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Continuous Tracking Changes in Systolic Blood Pressure using BCG and ECG

Shan He, Hilmi R. Dajani, Robert D. Meade, Glen P. Kenny, Miodrag Bolic*

University of Ottawa, Canada

*email: mbolic@uottawa.ca

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Motivation & Goal

Motivation

- Extending smart watches with “smart bands” based on ballistocardiography (BCG)
- Exploring using BCG for cuffless-based continuous blood pressure monitoring

Research goal

- Track systolic blood pressure trend cufflessly using time intervals (PTT & RJ) extracted from biomedical signals.

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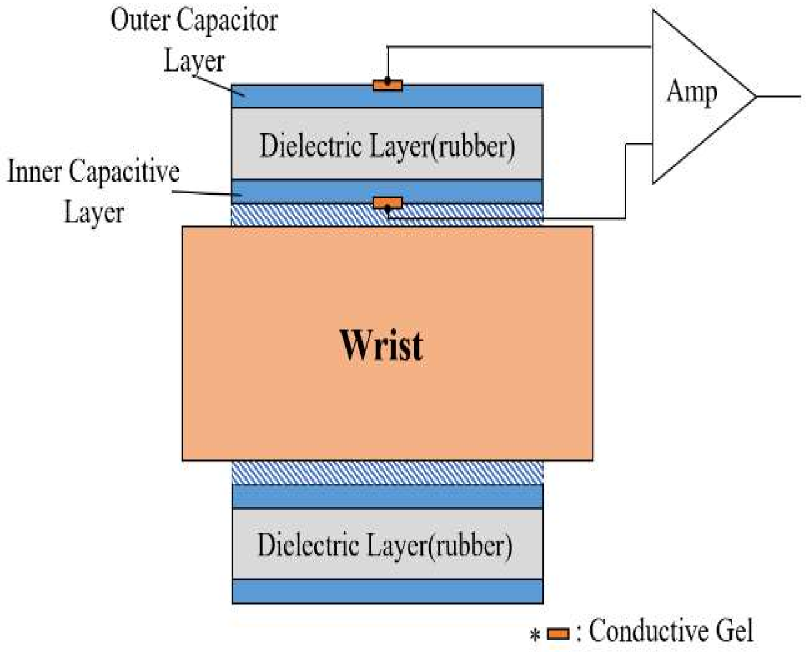
Ballistocardiography

- Ballistocardiography is a technique for producing a graphical representation of repetitive motions of the human body arising from the sudden ejection of blood into the great vessels with each heart beat (Wikipedia).
- BCG sensors can be embedded in ambient environments without the need for medical staff presence: chairs, bed sheets, ...
- Piezoelectric sensors were used typically to measure movements due to respiration and heartbeats during sleep.

