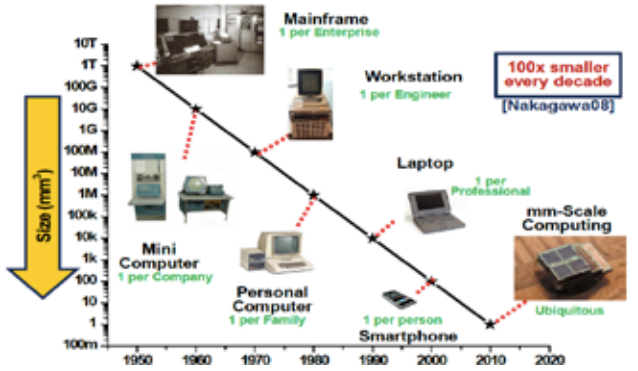
Wearable Wireless Biomedical Sensors: Challenges and Future

Dr. Yong LIAN
Fellow of IEEE and Fellow of Singapore Academy of Engineering
School of Microelectronics, Shanghai Jiao Tong University
Email: eleliany@gmail.com

Founder, ClearBridge VitalSigns Pte Ltd

Bell's Law



Source: B Bell, "Bell's Law for the Birth and Death of Computer Classes", Comms of ACM, 2008

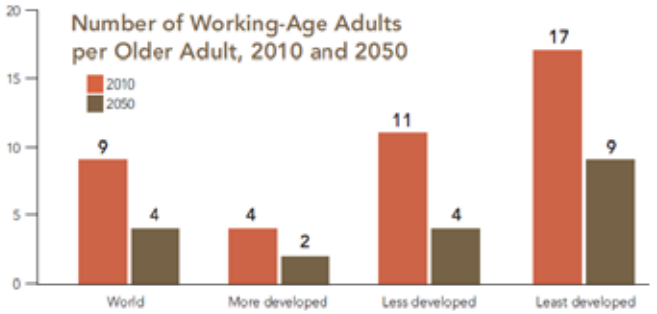
Maslow's Hierarchy of Needs

Our Aging World

We are aging—not just as individuals or communities but as a world. In 2006, almost 500 million people worldwide were 65 and older. By 2030, that total is projected to increase to 1 billion—1 in every 8 of the earth's inhabitants. Significantly, the most rapid increases in the 65-and-older population are occurring in developing countries, which will see a jump of 140 percent by 2030.

Source: National Institute on Aging, US Dept of Health and Human Services, http://www.nia.nih.gov/research/publication/why-population-aging-matters-global-perspective

Working-Age Adults per Older Adults



Source: Science, 333, (2011)

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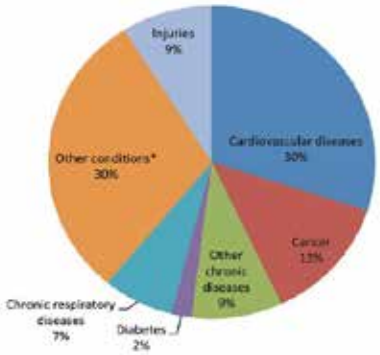
Chronic Diseases

- Chronic diseases
  - Constitute more than 60% of deaths worldwide
  - Cost $47 trillion in loss of productivity and treatment by 2030
- Increase in health care expenditure
  - 9.5% of GDP on average in 2009 up from 8.8% in 2008



Source :Harvard School of Public Health

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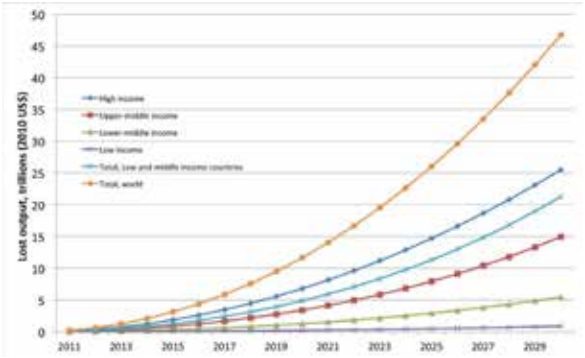
Output Loss



http://www3.weforum.org/docs/WEF_Harvard_HE_GlobalEconomicBurdenNonCommunicableDiseases_2011.pdf

