The MIT Ring: History, Technology, and Challenges of Wearable Health Monitoring

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Department of Mechanical Engineering
d'Arbeloff Bio-Robotics Lab
MIT
Wearable Health Monitoring:
Patient-in-the-loop

Clinical Services

Wearable Sensors
MIT Ring: A Photo-Plethysmograph (PPG) Sensor

- Anywhere, any time, and continuous
- Virtually imperceptible to the wearer, and
- Multi-functional: Pulse, pulse rate variability, Sat O2, and blood pressure

Wearable biosensor network with PPG ring sensor

MIT Home Automation and Health Care Consortium
1995-2002
@home

@ work

@ fitness

@ hospital

@ wheel.car

Ring Sensors

“Patient Monitoring Finger Ring Sensor”, US Patent 5,964,701
Outline of the Presentation

• The MIT Ring: Background
• Early continuous health monitoring technology
• Wearable blood pressure sensors
• Diagnostic signal processing
• Beyond the wearable sensors: Biological machines/robots for future health care
  – NSF Science and Technology Center: EBICS
Early Development

The first Ring Sensor, 1996

MIT Home Automation and Healthcare Consortium

1997

H.Harry Asada, Sokwoo Rhee, and Philip Shaltis

1998

1999
Video: Health Beat, Evening News

1997
Wireless Transmission

Low power consumption and small form factor
Radio Transmitter and Network Protocol

1998~99

PDA/Cellular

Internet

RF Transmitter

Antenna

Integrated Computer/Transmitter

Battery

Flash Memory

I/O

CPU

Modulation &
Active Sensing

Sensor

i-Coin
The first prototype of *i-Coin* was distributed to the member companies of the MIT Home Automation and Healthcare Consortium in 1999.
Millennial Net is pioneering the technology of integrating single-chip microcontrollers with low-energy RF transceivers for multiple access wireless network computing. This proprietary technology has lead to the successful development of a powerful, fully integrated data processing and wireless communication device, the i-Bean, which is merely the size of three stacked US quarters and runs on a 3 VDC cell battery for its entire life span.

**Small and Compact**
The i-Bean is the size of a thick quarter. Its size makes it portable, unobtrusive and easy to integrate into the smallest devices.

**Powerful and Flexible**
An integrated CPU with flash memory gives the i-Bean data processing muscle with the freedom to forgo back-end analog-digital translation.

**Minimal Installation**
The i-Bean communicates without wires and carries all the tools that it needs (CPU, transceiver, and power source). Installation is effortless and costs almost nothing.

**Energy Efficient**
Unique engineering makes the i-Bean a power miser, so that a single battery can power the i-Bean for the duration of its life.
Monitoring of Building Energy System

Drs. Sokwoo Rhee and Sheng Liu

Wireless Technology: Meshscape® 5

MeshScape 5 is Millennial Net's fifth generation high-end wireless mesh technology that delivers OEMs and system integrators all of the software, hardware, and tools to quickly and cost-effectively develop and deploy embedded wireless sensor networking applications.

www.millennial.net

April 2001
Information Technology

Sensors

Clinical Services & Utilization
Technical Challenges

- Miniaturization
- Low power consumption
- Motion artifact
- Accuracy
Photo Plethysmograph (PPG) Ring Sensors

1. Miniaturizable
2. Low power consumption
3. Rich information
   - Pulse
   - SaO2
   - Pulse rate variability
   - Blood Pressure
PPG is susceptible to motion.

PPG signal is Corrupted Under Bodily Acceleration

- Swinging hand with the ring sensor
- Stationary hand with 2\(^{nd}\) ring sensor

Correct Signal

Motion Corrupted Signal

Acceleration (x10g)

Time/sec
Approach: Noise Cancellation Using Accelerometer

Motion during daily chores and sports

Signal Source

Sensor (PPG)

Corrupted signal

Active Noise Cancellation

Recovered Signal

Accelerometer

PPG Ring Sensor
Approach: Active Noise Cancellation Using MEMS Accelerometers

Signal Source + Motion Source → Corrupted Signal

+ Motion-Induced Noise

MEMS Accelerometer → Noise Cancellation Filter

Parameter Estimation → Recovered Signal
Motion Artifact Reduction Result (Laguerre Basis)

- Recovered Signal
- Correct Signal
- Disturbed Signal
- Acceleration

Stationary hand w/ 2\textsuperscript{nd} ring sensor

Swinging hand with the ring sensor
The Mood Ring: The heart and the brain are tightly connected.

