(Towards) A pervasive real-time blood pressure system:

Estimation Models and Events Detector

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1. Context

- ¼ of adult population suffers from hypertension.

- Current BP devices can not be used continuously on a daily basis.

- A solution would be very useful for managing hypertension and prevent cardiovascular disease.

2. BP Estimation Models

Model 1- PTT only:

$$BP = a \cdot PTT + b$$

Model 2- PTT and HR (Reference model):

$$BP = a \cdot PTT + b \cdot HR + c$$

More robust to noisy measurements than other models derived from the Moens-Korteweg equation.

PTT – Pulse Transit Time (time duration between ECG peak and PPG peak/foot/max_slope)

HR – Instantaneous heart rate

{a,b,c} – Unknown model parameters

3. Parameter Estimation

Dataset containing **69 records** of invasive BP, ECG and PPG.

- **Offline** Methods – Access all values of invasive BP to calculate the unknown parameters and study their behaviour.

- **Online** Methods – Access only the necessary values of invasive BP to calibrate the system.

Study of BP is focused on Systolic BP (SBP) as it conveys more medical information than Diastolic BP (DBP).

3. Parameter estimation
Offline methods

Least Squares Fitting (LSF):

- Determines the {a,b,c} set that minimizes the Squared Error (MSE).

Recursive Least Squares (RLS):

- Unknown parameters are re-calculated each iteration;
- Requires an observed value of SBP.

Exponentially Weighted Regression (EWR):

- Extension of the RLS;
- Greater weight is given to more recent data;
- Forgetting factor, $\lambda \in]0,1]$.

3. Parameter estimation
Online methods

Exponentially-Weighted Regression (EWR) with calibration period T:

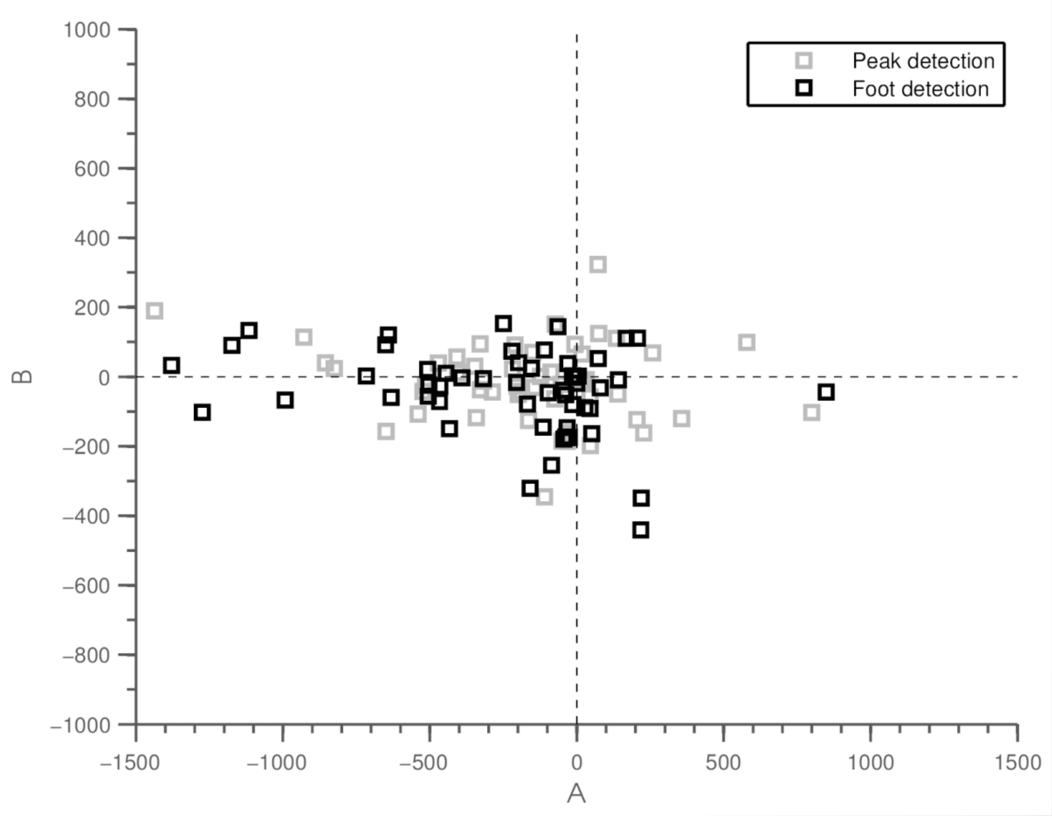
- Initial calibration is conducted in the first 5 minutes.
- EWR is applied every T minutes to re-calculate {a,b,c}.
- Requires an observation of SBP.
- Simulates the real operating environment.