BCG wristband



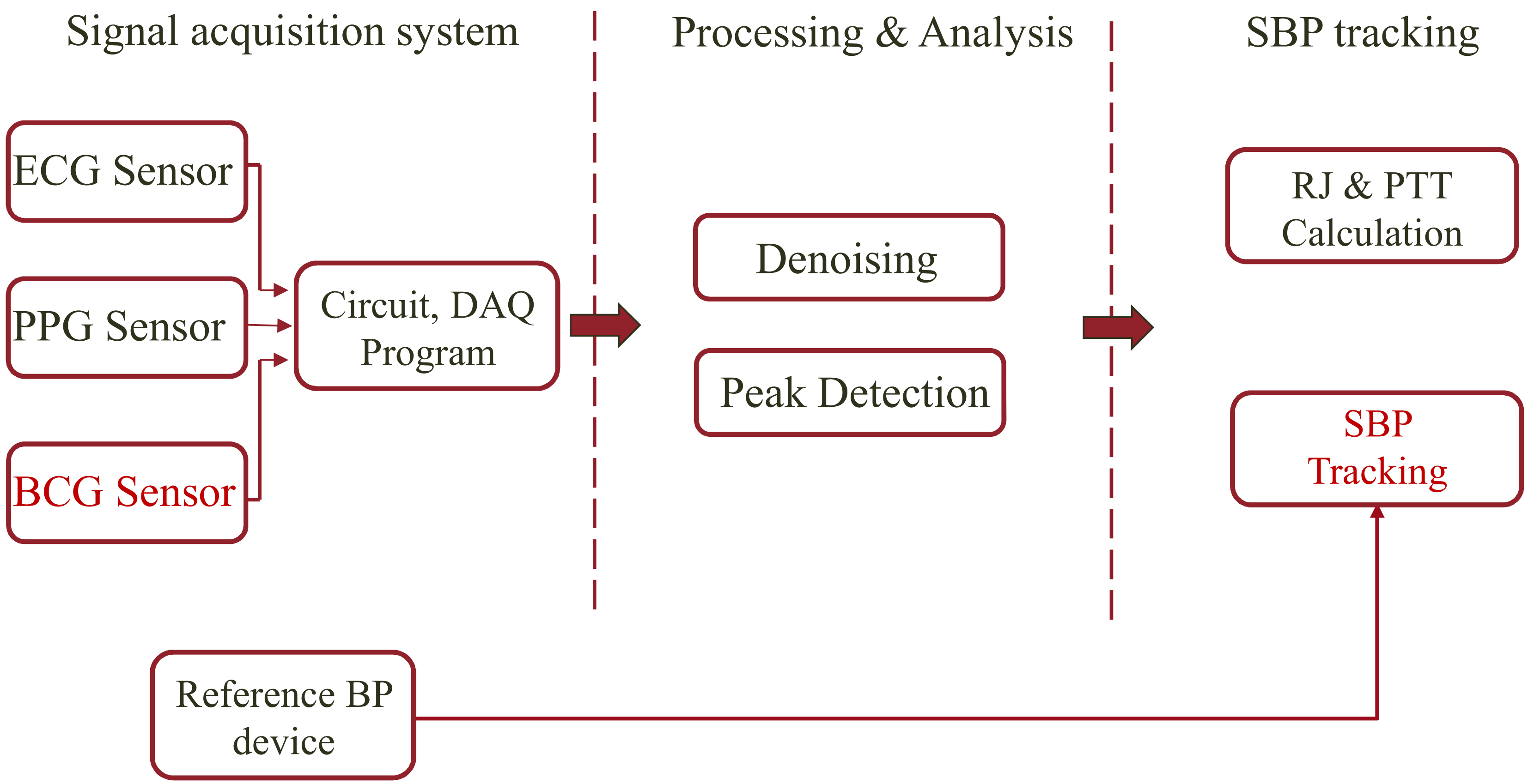
- Heart activity causes physical deformations of the sensor's geometry.
- Geometry of the soft electrodes changes, their electrical charges move with respect to each other.
- The charge shifts are measured by the electrodes, converted to a voltage signal, and subsequently displayed as a BCG related signal.

Advantages:

- Soft materials, comfortable to wear
- Can be modified into watch bands
- Low cost, under $10 (BCG electrode)

* The work of the new BCG wristband has been presented in EMBC 2018

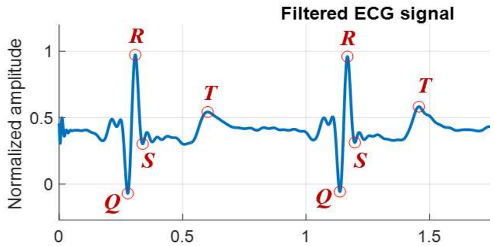
Overview of the System



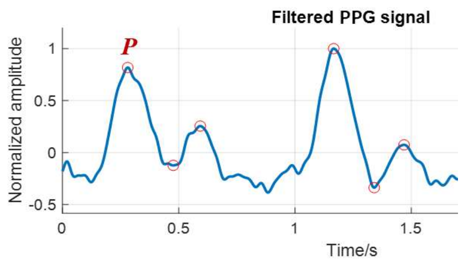
Signal Acquisition System

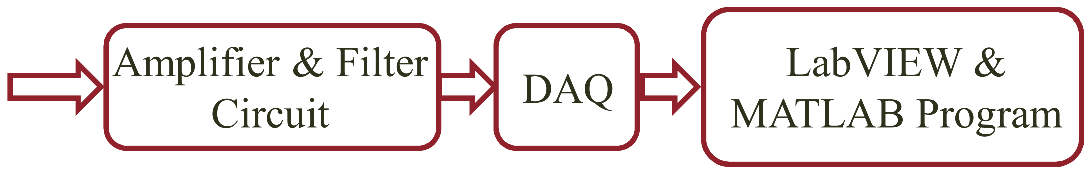
1.Lead 1 ECG:

(a)

