Continuous Tracking Changes in Systolic Blood Pressure using BCG and ECG

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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.
• 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.
• 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

- ECG Sensor
- PPG Sensor
- BCG Sensor

Circuit, DAQ Program

Processing & Analysis

- Denoising
- Peak Detection

SBP tracking

- RJ & PTT Calculation
- SBP Tracking

Reference BP device
1. Lead 1 ECG:

2. Optical Wrist PPG

3. Wrist BCG
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
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

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

& \[ E = E_0 \cdot e^{\alpha \cdot BP} \]

Where, \( E \) is Young’s modulus, \( h \) is vessel wall thickness, \( \rho \) is blood density and \( r \) is radius, \( E_0 \) is the modulus of elasticity when pressure is zero, \( BP \) is blood pressure and \( \alpha \) 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:
  $$SBP_{est} = A - B \cdot \ln(PTT^2) \quad (also \ for \ RJ)$$
# Results

## SBP trend track

<table>
<thead>
<tr>
<th></th>
<th>RJ vs SBP</th>
<th>PTT vs SBP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>MAD</td>
</tr>
<tr>
<td>mean</td>
<td>0.627</td>
<td>2.819 ± 0.87</td>
</tr>
</tbody>
</table>
Results:

![Graph showing reference SBP vs estimated SBP over cardiac cycles.](image)

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. 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. Oscillometric

Disadvantage:

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

Comparison:

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

60 Hz notch filter

EMD based denoising approach

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
• 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

![Diagram showing peak detection algorithm]

• Other waves, like BCG H, K waves and ECG T wave are detected as the local maxima within certain windows.
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, \( \rho \) 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, \( \alpha \) 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:

\[ BP = \frac{1}{\alpha} \cdot \ln \left( \frac{2 \cdot r \cdot \rho \cdot (PWV)^2}{h \cdot E_0} \right) \]
And PWV is defined as:

\[ PWV = \frac{\Delta Z}{PTT} \]

Where \( \Delta Z \) is the distance between two measurement points. It can be assumed that \( \Delta Z \) and \( E_0 \) remains constant and \( \rho, r \) and \( h \) show only small changes, and the equation can be expressed as:

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

Linear Model:

\[ PWV = \frac{1}{c \cdot BP - \frac{c}{4}} \quad PWV = \frac{\Delta Z}{PTT} \quad PTT = \Delta Z \left( c \cdot BP - \frac{c}{4} \right) \rightarrow BP = A + B(PTT) \]
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
Comparison with other works

Table 4. Pearson’s correlation coefficients between tested models and BP_f.

<table>
<thead>
<tr>
<th>#</th>
<th>Signal</th>
<th>Number of data pairs</th>
<th>Pearson’s r coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>length (s)</td>
<td></td>
<td>BP_fLin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>raw</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>77</td>
<td>0.39</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>33</td>
<td>0.42</td>
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<td>3</td>
<td>400</td>
<td>356</td>
<td>0.32</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>82</td>
<td>0.37</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
<td>616</td>
<td>0.49</td>
</tr>
<tr>
<td>6</td>
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<td>616</td>
<td>0.26</td>
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<td>7</td>
<td>800</td>
<td>345</td>
<td>0.47</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>59</td>
<td>0.44</td>
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<tr>
<td>Average</td>
<td>275</td>
<td>203.5</td>
<td>0.4</td>
</tr>
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</table>

Table 8. Pearson’s correlation coefficients between tested models and BP_fFin.

<table>
<thead>
<tr>
<th>#</th>
<th>Signal</th>
<th>Number of data pairs</th>
<th>Pearson’s r coefficient</th>
</tr>
</thead>
<tbody>
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<td>692</td>
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<tr>
<td>3</td>
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<td>268</td>
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<td>4</td>
<td>260</td>
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<td>5</td>
<td>600</td>
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<tr>
<td>Average</td>
<td>396</td>
<td>383.6</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Reference BP: invasive BP

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.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Number of data pairs</th>
<th>$r^2$ Linear regression</th>
<th>$R^2$ Non-linear regression</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>sBP</td>
<td>dBP</td>
</tr>
<tr>
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<td>0.95</td>
<td>0.12</td>
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<td>8</td>
<td>0.87</td>
<td>0.70</td>
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<tr>
<td>3</td>
<td>9</td>
<td>0.96</td>
<td>0.73</td>
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<tr>
<td>4</td>
<td>8</td>
<td>0.93</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>0.97</td>
<td>0.53</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>0.98</td>
<td>0.22</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0.89</td>
<td>0.38</td>
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<tr>
<td>8</td>
<td>9</td>
<td>0.98</td>
<td>0.61</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>0.92</td>
<td>0.07</td>
</tr>
<tr>
<td>10</td>
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<td>0.94</td>
<td>0.55</td>
</tr>
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<td>11</td>
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<td>0.96</td>
<td>0.55</td>
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<tr>
<td>12</td>
<td>8</td>
<td>0.93</td>
<td>0.76</td>
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<td>13</td>
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<td>0.92</td>
<td>0.33</td>
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<tr>
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<td>8</td>
<td>0.93</td>
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<td>0.92</td>
<td>0.27</td>
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<td>0.93</td>
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<td>0.98</td>
<td>0.01</td>
</tr>
<tr>
<td>20</td>
<td>9</td>
<td>0.96</td>
<td>0.04</td>
</tr>
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</table>

Correlation coefficient: 0.9+
# SBP Tracking using Time Intervals

## Results:

<table>
<thead>
<tr>
<th>Subject#</th>
<th>RJ-SBP</th>
<th></th>
<th>PTT-SBP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>MAD</td>
<td>RMSD</td>
<td>r</td>
</tr>
<tr>
<td>1</td>
<td>0.76</td>
<td>2.34</td>
<td>2.91</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>2.11</td>
<td>2.53</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>0.68</td>
<td>3.07</td>
<td>3.86</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>0.61</td>
<td>2.98</td>
<td>3.77</td>
<td>0.47</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
<td>1.83</td>
<td>1.77</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>0.42</td>
<td>3.79</td>
<td>4.78</td>
<td>0.82</td>
</tr>
<tr>
<td>7</td>
<td>0.66</td>
<td>1.92</td>
<td>2.37</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>0.49</td>
<td>4.59</td>
<td>5.42</td>
<td>0.65</td>
</tr>
<tr>
<td>9</td>
<td>0.63</td>
<td>2.97</td>
<td>3.81</td>
<td>0.71</td>
</tr>
<tr>
<td>10</td>
<td>0.68</td>
<td>2.59</td>
<td>3.43</td>
<td>0.63</td>
</tr>
</tbody>
</table>

| 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)