4. Results

Offline methods

LSF method:

- 17 out of 69 records did not meet AAMI's clinical requirement ✝.
- No strong relantionship between *a* and *b* (ρ = -0.190).
- Not enough data to explain bad performance cases.



✝ - AAMI's requirement: Measurements' error means between [-5,5] mmHg and standard deviations below 8 mmHg.

Fig 1. Distribution of pairs *a, b* obtained by LSF, using Model 2, for records that met AAMI's requirement.

4. Results
Online methods

- STD and MSE increase considerably with T.
- Parameters become less meaningful within 30 to 60 minutes of operation.

	EWR with period T – Estimation errors		
Calibration period	**Mean** (mmHg)	**St.D.** (mmHg)	**MSE** ($mmHg^2$)
$T = 1\ min$	-0.17	4.63	36.94
$T = 5\ min$	-0.51	6.76	105.65
$T = 15\ min$	-0.48	7.96	163.81
$T = 30\ min$	-0.77	8.68	228.23
$T = \infty$	-1.48	9.96	373.64

Table 1. Estimation errors for Model 2, averaged over all records, applying the EWR algorithm with different periods of calibration T, T = ∞ denotes that no re-calibration is performed after the initial calibration.

4. Results

Online methods

- Large variability of parameters between calibrations.
- That may be due to noisy measurements of SBP, PTT and HR.
- Robustness enhancement may be applied.

	EWR with period T - Parameters			
Calibration period	**Mean(a)**	**Std(a)**	**Mean(b)**	**Std(b)**
$T = 1\ min$	-206.87	252.49	-26.66	88.70
$T = 5\ min$	-229.95	260.41	-46.79	95.06
$T = 15\ min$	-178.25	263.23	-47.00	90.91
$T = 30\ min$	-144.33	300.74	-28.00	83.69
$T = \infty$	-283.46	0.00	-46.99	0.00

Table 2. Mean and standard deviation of the unknown parameters calculated initially and re-calculated at every point of calibration. T = ∞ denotes that no re-calibration is performed after the initial one.

5. BP Event Detector (BED)

Motivation

- Full to partial similarity in 71% of the records.
- BP event:
  - Variation of amplitude 20 mmHg or higher.
  - 20 minutes time windows.
- Can the estimation models detect the majority of BP events?