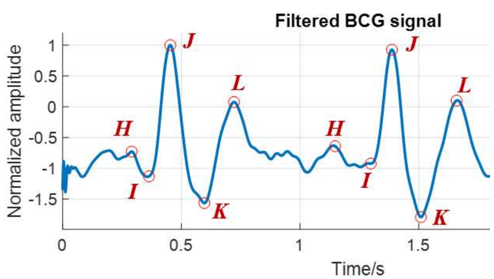


2.Optical Wrist PPG



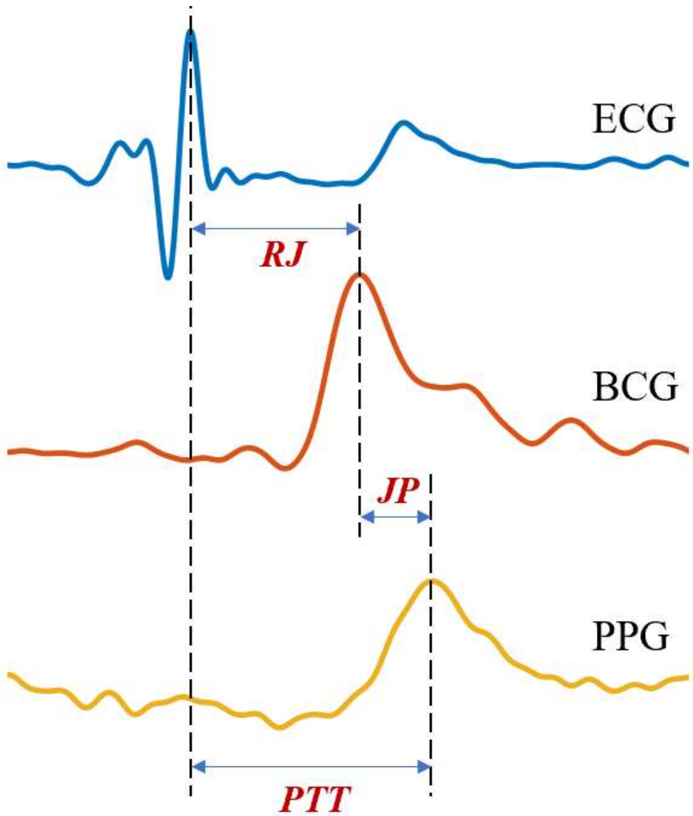


3. Wrist BCG



Time Intervals

1. RJ interval and PTT calculation



- RJ interval is the time difference between ECG R peak and BCG J peak

- Pulse transit time is the time difference between ECG R peak and PPG P peak

SBP Tracking using Time Intervals

2. How to estimate SBP using time intervals?

- BP increases, pulse wave velocity (PWV) increases and PTT decreases
- BP decreases, pulse wave velocity (PWV) decreases and PTT increases

