An Innovative Ring-type Wearable Device Equipped with Deep Learning Analysis of Photoplethysmographic Signals to Detect Atrial Fibrillation

Speaker: Soonil Kwon, MD, BSc Physics

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    Stockholder of Sky Labs

BKK: Stockholder of Sky Labs

YY: Research grant from Sky Labs

The remaining co-authors have nothing to disclose
Introduction

Why do we need this study?
Introduction

- Atrial fibrillation (AF)
  - Increasing prevalence \(^1\)
  - Increasing medical expenses \(^2\)
  - Prevention of ischemic stroke
  - Need for early diagnosis

- Early stage of AF
  - Paroxysmal nature \(^3\)
  - Simple ECG screening: No effect
  - Unmet needs of Dx strategy

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Continuous AF monitoring may be helpful for early detection

Adapted from Wyse DG, J Am Coll Cardiol 2014
Introduction

• Photoplethysmography (PPG)
  • Good correlation with ECG
  • AF diagnosis\textsuperscript{1}
  • Deep learning analysis\textsuperscript{2}

• PPG measurements
  • Medical pulse oximeters
  • Smartphones\textsuperscript{3}
  • Wearable devices\textsuperscript{4}

\textbf{Smartphones:} Continuous monitoring (x)
\textbf{Wearable devices:} Mostly wrist-type nowadays

\textsuperscript{1}Poh M, Heart. 2018; \textsuperscript{2}Kwon S, JMIR \textit{mHealth} and \textit{uHealth}. 2019; \textsuperscript{3}Chan PH, J Am Heart Assoc. 2016; \textsuperscript{4}Fallet S, Med Biol Eng Comput. 2019
## Introduction

### PPG vs. ECG

<table>
<thead>
<tr>
<th></th>
<th>PPG</th>
<th>ECG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagnosis</strong></td>
<td>Non-standard</td>
<td>Gold standard (12-lead)</td>
</tr>
<tr>
<td><strong>Atrial activity</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Differential Dx</strong></td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td><strong>Frequent measurements</strong></td>
<td>Easy</td>
<td>Difficult</td>
</tr>
<tr>
<td><strong>Smartphone, Wearables</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>User efforts</strong></td>
<td>Little</td>
<td>Much</td>
</tr>
<tr>
<td><strong>User compliance</strong></td>
<td>Better (?)</td>
<td>Not good</td>
</tr>
<tr>
<td><strong>Long-term, continuous monitoring?</strong></td>
<td></td>
<td>Invasive methods (e.g. ILR)</td>
</tr>
</tbody>
</table>

### Advantages of PPG

- Ease of measurements
- Possibly better compliance with lesser efforts
- Better for continuous monitoring
• PPG measurement, from *Where*?
  • Wrist vs. Finger

<table>
<thead>
<tr>
<th></th>
<th>Finger</th>
<th>Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Device type</td>
<td>Ring</td>
<td>Watch, strap</td>
</tr>
<tr>
<td>Device size</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Pulse peak</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Pulse width</td>
<td>Narrower</td>
<td>Wider</td>
</tr>
<tr>
<td>SNR</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

For the best diagnostic potential

→ Finger is the ideal location to measure PPG signals
→ Ring-type may be more appropriate than wrist-type

Adapted from Hartmann V, Front Physiol. 2019
Introduction

• Our previous study
  • Deep learning analysis & PPG signals
  • High diagnostic performance

Previous study:
Based on PPG signals from a conventional device

Adapted from Kwon S, JMIR mHealth and uHealth. 2019
The Aim of the Study

1) Develop a ring-type wearable device to detect AF
   • With deep learning analysis of PPG signals

2) Validate its diagnostic performance
Methods
Methods

• Study design
  • Prospective, single-center study

• Inclusion criteria
  1) Persistent AF, elective DC CV
  2) Intracardiac thrombi (-)
  3) Aged ≥20 years

• Exclusion criteria
  1) Not AF (at the time of CV try)
  2) Failed CV
  3) Measurement errors

Patients with persistent AF and admitted for elective direct-current cardioversion during 2018-2019 (n = 139)

Exclusion:
- Failed to be cardioverted (n = 1)
- Atrial flutter (n = 7)
- Atrial tachycardia (n = 5)
- Measurement error (n = 26)