- Stress
- Anger/Frustration
- Etc.
- Calm
- Appreciation
- Etc.

Sympathetic Nerve System

Parasympathetic Nerve System

Heart Rate

The heart is a brain.
Heart Rate varies depending on sympathetic and parasympathetic tones and others.

Model of Heart Rate Mechanism

Heart Rate

Pacemaker

Cardiac Output
Blood Pressure
Hemodynamic State

Renin-Angiotensin System

Parasympathetic System

Sympathetic System

Thermoregulatory System

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Varying Beat-to-Beat Heart Rate

Comparison of Beat-to Beat Heart Rate measured by Ring Sensor, NellCor Sensor and ECG
Known relationship between different frequency bands of HRV and mental activities

<table>
<thead>
<tr>
<th>Freq. Band</th>
<th>Freq. Range</th>
<th>Mental Activities Associated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Freq.</td>
<td>0.01-0.08Hz</td>
<td>Mainly sympathetic activities (stress/frustration)</td>
</tr>
<tr>
<td>Medium Freq.</td>
<td>0.08-0.15Hz</td>
<td>Mixed sympathetic and parasympathetic activities</td>
</tr>
<tr>
<td>High Freq.</td>
<td>0.15-0.50Hz</td>
<td>Respiratory sinus arrhythmia and is almost exclusively due to parasympathetic activity</td>
</tr>
</tbody>
</table>
Comparing HRV Results from Different Sensors

Comparison of HRV result by Ring Sensor, Nellcor Sensor and ECG

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Driver Mood Monitoring

Road Tests
Road Test Results
Road Test Course

Interstate 93

Less traffic: Newton
Heavier traffic: Cambridge, Boston

Interstate 90 (Mass Pike)
Big Dig Construction Site

Rt. 128

asada@mit.edu
Actual Road Test HRV Analysis (Entire Ten Minutes Session)
HRV Break-up in Five Minutes Sessions

asada@mit.edu
Contributions

- Ring sensor development
  - Motion artifact resistive design; 3G acceleration
- Heart rate variability estimation
  - Spectrum analysis for incomplete data having missing periods
- Initial road tests
  - Detection of sympathetic and parasympathetic activities

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Challenge

Wearable Blood Pressure Measurement

H. Harry Asada, Ph.D
Devin McCombie, Ph.D
Jin-Oh Hahn, Ph.D
Phil Shaltis, Ph.D
Massachusetts Institute of Technology
and
Andrew Reisner, MD
Massachusetts General Hospital
Patient-in-the-loop Hypertension Management System using Wearable Blood Pressure sensors

Alert, Medication, etc.

Pressure Regulator → Wearable ABP Sensor
Why Monitor Arterial Blood Pressure (ABP)?

Rich Information

**Diagnostically**
- Chronic *High* ABP → heart disease
- *Low* ABP → life-threatening emergencies

**Therapeutically**

*High* ABP reflects
- insufficient medication
- missed doses

Many Applications

**Clinically**
- Enables patient mobility
- Enhances rehabilitation

**Home**
- Provides vigilance
- Improves early release care

**Field**
- Permits disaster monitoring
- Augments on-sight treatments
Technological Goal

Long-Term, Continuous Monitoring

Blood Pressure

BP varies at all times

Traditional BP measurement is a snap-shot measurement.
Technological Goal

Long-Term, Continuous Monitoring

Blood Pressure

BP varies at all times

Traditional BP measurement is a snap-shot measurement.

Long-Term, Continuous BP measurement:
- Average out the fluctuation,
- Keep track of variation
Non-Invasive Devices for Blood Pressure Monitoring

<table>
<thead>
<tr>
<th>Originally Developed</th>
<th>Auscultation</th>
<th>Oscillometry</th>
<th>Tonometry</th>
<th>Volume Clamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riva Rocci, Kortokoff (1896, 1905)</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td><strong>NO</strong></td>
<td><strong>NO</strong></td>
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<tr>
<td>Automated* Inman (1962)</td>
<td></td>
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<td>Pressman and Newgard (1963)</td>
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<tr>
<td>Penaź and Wesseling (1973, 1984)</td>
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<table>
<thead>
<tr>
<th>‘Wearability’</th>
<th>Auscultation</th>
<th>Oscillometry</th>
<th>Tonometry</th>
<th>Volume Clamp</th>
</tr>
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<tbody>
<tr>
<td><strong>YES</strong></td>
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<tr>
<th>Easy to Use</th>
<th>Auscultation</th>
<th>Oscillometry</th>
<th>Tonometry</th>
<th>Volume Clamp</th>
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<tr>
<td><strong>NO</strong></td>
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<tr>
<th>Continuous</th>
<th>Auscultation</th>
<th>Oscillometry</th>
<th>Tonometry</th>
<th>Volume Clamp</th>
</tr>
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<tbody>
<tr>
<td><strong>NO</strong></td>
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<td><strong>YES</strong></td>
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<tr>
<td><strong>YES</strong></td>
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</table>