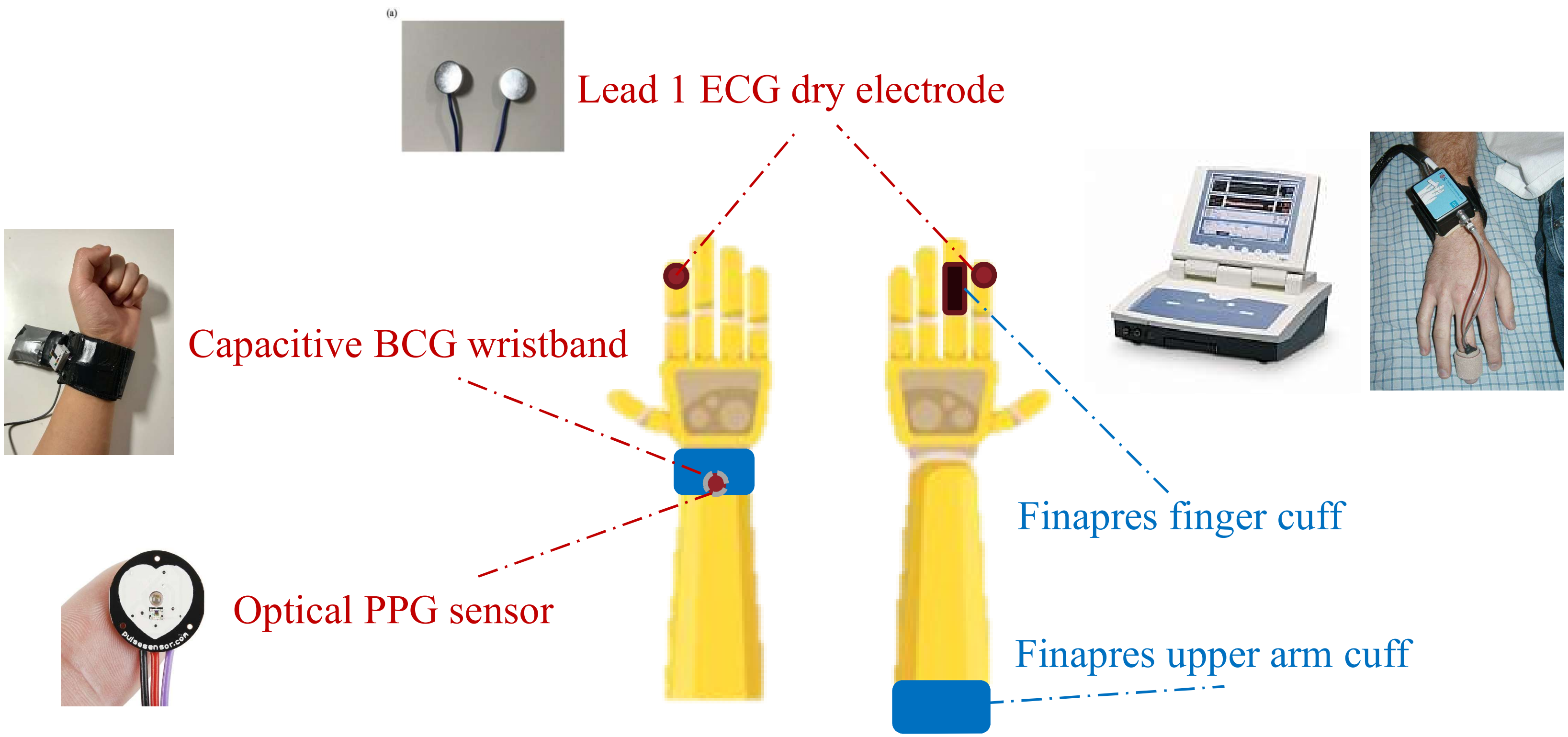
Moens-Korteweg equation $$PWV = \sqrt{\frac{E \cdot h}{2\rho r}} \quad \& \quad E = E_0 \cdot e^{\alpha \cdot BP}$$

Where, E is Young's modulus, h is vessel wall thickness, ρ is blood density and r is radius, E_0 is the modulus of elasticity when pressure is zero, BP is blood pressure and α is a constant that depends on vessel.

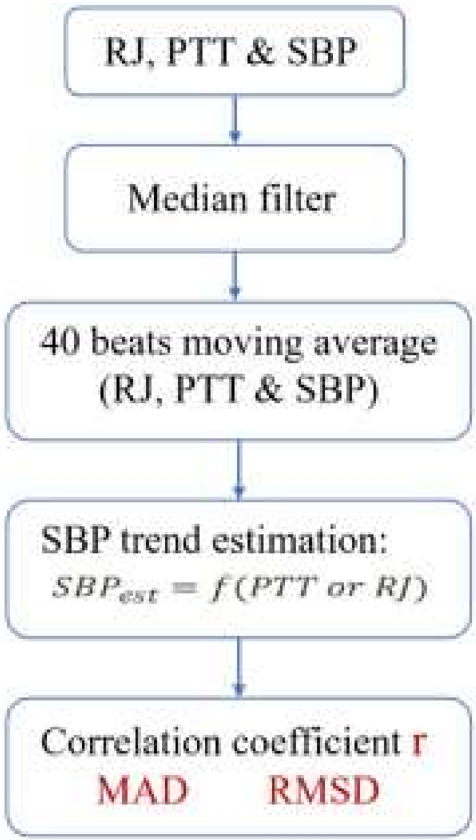
Exponential model: $SBP = A - B \cdot ln(PTT^2)$

Data Collection

- 10 subjects, 15 min data collection (ECG, BCG, PPG & SBP)
- Valsalva maneuver is suggested to be performed every 2 min.