The study population (n = 100)
Methods

• Data acquisition
  • Finger 1 – The ring
  • Finger 2 – Conventional PO
  • Chest – Single-lead ECG
  • Both before and after CV

Required to rest at the bed
→ Assumption of minimized motion artifacts

• Rhythm validation
  • ECG-rhythm – 2 Cardiologists
  • PPG-rhythm – Simultaneous ECG

Adapted from Kwon S, Heart Rhythm 2019, Oral abstract presentation
Methods

• PPG signal analysis
  • PPG sample length – 30-second
  • Labeling for learning – AF or SR
  • Deep learning algorithm – CNN
  • NN structure – 9 layers

Adapted from Kwon S, Heart Rhythm 2019, Oral abstract presentation
Methods

• Evaluation of diagnostic performance
  • Training & testing – 5-fold cross validation
  • 10x each set of training & testing → 50 validations
  • Average ROC curves, Accuracy, SN, SP, PPV, and NPV
    • Cf. Accuracy = (# of correct tests) / (# of total tests)
  • CNN vs. SVM
    • Cf. SVM ← Features: RMSSD or autocorrelation, or both

• Algorithm development environment
  • Software: Phyton, Tensorflow
  • Hardware: NVIDIA Titan XP
Methods

• Calculation of AF- or SR-probability
  • Softmax function

$$e^{\frac{z}{1}} \sum_{k=1}^{n} e^{\frac{z}{k}}$$

AF, 10%
SR, 90%

Diagnosis
Output
AF, 90%

Neural network
Methods

- The ring
  - PPG sensing from 2x proper palmar digital arteries
  - Green LED
  - 2x optical sensors
  - Transmitting signals to user’s smartphone by Bluetooth
  - Multiple sizes to fit user’s finger properly

The courtesy of Sky Labs, Inc., Republic of Korea
Results
Results

• Baseline characteristics

A total of 100 AF participants

Mean age 63.8 years
Male 81.0%
Median CHA$_2$DS$_2$-VASc 2
AF ≥1 year, 19%

• Sample total N = 13,038

<table>
<thead>
<tr>
<th>Demographics</th>
<th>N (Total 100)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>63.8 ± 8.5</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>81</td>
<td>81.0</td>
</tr>
<tr>
<td>Body mass index (kg/m$^2$)</td>
<td>25.3 (23.5-27.1)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Types of AF</th>
<th>N (Total 100)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent (≤1 month &amp; &lt;1 year)</td>
<td>81</td>
<td>81.0</td>
</tr>
<tr>
<td>Long-standing persistent (≥1 year)</td>
<td>19</td>
<td>19.0</td>
</tr>
</tbody>
</table>

| CHA$_2$DS$_2$-VASc score     | 2 (1-3)      |    |

<table>
<thead>
<tr>
<th>Comorbidity</th>
<th>N (Total 100)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestive heart failure</td>
<td>15</td>
<td>15.0</td>
</tr>
<tr>
<td>Hypertension</td>
<td>57</td>
<td>57.0</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>27</td>
<td>27.0</td>
</tr>
<tr>
<td>Stroke or TIA</td>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td>6</td>
<td>6.0</td>
</tr>
<tr>
<td>Valvular heart disease</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>Dyslipidemia</td>
<td>35</td>
<td>35.0</td>
</tr>
<tr>
<td>Chronic renal failure</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>COPD</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Hyperthyroidism</td>
<td>3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antiarrhythmic agents</th>
<th>N (Total 100)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propafenone</td>
<td>17</td>
<td>17.0</td>
</tr>
<tr>
<td>Flecainide</td>
<td>10</td>
<td>10.0</td>
</tr>
<tr>
<td>Pilsicainide</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>Sotalol</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Amiodarone</td>
<td>64</td>
<td>64.0</td>
</tr>
<tr>
<td>Beta blocker</td>
<td>24</td>
<td>24.0</td>
</tr>
<tr>
<td>Calcium channel blocker</td>
<td>27</td>
<td>27.0</td>
</tr>
<tr>
<td>Digoxin</td>
<td>2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anticoagulant</th>
<th>N (Total 100)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td>Warfarin</td>
<td>8</td>
<td>8.0</td>
</tr>
<tr>
<td>NOAC</td>
<td>88</td>
<td>88.0</td>
</tr>
</tbody>
</table>
## Results