No single sensor currently meets all of the monitoring criteria!
# Commercially Available BP Modalities

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Areas of Use</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sphygmomanometer</strong></td>
<td>Upper arm measurements are most common</td>
<td>Transportable, well-established; can be used on most patients</td>
<td>Manual devices can have observer bias; affected by body position</td>
</tr>
<tr>
<td><strong>Devices relying on Oscillometric, Doppler, or photo cell methods</strong></td>
<td>Palpable arteries (wrist, toe, finger, etc.)</td>
<td>No observer bias, can be less susceptible to positioning errors; potential for continuous BP</td>
<td>Large performance variations; can be expensive; typically require a palpable artery</td>
</tr>
<tr>
<td><strong>Tonometric devices</strong></td>
<td>Palpable arteries (wrist, toe, finger, etc.)</td>
<td>Potential for continuous BP; No observer bias</td>
<td>Difficult to properly position; Requires additional calibration</td>
</tr>
<tr>
<td><strong>Invasive/ Implantable probes</strong></td>
<td>Larger arteries (radial, brachial, etc.)</td>
<td>No observer bias; Minimal measurement confounders</td>
<td>Invasive; requires clinician;</td>
</tr>
</tbody>
</table>

Adapted from:

“Recommendations for Blood Pressure Measurement in Humans and Experimental Animals...,” Hypertension, March 2006.

ABP Measurement based on Pulse Wave Velocity

\[ PWV = \left( \frac{\Delta x}{PTT} \right) \]
BP Measurement based on Pulse-Wave-Velocity: No Cuff, No Actuator Needed

No cuff, no actuator:
• Minimal interference with daily activities and sleep
• Reduced energy consumption
Pulse Wave Velocity

- No mechanical pressure sensor needed
- Time line measurement rather than amplitude measurement
The calibration curve is time varying!

Blood Pressure (mmHg)

Pulse Wave Velocity (m/s)
Traditional Methods for PWV based BP Measurement

ECG

Inaccurate Velocity Measure

$$PWV = \left( \frac{\Delta x}{PTT} \right)$$

Varying BP-PWV Relation

$$BP = fcn(PTT)$$

<table>
<thead>
<tr>
<th>BP</th>
<th>PTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>84</td>
<td>0.02</td>
</tr>
<tr>
<td>80</td>
<td>0.03</td>
</tr>
<tr>
<td>78</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Derive accurate PWV estimates from two in-line PPG sensors

\[ \Delta P(t) = \rho g (h_2 - h_1) \]

Provide adaptive PWV to BP calibration using Height measurement
Calibration of Blood Pressure - Pulse Transmit Time Relationship

\[
\ln \left( PTT(t)^{-2} \right) = k_1 P(t) + \ln \left( PTT_0^{-2} \right)
\]

\( y(t) \)

\( y_0(t) \)

\[
y_0 = \ln \left( PTT^{-2} \right) \bigg|_{P=0}
\]

\( \frac{1}{k_1} \)

Blood Pressure

(Pulse Transmit Time)
Auto-calibration
using hydrostatic pressure challenge

\[ \Delta P(t) = \rho g \Delta h(t) \]

Hydrostatic pressure =
Absolute gauge that people can use anywhere at any time
Micro Accelerometer Height Sensor

- Two dual-axis MEMS accelerometers:
  - One at the height of the upper arm
  - One within the BP sensor

- The two MEMS accelerometers are aligned with the upper arm and forearm, respectively.

- Knowing the lengths $\ell_1, \ell_2$ the height of the BP sensor from the heart is given by:

\[ h = \ell_1 \cdot \cos \theta_1 + \ell_2 \cdot \cos \theta_2 \]
Dual Accelerometer Height Sensor

Graph showing the relationship between estimated arm height relative to the heart and true arm height relative to the heart. The graph includes data points and a trend line. The diagram illustrates the placement of PD Array Pressure Sensor, Pressure Sensor, Accelerometer, and LEDs.
Sensor Location and Modality

- **Wrist and finger: the right location?**
  - Away from the central pressure
  - The distance is too short to measure the time difference
  - Physiologic state of hands is so changeable?