Data Analysis



- The simultaneous time interval (RJ & PTT) and reference SBP were plotted in MATLAB
- The coefficients A and B of the exponential model were obtained by Curve Fitting
- The estimated SBP values were obtained by applying the obtained coefficients in the exponential model

$$SBP_{est} = A - B \cdot ln(PTT^2) \quad \text{(also for } RJ\text{)}$$

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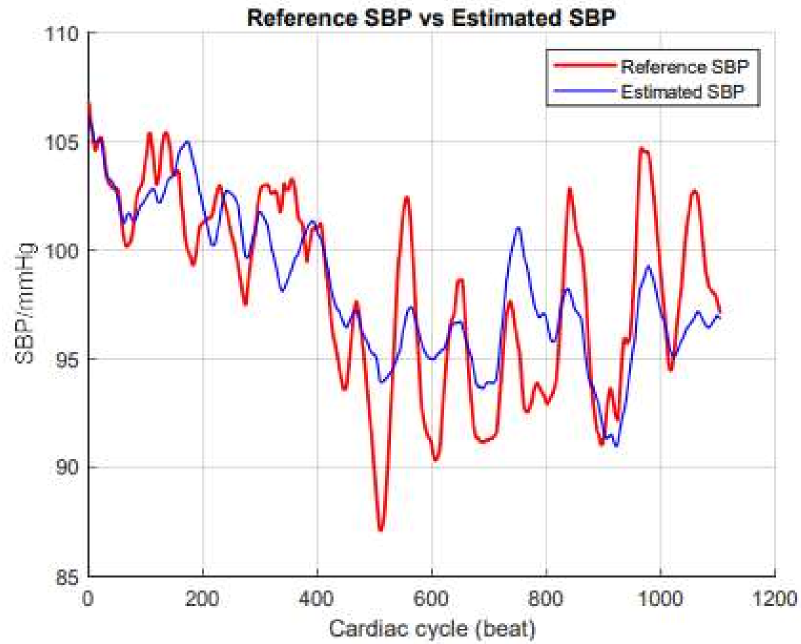
Results

	SBP trend track			
	RJ vs SBP		PTT vs SBP	
	R	MAD	R	MAD
mean	0.627	2.819±0.87	0.552	2.782±0.44

SBP Tracking using Time Intervals

Results:



Conclusion:

- RJ interval and PTT are able to track SBP trend
- RJ interval has the potential to be the surrogate of PTT in cuffless SBP tracking

Conclusions

- The newly designed BCG electrode can detect BCG on the wrists.
- The most common cuffless BP monitoring method is based on pulse transit time (PTT). In this research, a new time interval, RJ interval was employed to track BP.
- The results obtained from this research are encouraging, the RJ interval has the similar performance at PTT in tracking systolic blood pressure.
- Future work:
    - Calibration procedure needs to be developed
    - Single point BP monitor device using JP interval (BCG & PPG) will be evaluated and tested.

Review: Blood pressure measurement

Traditional method

- Sphygmomanometer & arterial invasive line
- Oscillometry-based BP arm or wrist cuffs

Cons: discontinuous nature, patient discomfort, sensitive to motion

New method

- PTT (pulse transit time) based method can estimate BP mathematically and the results are promising, the estimation accuracy is 0.6 ± 9.8 and 0.9 ± 5.6 mmHg for SBP and DBP [1].

[1] C. Poon and Y. Zhang, "Cuff-less and Noninvasive Measurements of Arterial Blood Pressure by Pulse Transit Time," 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, 2005

Photo copies from. [1].http://www.eoinobrien.org/wp-content/uploads/2008/08/19.ABC_.Chapter-4.-Measurement-of-blood-pressure.pdf; [2]. https://www.quora.com/What-is-the-mechanism-of-occurrence-of-korotkoff-sounds-that-we-hear-during-auscultatory-Method-of-BP-measurement; [3]. https://healthmanagement.org/products/view/automatic-blood-pressure-monitor-electronic-arm-mc3100-healthstats-international-pte-ltd; [4]. http://tensoval.com/oscillometric-measurement-devices.php

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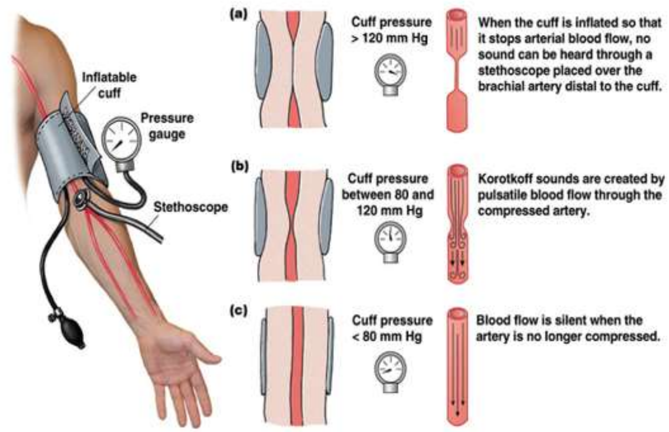
1.Review of BP Measurement

