{T2}$	6	5.6	-0.2	-5.8 – 5.4	100.0	75.2
	$X_{B2}E_{T3}$	7	5.7	-0.2	-5.9 – 5.4	100.0	74.3
	$X_{B2}E_{T2}F_{T1}$	8	5.7	-0.2	-6 – 5.5	100.0	69.3
	$X_{B2}E_{T5}$	9	5.7	0.5	-5.2 – 6.3	100.0	74.9
	$X_{B2}E_{T3}F_{T1}$	10	5.8	-0.2	-6.0 – 5.6	100.0	69.8
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	11	5.9	0.0	-5.9 – 6.0	100.0	66.6
PPG	$X_{B1,2,3}E_{T4}F_{M1}$	15	6.2	1.0	-5.1 – 7.2	54.2	71.5
	$X_{B1,2,3}E_{T1}F_{M1}$	17	6.5	-1.0	-7.5 – 5.5	62.1	62.1
	$X_{B1,2,3}E_{T1}F_{M1}F_{T1}$	35	7.0	-1.3	-8.3 – 5.7	100.0	54.2
	$X_{B2}E_{T5}F_{T1}$	46	7.5	3.0	-4.5 – 10.5	100.0	44.3
	$X_{B5}E_{T1}F_{T1}$	48	7.6	0.7	-6.9 – 8.3	100.0	57.0
	$X_{B2}E_{T2}F_{T1}$	53	7.6	2.7	-4.9 – 10.3	100.0	47.2
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	54	7.8	1.1	-6.8 – 8.9	97.3	57.2
	$X_{B1,2,3}E_{T5}F_{M1}$	55	7.8	3.8	-4.0 - 11.5	70.9	49.8
	$X_{B2}E_{T4}F_{T1}$	56	7.9	0.3	-7.7 – 8.2	100.0	60.5
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	$X_{B1,2,3}E_{T2}F_{M1}$	2	5.2	1.4	-3.8 – 6.4	72.3	72.6
	$X_{B1,2,3}E_{T5}F_{M1}$	3	5.2	2.0	-3.3 – 7.2	75.4	69.1
	$X_{B1,2,3}E_{T3}F_{M1}$	4	5.3	1.4	-3.8 – 6.7	72.5	73.0
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	$X_{B2}E_{T2}F_{T1}$	8	5.7	-0.2	-6 – 5.5	100.0	69.3
	$X_{B2}E_{T5}$	9	5.7	0.5	-5.2 – 6.3	100.0	74.9
	$X_{B2}E_{T3}F_{T1}$	10	5.8	-0.2	-6.0 – 5.6	100.0	69.8
	$X_{B1,2,3}E_{T4}F_{M1}F_{T1}$	11	5.9	0.0	-5.9 – 6.0	100.0	66.6
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	$X_{B1,2,3}E_{T1}F_{M1}F_{T1}$	35	7.0	-1.3	-8.3 – 5.7	100.0	54.2
	$X_{B2}E_{T5}F_{T1}$	46	7.5	3.0	-4.5 – 10.5	100.0	44.3
	$X_{B5}E_{T1}F_{T1}$	48	7.6	0.7	-6.9 – 8.3	100.0	57.0
	$X_{B2}E_{T2}F_{T1}$	53	7.6	2.7	-4.9 – 10.3	100.0	47.2
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	$X_{B1,2,3}E_{T2}F_{M1}F_{T1}$	58	7.9	3.7	-4.2 – 11.5	100.0	60.5

ECG vs PPG

- Significant difference in 2SD (median):
  - ECG: 11.6 bpm
  - PPG: 12.4 bpm
- 64% of algorithms more precise on ECG
- Different physiological mechanisms

Discussion

Limitations

- Not all algorithms implemented
- Invite contributions
- Statistics based on normally distributed errors
- Cannot extrapolate to other scenarios

Future Work

- Investigate effects of:
  - Subject population
  - Recording equipment
  - Movement artifact

- Weighting modulations according to signal quality

Conclusions

- 314 algorithms assessed under ideal conditions
- According to these results …
  - feature-based respiratory signal extraction,
  - time-domain RR estimation, and
  - fusion of estimates

    … resulted in superior performance.
- Four ECG-based algorithms outperformed IP
- ECG preferable to PPG
- Toolbox of algorithms and dataset publicly available

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J Birks and S Gerry

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References and Resources

Charlton P.H. and Bonnici T. *et al.* **An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram**, *Physiological Measurement*, 37(4), 2016. DOI: 10.1088/0967-3334/37/4/610

The complete **table of results** is available in the Supplementary Material

A complete list of **references** is available here.

The **dataset** is available here.

The **algorithms** and user manual are available here.

This presentation is part of the **Respiratory Rate Estimation Project** at:

http://peterhcharlton.github.io/RRest/

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