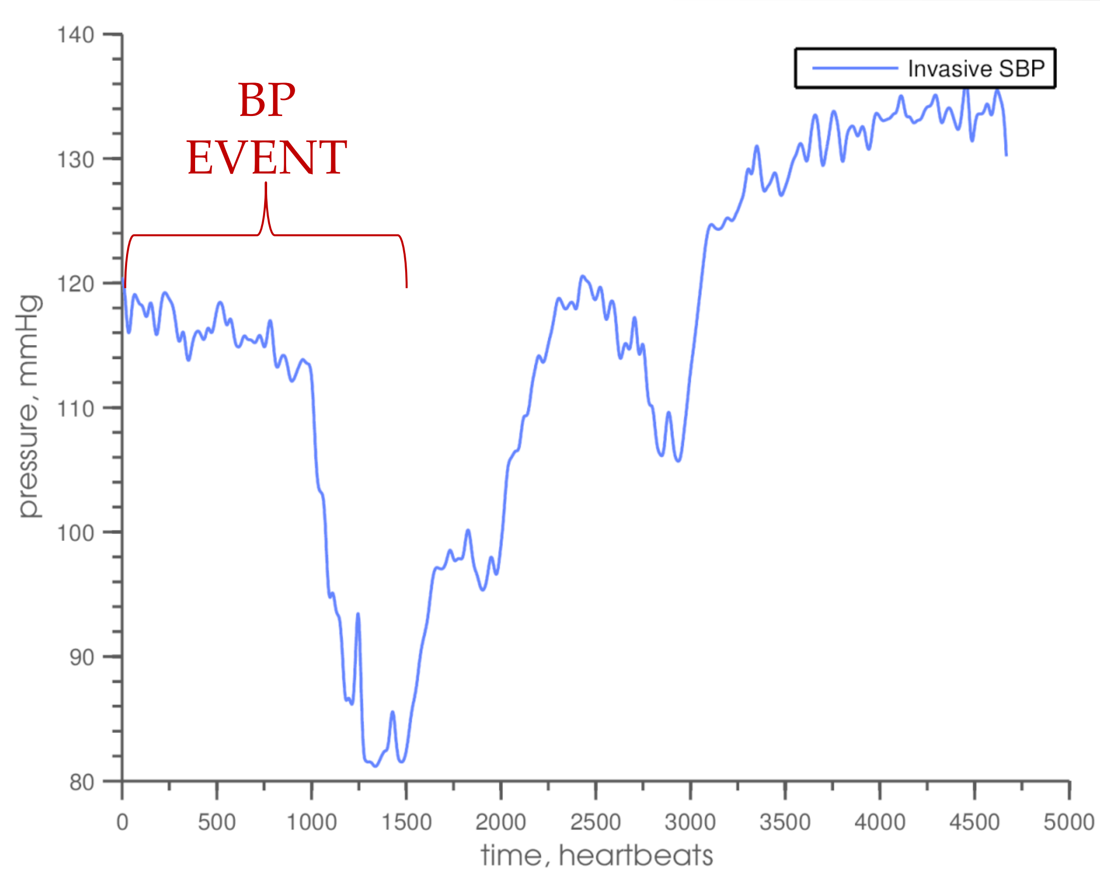


Fig 3. BP event example on invasive SBP signal.

5. BP Event Detector (BED)

Steps

STEPS in a BP event detection sequence:

1. Generation of Ground Truth

2. Get estimated SBP signals and detection of events

3. Processing of events

4. Comparison of events and performance metrics

5. Generation of a ROC curve by applying steps 2-4 repeatedly for threshold values varying from [0, 80], with Δ= 0.5

5. BP Event Detector (BED)

Results

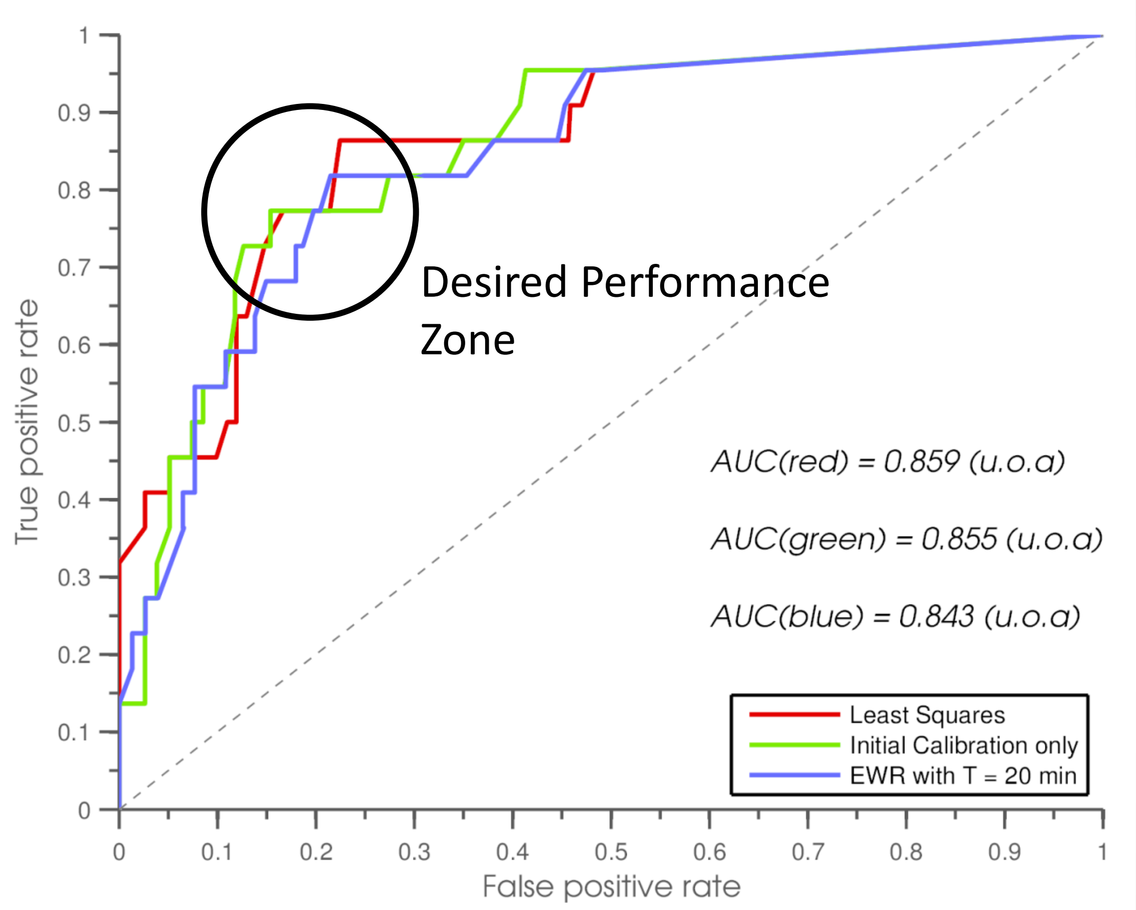


Fig 3. ROC performance curves for SBP event detection using three methods of estimating SBP.