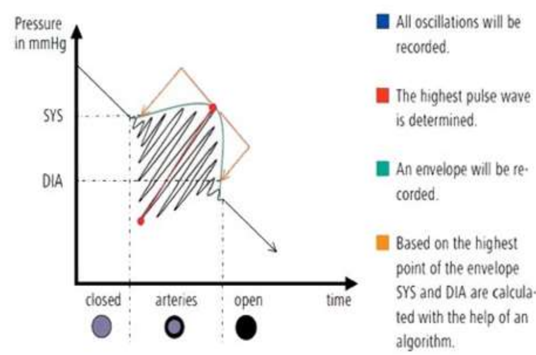
The auscultatory BP device (left) [1] and the methodology of auscultatory BP measurement (right) [2]

1. Auscultatory



The oscillometric BP device (left) [3] and the methodology of oscillometric BP measurement (right) [4]

2. Oscillometeric



Disadvantage:

1. Unable to measure continuously
2. Inflated cuff may cause discomfort

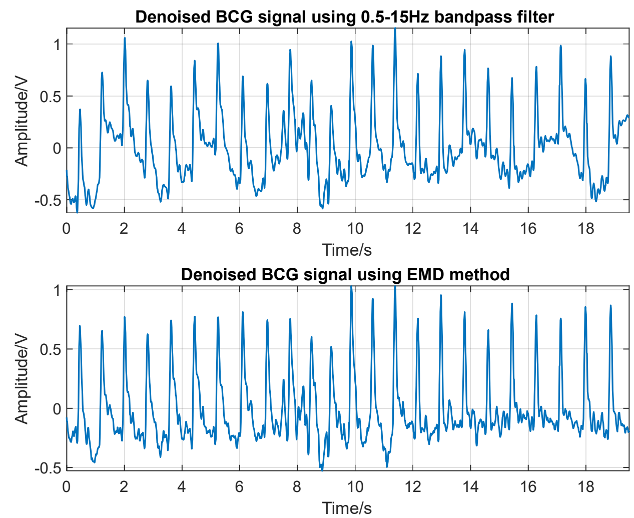
Signal Denoising

60 Hz notch filter

0.5-25Hz ECG
0.5-15Hz BCG
0.5-7Hz PPG

EMD based denoising approach

Comparison:



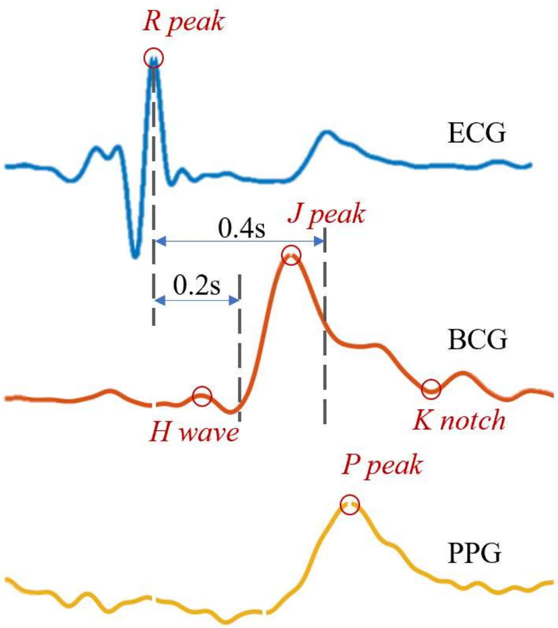
The mean±std of NSDE (Normalized standard deviation from ensemble):

- 0.1443 ±0.0666 for bandpass filter method
- 0.1308 ±0.0665 for EMD based denoising method

Performance: EMD > filter

Peak Detection Algorithm

- ECG R peak and PPG P peak are located by finding local maxima
- BCG J peak is defined as the local maxima with a time window 0.2-0.4s behind ECG R peak



- Other waves, like BCG H, K waves and ECG T wave are detected as the local maxima within certain windows.