- **Dignostic performance of the ring by algorithms**

### Current study – The ring device

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Accuracy</th>
<th>SN</th>
<th>SP</th>
<th>PPV</th>
<th>NPV</th>
<th>AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNN</td>
<td>96.9</td>
<td>99.0</td>
<td>94.3</td>
<td>95.6</td>
<td>98.7</td>
<td>0.993 (0.992-0.993)</td>
</tr>
<tr>
<td>SVM, ensemble†</td>
<td>91.5</td>
<td>91.3</td>
<td>91.7</td>
<td>93.1</td>
<td>89.6</td>
<td>0.983 (0.982-0.983)</td>
</tr>
<tr>
<td>SVM, auto‡</td>
<td>91.4</td>
<td>92.2</td>
<td>90.4</td>
<td>92.2</td>
<td>90.4</td>
<td>0.982 (0.981-0.982)</td>
</tr>
<tr>
<td>SVM, RMSSD+ShE§</td>
<td>84.1</td>
<td>90.7</td>
<td>76.1</td>
<td>82.3</td>
<td>86.9</td>
<td>0.887 (0.885-0.889)</td>
</tr>
</tbody>
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<tr>
<td>CNN</td>
<td>97.6</td>
<td>99.3</td>
<td>95.9</td>
<td>96.0</td>
<td>99.3</td>
<td>0.998 (0.995-1.000)</td>
</tr>
<tr>
<td>SVM, ensemble†</td>
<td>90.7</td>
<td>88.6</td>
<td>92.9</td>
<td>92.5</td>
<td>89.1</td>
<td>0.976 (0.970-0.981)</td>
</tr>
<tr>
<td>SVM, auto‡</td>
<td>91.4</td>
<td>93.3</td>
<td>89.6</td>
<td>89.9</td>
<td>93.0</td>
<td>0.977 (0.972-0.982)</td>
</tr>
<tr>
<td>SVM, RMSSD+ShE§</td>
<td>86.8</td>
<td>89.1</td>
<td>84.5</td>
<td>85.2</td>
<td>88.6</td>
<td>0.868 (0.854-0.881)</td>
</tr>
</tbody>
</table>

### Previous study – Conventional PO

Best of prior algorithms:

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Accuracy</th>
<th>SN</th>
<th>SP</th>
<th>PPV</th>
<th>NPV</th>
<th>AUC</th>
</tr>
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<tbody>
<tr>
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<td>94.3</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>91.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The data are generated by averaging 10 times of 5-fold cross validation processes.

The data are presented as mean values in percentage.

† The algorithm of Support Vector Machine (SVM) using RMSSD and Shannon entropy (ShE) as features
‡ SVM using autocorrelation as a feature
§ SVM using RMSSD, ShE and autocorrelation as features
Results

• Dignostic performance of the ring by algorithms

• The ring measured PPG signals from the finger

• With deep learning analysis, the ring’s performance can be maximzed
Results

• Diagnostic performance: The ring vs. Conventional PO

(a) The ring device
(b) Conventional PO

• Performance tuning by filtering low-quality samples
• Higher performance counter-balanced by more filterings
• The ring has comparable performances to conventional PO
Results

• Diagnostic performance: The ring vs. Conventional PO

The ring showed a comparable performance to a medical-grade conventional PO
Results

• Diagnostic performance of the ring by measurement durations

• Potentially, 5~10-second is enough for AF detection with the ring
Summary

With...

1) Deep learning analysis of PPG signals
2) The ring-type wearable device

AF detection can be...

1) Accurate (Accuracy 96.9%, SN 99.0%, SP 94.3%)
2) Comparable to a conventional medical-grade PO
Limitations

1) Under non-ambulatory setting
2) Participant N = 100
3) Other than AF
4) Participant experiences with the ring
5) Potential safety issues
Conclusions

1) A ring-type wearable device with deep learning analysis of PPG signals can diagnose AF with high performance

2) This technology can be a new strategy to monitor and detect AF in the future

3) Further study is needed to screening results among the ambulatory patients with high-risk of AF
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