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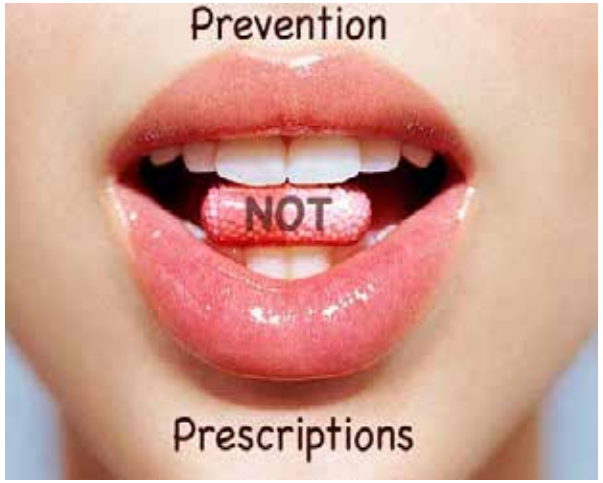
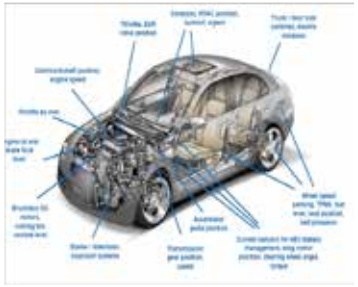
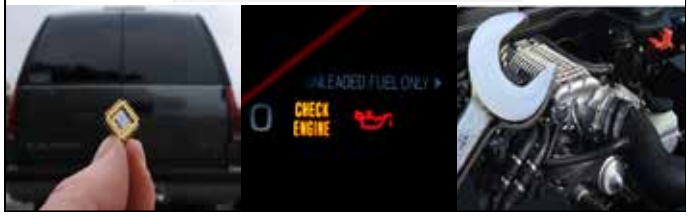
Healthcare in Future







Body Sensor Network

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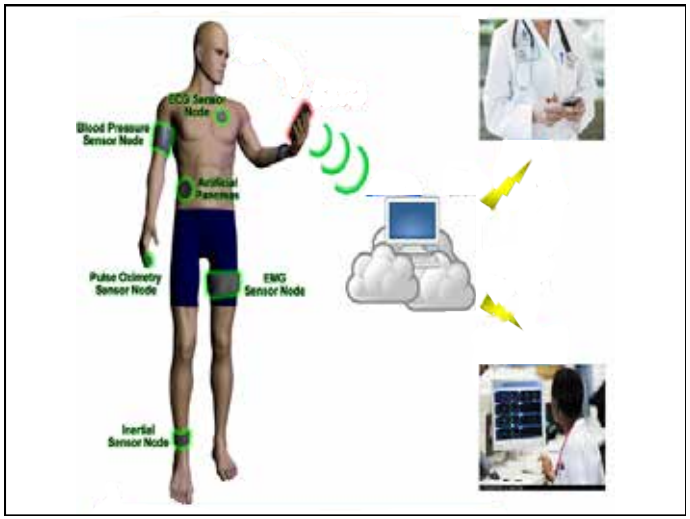
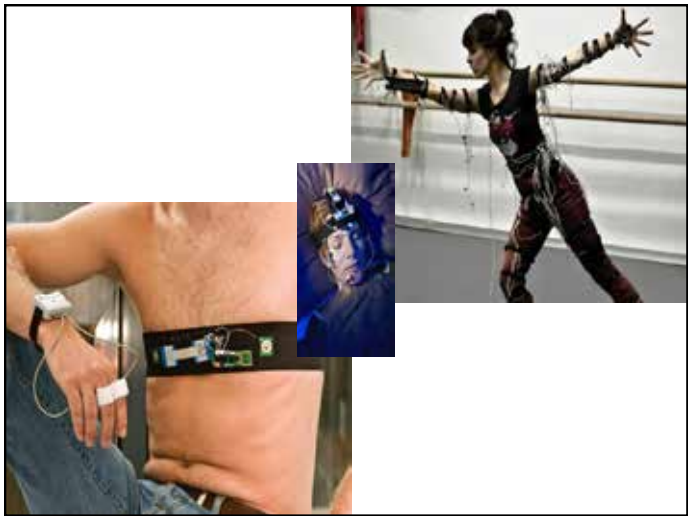
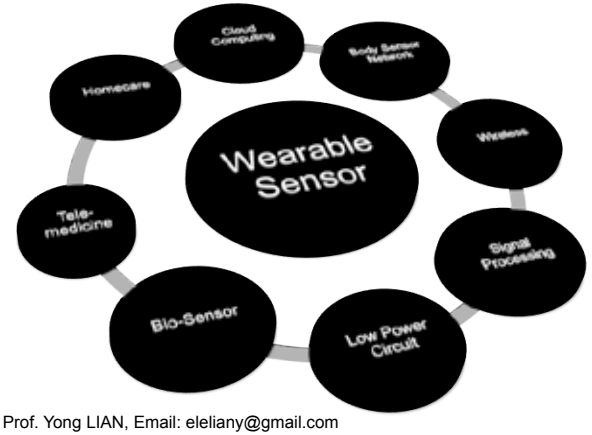