PTT-BP model

- M-K model:

$$PWV = \sqrt{\frac{h \cdot E}{2 \cdot r \cdot \rho}}$$

Where, E is Young's modulus, h is vessel wall thickness, ρ is blood density and r is radius. The Young's modulus E describes the elasticity of the arterial wall which is pressure-dependent.

$$E = E_0 \cdot e^{\alpha \cdot P}$$

Where E_0 is the zero pressure modulus, α is a constant that depends on the vessel and P is pressure. Thus, the relation between PWV and BP can be expressed as:

$$PWV = \sqrt{\frac{h \cdot E_0 \cdot e^{\alpha \cdot BP}}{2 \cdot r \cdot \rho}}$$

Thus:

$$BP = \frac{1}{\alpha} \cdot \ln\left(\frac{2 \cdot r \cdot \rho \cdot (PWV)^2}{h \cdot E_0}\right)$$

PTT-BP Model

And PWV is defined as:

$$PWV = \frac{\Delta Z}{PTT}$$

Where ΔZ is the distance between two measurement points. It can be assumed that ΔZ and E_0 remains constant and ρ, r and h show only small changes, and the equation can be expressed as:

$$BP = \frac{1}{\alpha} \cdot ln\left(\left(\frac{\Delta Z}{PTT}\right)^2\right) + \frac{1}{\alpha} \cdot ln\left(\frac{2 \cdot r \cdot \rho}{h \cdot E_0}\right) = k_2 - k_1 \cdot \ln(PTT^2)$$

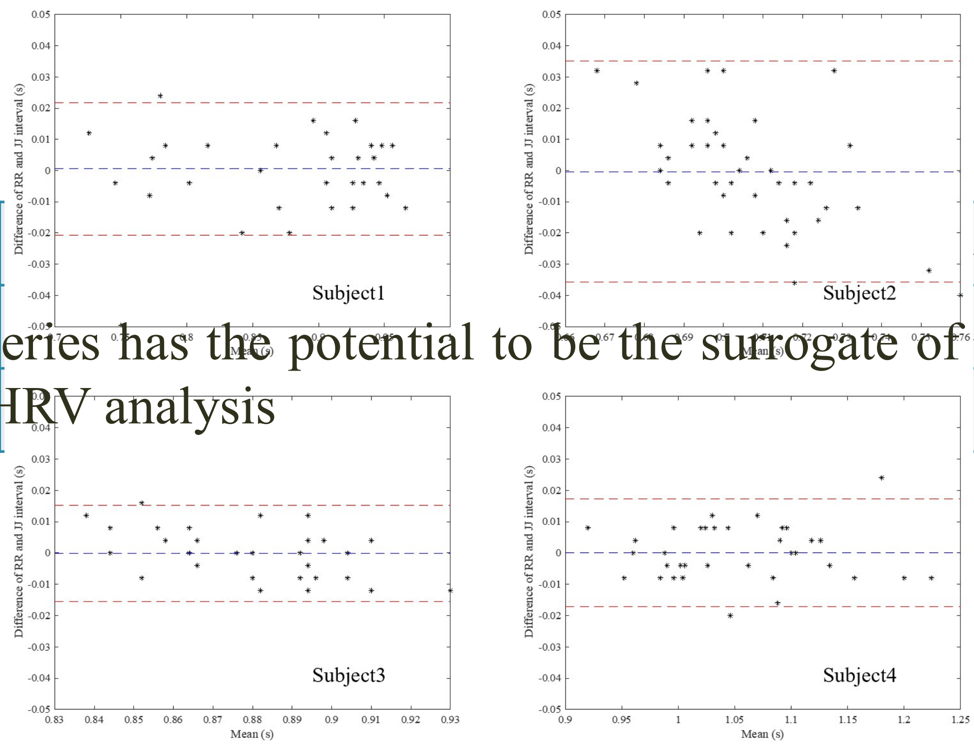
Linear Model:

$$PWV = \frac{1}{c \cdot BP - \frac{c}{4}} \qquad PWV = \frac{\Delta Z}{PTT} \Rightarrow PTT = \Delta Z\left(c \cdot BP - \frac{c}{4}\right) \to BP = A + B(PTT)$$

HRV Analysis

- The RR interval of ECG is the gold standard in HRV analysis
- The HRV test is implemented in time and frequency domain
- Data set: 5-min stationary BCG and ECG collected from each subject (2 males+2 females)

Result:
BCG JJ series has the potential to be the surrogate of ECG RR series in HRV analysis



Bland-Altman plots of ECG RR series and BCG JJ series

[8]. Zienkiewicz, Aleksandra. "BLOOD PRESSURE ESTIMATION USING PULSE TRANSIT TIME MODELS." (2017).[9]. Wibmer, T., et al. "Pulse transit time and blood pressure during cardiopulmonary exercise tests." *Physiological research* 63.3 (2014).