Conclusions

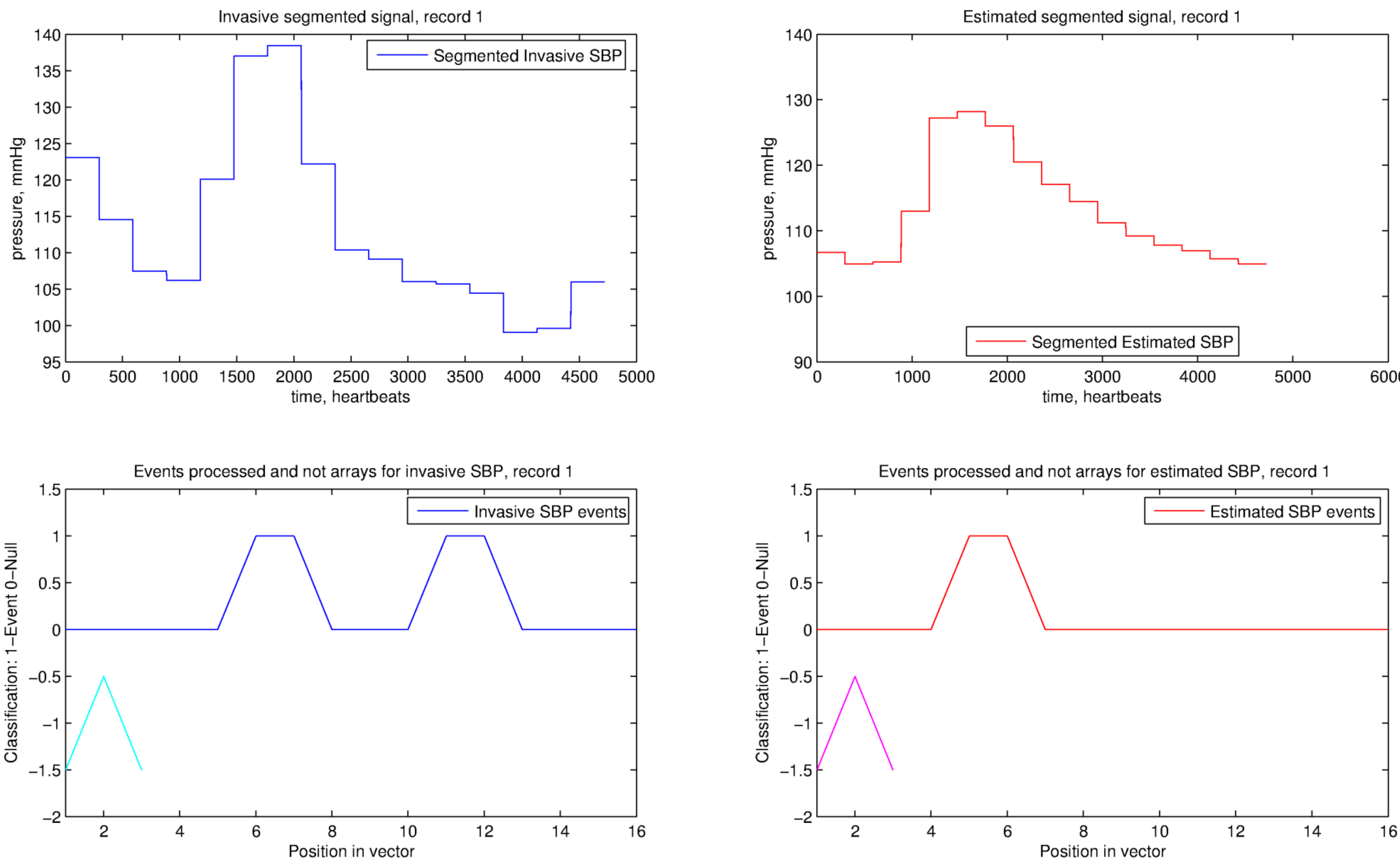
In overall, a PTT-based model:

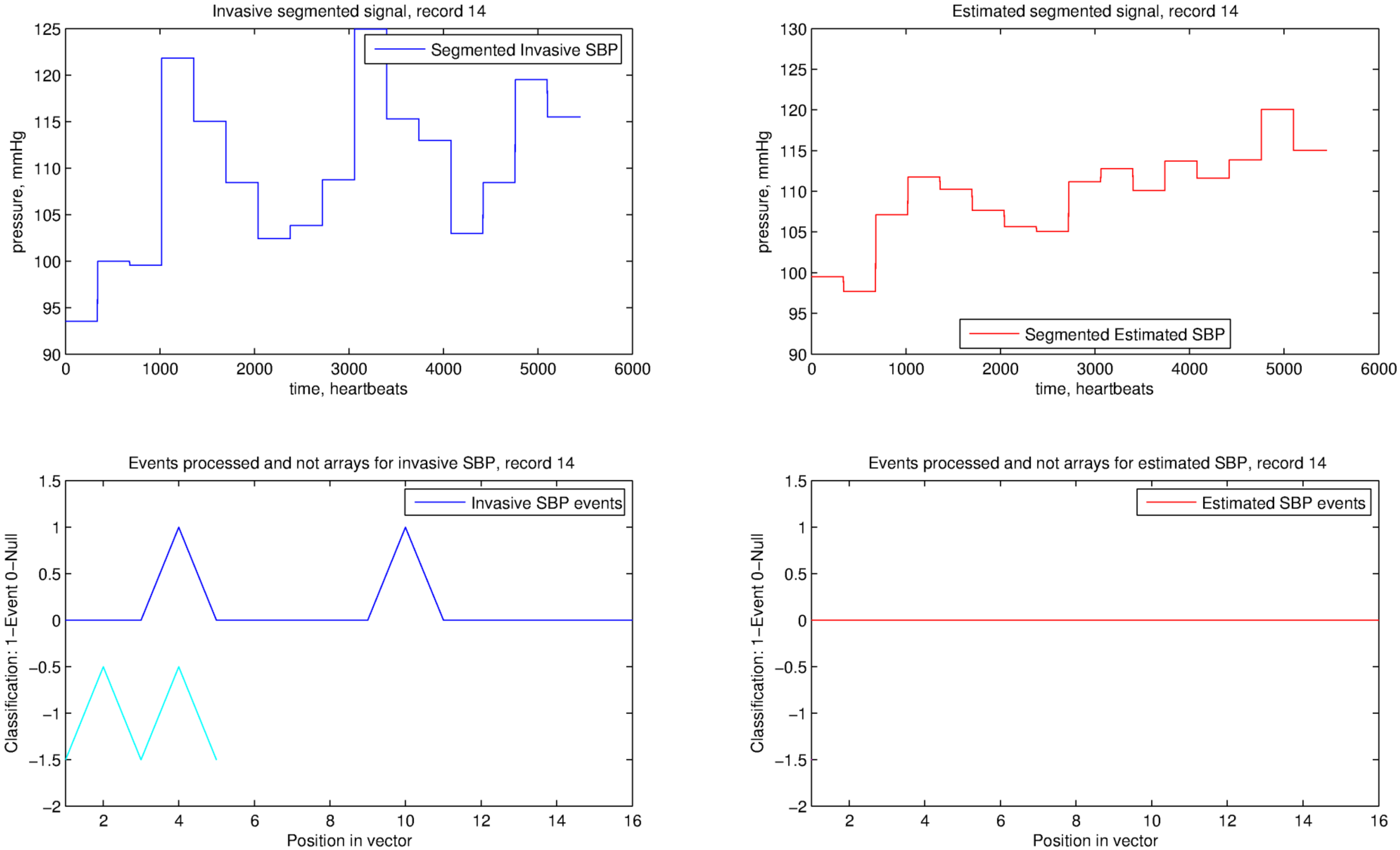
- Does not meet requirements for continuous BP measurement.
- Can detect BP events.
- Provides reasonable performance for online methods, using a threshold of 12.5 mmHg.
- Can be integrated with current technology for ABPM for BP event detection.