Wearable Sensor: A Melting Pot



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Requirements for WBS

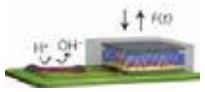
- Clinical requirement
  - accurate measurement, minimum motion artifact
- User requirement
  - minimum invasive, comfortable, easy to use, no need to change/charge battery
- Device requirement
  - Function: amplification, signal processing, wireless, data security
  - Form factor: thin, small, and flexible
  - Power consumption: Less than 1mW

Prof. Yong LIAN, Email: eleliany@gmail.com

Human Energy Scavenging

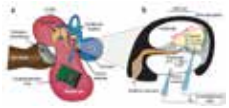
- Wearable devices can generate 0.3mW – 8 W from breathing, finger motion, blood pressure, body heat, walking.
- Implantable nanowire devices:
  - Output voltage: ~96mV
  - Power density: 2.7mW/ cm^3
- Implantable glucose fuel cell:
  - Output voltage: ~350mV
  - Power density: 30μW/ cm^2

Glucose fuel cell in snail



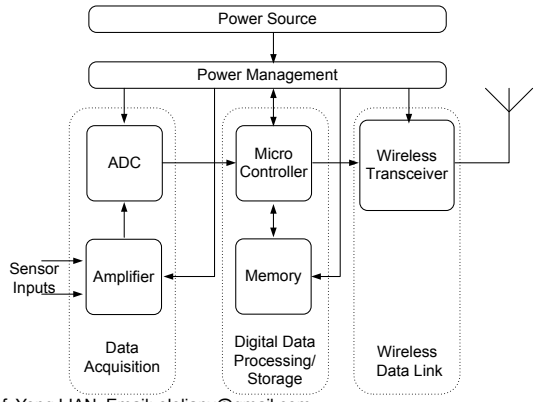
Z.L. Wang, *et al* "Self-powered nanowire devices", *Nature Nanotechnology*, Mar 2010.

Nanowire device in rat



Energy harvesting from inner ear

Design Challenges for Zero-Powered Wireless Biomedical Sensor (WBS)



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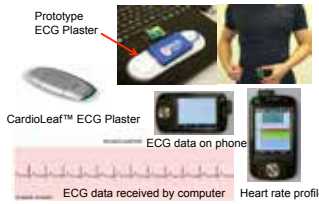
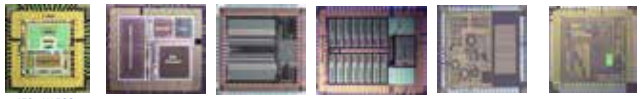
A Snapshot of Our Research

- **Research areas:**
  - Low voltage low power circuit design techniques
  - Continuous-time signal processing techniques
  - Ultra low power wireless sensor platform
- **Research highlights:**
  - World's first 450-nW ECG sensor chip
  - World's first 690-nW 32-channel EEG chip
  - 0.5-V 1.13-μW/channel neural recording chip with digital multiplexing scheme
  - 17.4 μW wireless ECG-on-chip
  - 200nW ECG A2I chip with QRS detection
  - 535nW/channel ECG chip with data compression
  - 0.6-V 82-dB 28.6μW CT Delta-Sigma ADC

CardioLeaf™ 3-Lead ECG

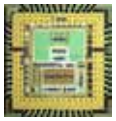




450-nW ECG chip | 2.3μW ECG-on-Chip with QRS Detector | 22μW 32-channel EEG chip | 0.5V 1.13μW/channel neural recording chip | 4mW wireless 8-Ch neural recording chip | Sub-mW wireless UWB transceiver

Low Cost Wearable Wireless ECG Plaster for Managing Cardiovascular Disease

CardioLeaf®
3-Lead ECG



450nW ECG Chip*

The world's first fully integrated 450nW ECG (electrocardiogram) recording chip

- Low noise figure, tunable band-pass filter, programmable gain, 12-bit ADC, and on-chip oscillator
- Collaborations with YLL School of Medicine, SSH School of Public Health, SGH, I2R, and IME
- Clinical trials in NUH, Duke-NUS, UK and Russia

*X Zou, et. al. "A 1-V 450-nW Fully Integrated Programmable Biomedical Sensor Interface Chip", JSSC, Vol.44, No.4, April 2009.

Low Cost Wearable Wireless ECG Plaster for Managing Cardiovascular Disease

Why Electrocardiogram (ECG)?