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Comparison with other works

Master thesis: "Blood pressure estimation using pulse transit time models" [8]

Table 4. Pearson's correlation ceofficients between tested models and BP_I.

#	Signal length (s)	Number of data pairs	Pearson's r coefficient					
			BP_{LIN}		BP_{M-K}		BP_G	
			raw	SG	raw	SG	raw	SG
1	100	77	0.39	0.65	0.4	0.65	0.4	0.65
2	100	33	0.42	0.68	0.42	0.68	0.42	0.68
3	400	356	0.32	0.64	0.31	0.64	0.31	0.64
4	100	82	0.37	0.54	0.37	0.54	0.37	0.54
5	600	616	0.49	0.59	0.49	0.6	0.46	0.6
6	200	76	0.26	0.39	0.26	0.39	0.26	0.39
7	600	345	0.47	0.51	0.47	0.51	0.47	0.51
8	100	59	0.44	0.43	0.45	0.44	0.45	0.44
Average	275	205.5	0.4	0.55	0.4	0.56	0.39	0.56

Reference BP: invasive BP

Table 8. Pearson's correlation coefficients between tested models and BP_{FIN}.

#	Signal length (s)	Number of data pairs	Pearson's r coefficient					
			BP_{LIN}		BP_{M-K}		BP_G	
			raw	SG	raw	SG	raw	SG
1	170	174	0.31	0.62	0.31	0.61	0.32	0.61
2	700	692	0.3	0.43	0.3	0.44	0.31	0.44
3	250	268	0.25	0.6	0.24	0.6	0.21	0.59
4	260	245	0.13	0.46	0.14	0.46	0.12	0.45
5	600	539	0.23	0.48	0.22	0.48	0.22	0.45
Average	396	383.6	0.24	0.52	0.24	0.52	0.24	0.51

Reference BP: Finometer

Pulse Transit Time and Blood Pressure During Cardiopulmonary Exercise Tests [9]

Table 3. Coefficients of determination r^2 and R^2 of linear and non-linear regression for each individual patient.

Patient	Number of data pairs	r^2 Linear regression		R^2 Non-linear regression	
		sBP	dBP	sBP	dBP
1	8	0.95	0.12	0.97	0.23
2	8	0.87	0.70	0.87	0.78
3	9	0.96	0.73	0.97	0.73
4	8	0.93	0.58	0.95	
5	8	0.97	0.53	0.98	0.54
6	7	0.98	0.22	0.98	0.36
7	7	0.89	0.38	0.97	
8	9	0.98	0.61	0.99	0.62
9	9	0.92	0.07	0.97	0.32
10	9	0.94	0.55	0.94	0.55
11	8	0.96	0.55	0.96	0.55
12	8	0.93	0.76	0.96	0.79
13	9	0.87	0.46	0.87	0.46
14	9	0.92	0.33	0.92	0.33
15	8	0.93	0.03	0.95	
16	7	0.92	0.27	0.94	0.48
17	7	0.93	0.14	0.93	0.14
18	9	0.93	0.46	0.93	0.53
19	6	0.98	0.01	0.98	0.30
20	9	0.96	0.04	0.97	0.05

Correlation coefficient: 0.9+

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SBP Tracking using Time Intervals

Results:

Subject#	RJ-SBP			PTT-SBP		
	r	MAD	RMSD	r	MAD	RMSD
1	0.76	2.34	2.91	0.69	2.70	3.22
2	0.48	2.11	2.53	0.23	2.33	2.80
3	0.68	3.07	3.86	0.52	3.45	4.51
4	0.61	2.98	3.77	0.47	3.16	4.21
5	0.85	1.83	1.77	0.30	2.82	3.24
6	0.42	3.79	4.78	0.82	2.30	2.99
7	0.66	1.92	2.37	0.50	2.08	2.71
8	0.49	4.59	5.42	0.65	3.14	4.73
9	0.63	2.97	3.81	0.71	2.85	3.47
10	0.68	2.59	3.43	0.63	2.99	3.66
mean±std	0.63±0.13	2.82±0.87	3.47±1.11	0.55±0.19	2.78±0.44	3.55±0.71

* r: correlation coefficient, MAD: mean absolute difference, RMSD: root mean standard deviation (the unit of MAD and RMSD: mmHg)