- **How useful is the measurement?**
  - What is measured, diastolic pressure alone?
  - Continuous?

- **Easy and reliable to use?**
  - Long term wearability
  - How reliable?
  - Optical sensors: the right sensor modality?
SENSOR Modality

Optical Method:
Photoplethysmograph (PPG)

- Localized and focused
- Good SNR
- Miniaturizable
- Light weight
- Low power
- Low cost

Alternative sensor modality:
- Pressure/haptic sensors: Expensive, not focused
- Bio-impedance, EIP: Not focused, but easy to use
POTENTIAL MEASUREMENT SITES

- Brachial Artery
- Radial Artery
- Ulnar Artery

- Signal strength
- Natural posture
- Easy placement
- Transit distance
- Comfort and wearability
\[ PTT = \Delta x \left( \frac{2pR}{hE_0 \exp(kP)} \right)^{0.5} \]
Investigation into Multi-Level PTT Measurement Using a Cardiovascular System Simulator

Courtesy of Roger Kamm
Multi-Level PTT Measurement Using 2 BP Signals

![Diagram showing inlet-to-halfway and halfway-to-exit PTT measurements with corresponding time and radial BP values.

Legend:
- Blue line: Inlet
- Red dashed line: Halfway
- Purple dashed line: Exit

Key:
- 5% to 40% intervals

Graph: Time [sec] vs. Radial BP [mmHg]
\( P(t) = P_D(t) + P_H(t) \)

\( y(t) = \ln(PTT^2(t)) \)

\( T_{span} \approx 60 \text{ seconds} \)

\( f_{ARM} = 0.05 - 0.03 \text{ Hz} \)

\( \tau = 10-15 \text{ seconds} \)
PWV to BP estimation (adult female)
Experimental results (MIT student)

PTT, Hydrostatic, and Finapres™ Data collected from the same person for 1 minute

\[ \hat{y}_0 = y(t) - \hat{k}_1 P_{\text{Finapres}} \]

<table>
<thead>
<tr>
<th>Method</th>
<th>( \hat{k}_1 )</th>
<th>( \hat{Y}_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our method</td>
<td>0.0570</td>
<td>2.61*</td>
</tr>
<tr>
<td>Finapres™ BP</td>
<td>0.0561</td>
<td>2.67</td>
</tr>
<tr>
<td>Parameter Error</td>
<td>1.67%</td>
<td>2.53%</td>
</tr>
</tbody>
</table>
Continuous Mean Arterial Pressure Estimation
New Possibilities of Continuous BP Measurement

1. Respiration rate
2. Activity level
3. Mental state: Mood sensor
4. and more
MGH patient testing

Testing Goals

- Evaluate hydrostatic pressure challenge vs. invasive BP measurements
- Correlation of in-line PPG based PWV measurements with invasive BP
- Test hydrostatic PWV calibration vs. invasive BP measurements

Device Components

- MGH compliant circuitry
- Wrist PPG
- Finger PPG with pressure sensor
- Height Sensor
MGH patient testing

Testing Goals

• Evaluate hydrostatic pressure challenge vs. invasive BP measurements
• Correlation of in-line PPG based PWV with invasive BP measurements
• Test hydrostatic PWV calibration vs. invasive BP measurements

Device Components

• MGH compliant circuitry
• Wrist PPG
• Finger PPG w/pressure sensor
• Height Sensor

Approved by MGH in July 2007
**EXPERIMENTAL RESULTS**

- **8 Test Subjects**

<table>
<thead>
<tr>
<th>Subject</th>
<th>$r_{y,P}$</th>
<th>$k_{1,\text{AHSI}}$</th>
<th>$k_{1,\text{Finapres}}$</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.81</td>
<td>0.479</td>
<td>0.0476</td>
<td>0.56</td>
</tr>
<tr>
<td>2</td>
<td>0.53</td>
<td>0.0395</td>
<td>0.0366</td>
<td>14.05</td>
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<tr>
<td>3</td>
<td>0.75</td>
<td>0.0471</td>
<td>0.0464</td>
<td>1.33</td>
</tr>
<tr>
<td>4</td>
<td>0.91</td>
<td>0.0570</td>
<td>0.0561</td>
<td>1.67</td>
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<tr>
<td>5</td>
<td>0.85</td>
<td>0.0366</td>
<td>0.0363</td>
<td>0.89</td>
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<tr>
<td>6</td>
<td>0.93</td>
<td>0.0668</td>
<td>0.0684</td>
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<td>7</td>
<td>0.55</td>
<td>0.0530</td>
<td>0.0509</td>
<td>4.14</td>
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<tr>
<td>8</td>
<td>0.79</td>
<td>0.0258</td>
<td>0.0263</td>
<td>1.90</td>
</tr>
</tbody>
</table>