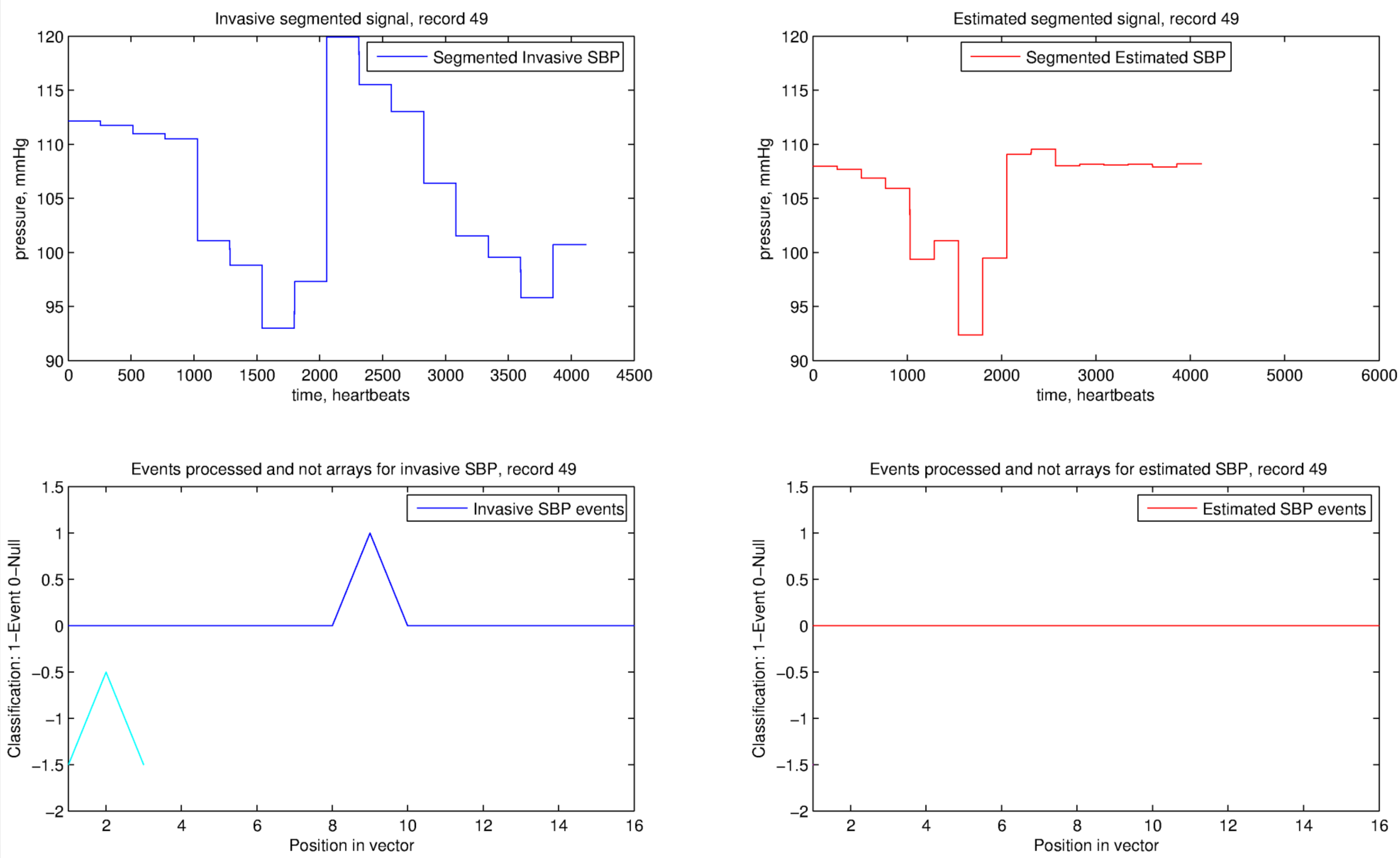
Future Work

- Circadian study of parameters.
- Objective method to measure signal resemblance.
- Enhance robustness in online methods.
- Use a larger clinically marked dataset for BP event detection.


Thank you!


Invasive segmented signal, record 1
Segmented Invasive SBP
pressure, mmHg
time, heartbeats
140
135
130
125
120
115
110
105
100
95
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Estimated segmented signal, record 1
Segmented Estimated SBP
pressure, mmHg
time, heartbeats
140
130
120
110
100
90
0
1000
2000
3000
4000
5000
6000
Events processed and not arrays for invasive SBP, record 1
Invasive SBP events
Classification: 1−Event 0−Null
Position in vector
1.5
1
0.5
0
−0.5
−1
−1.5
−2
2
4
6
8
10
12
14
16
Events processed and not arrays for estimated SBP, record 1
Estimated SBP events
Classification: 1−Event 0−Null
Position in vector
1.5
1
0.5
0
−0.5
−1
−1.5
−2
2
4
6
8
10
12
14
16


Invasive segmented signal, record 14
Segmented Invasive SBP
pressure, mmHg
time, heartbeats
Estimated segmented signal, record 14
Segmented Estimated SBP
pressure, mmHg
time, heartbeats
Events processed and not arrays for invasive SBP, record 14
Invasive SBP events
Classification: 1−Event 0−Null
Position in vector
Events processed and not arrays for estimated SBP, record 14
Estimated SBP events
Classification: 1−Event 0−Null
Position in vector


Invasive segmented signal, record 49
Segmented Invasive SBP
pressure, mmHg
time, heartbeats
Estimated segmented signal, record 49
Segmented Estimated SBP
pressure, mmHg
time, heartbeats
Events processed and not arrays for invasive SBP, record 49
Invasive SBP events
Classification: 1−Event 0−Null
Position in vector
Events processed and not arrays for estimated SBP, record 49
Estimated SBP events
Classification: 1−Event 0−Null
Position in vector