- Large SNR → Strong y-P Correlation → Excellent $k_1$ Identification
- Need to develop a screening process to recognize poor waveform data
Long-Term Experimental results

PTT, Hydrostatic, and Finapres™ Data collected from the same person at two different times in the same day.

<table>
<thead>
<tr>
<th></th>
<th>10:00am</th>
<th>2:00pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our method $\hat{k}_1$</td>
<td>0.0258</td>
<td>0.0178</td>
</tr>
<tr>
<td>Finapres™ $\hat{k}_1$</td>
<td>0.0263</td>
<td>0.0172</td>
</tr>
<tr>
<td>Our method $\hat{y}_0$</td>
<td>4.65</td>
<td>5.06</td>
</tr>
<tr>
<td>Finapres™ $\hat{y}_0$</td>
<td>4.61</td>
<td>5.11</td>
</tr>
<tr>
<td>Bland-Altman, $\sigma$</td>
<td>5.51 mmHg</td>
<td>6.31 mmHg</td>
</tr>
</tbody>
</table>

Identified using Adaptive Hydrostatic system ID

Calibration parameters vary throughout the day
Target Markets for Wearable Blood Pressure Sensors (A. Reisner)

- **Chronic Hypertension (High Blood Pressure)**
  - Afflicts 25% - 50% of all Americans
  - Fewer than *half of these cases* are under adequate medical control

- **Other Targets:**
  **Smaller Markets, More Exacting Specifications**
  - BP Monitoring for Chronic Heart Failure
    - Prevent expensive, dangerous hospitalizations preceded by abnormal blood pressures
  - Convalescence (Hospital and Home)
    - Ensure that post-surgery patients at home don’t develop dangerously low blood pressure
    - Ensure patients getting home treatment for infections, e.g. pneumonia or skin infections, don’t develop dangerously low blood pressure
    - Etc.
  - Hazardous Duty
    - Monitor soldiers, in case of combat injuries
Value of Wearable Blood Pressure Sensors in Chronic Hypertension

○ What We Know about Brachial Artery Inflatable Cuffs:
  ● Patients who regularly check their own BP at home are less likely to forget to take their medication.
  ● When BP is measured intensively for 24 hours (snap-shot every 15 minutes), the information is superior for predicting cardiovascular disease and adjusting medication.

○ What We Hypothesize about Wearable BP Sensors:
  ● Patients may wear them all the time, so they will be even less likely to forget to take their medication.
  ● BP information from days, or weeks, of continual BP sensor may be superior for predicting cardiovascular disease and adjusting medication.
  ● We may also detect when patients take too much BP medication, which can be dangerous.
Conclusions

• PTT based BP measurement using hydrostatic pressure challenge is promising.
• Dual In-Line PPG with built-in MEMS accelerometers has shown encouraging experimental results.
• Diastolic pressure as well as mean pressure may be measured reliably.
• Wearable BP sensors will open up new markets of home health monitoring
Future Direction

Biological Implantable Sensors

Tension Measurement

Neuron-Optics Interface

ABP Monitoring

Neuromuscular Junction

Drug Dispense

Implant
NSF STC Emergent Behavior of Integrated Cellular Systems (EBICS)

*Development of autonomous bio-bots*

Differentiation

- Myoblast
- Neuron Cell
- Endothelial Cell
Thank you
Acknowledgement

• Collaborators:
  – Dr. Andrew Reisner
  – Dr. Boo-Ho Yang
  – Dr. Sheng Liu
  – Dr. Sokwoo Rhee
  – Dr. Phil Shaltis
  – Dr. Devin McCombie
  – Professor Jin-Oh Hahn
  – Dr. Yi Zhang
  – Professor Randall Zusman
  – Professor Roger Kamm

• Sponsors:
  – MIT Home Automation and Healthcare Consortium
  – National Institute of Health
  – National Science Foundation
  – Sharp Corporation
  – Toyota Motor Corporation