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Cardiovascular Disease (CVD)

CVD (heart disease) is a range of conditions that affect the heart.

- Heart valve problems
- Arrhythmia
- Heart attack
- Stroke

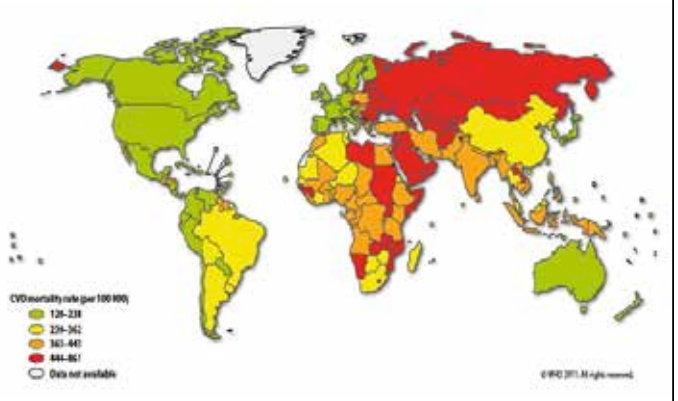
Prof. Yong LIAN, Email: eleliany@gmail.com

Cardiovascular diseases are the leading cause of deaths globally[1]

The direct costs of heart diseases was US $190b in USA alone[2]

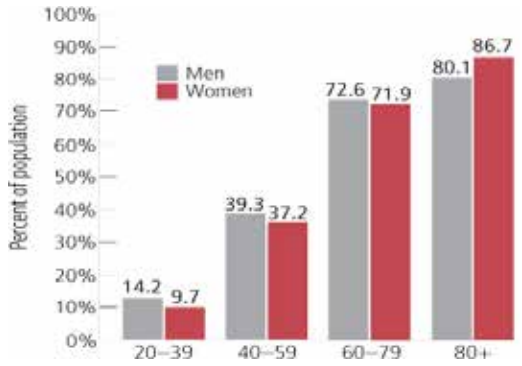
Source: 1. World Health Organization, http://www.who.int
2. Heart Disease and Stroke Statistics, American Heart Association, 2010

Global Distribution of CVD Deaths



Source: World Health Organization, http://www.who.int/cardiovascular_diseases/en/

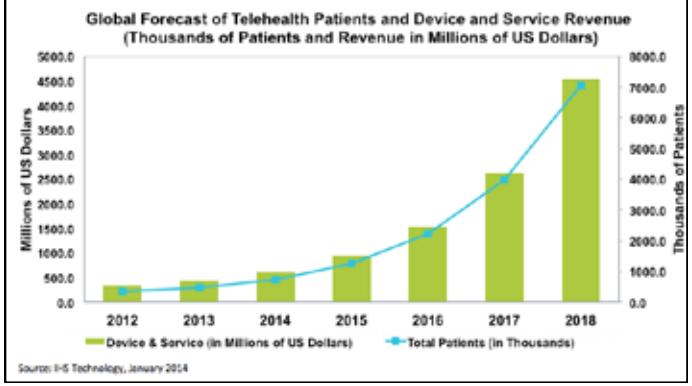
Risks of CVD in Men and Women



Source: Harvard Med. Sch. http://www.patienteducationcenter.org/heart-disease

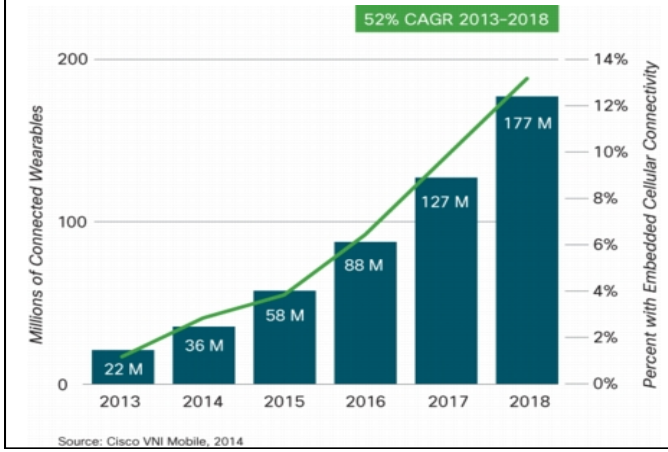
Global Telehealth Forecast

	2012	2013	2014	2015	2016	2017	2018
Device & Service (in Millions of US Dollars)	349.2	640.6	611.2	943.3	1589.9	2637.7	4548.0
Total Patients (in Thousands)	344.3	482.7	725.0	1255.5	2230.3	3968.8	7057.3



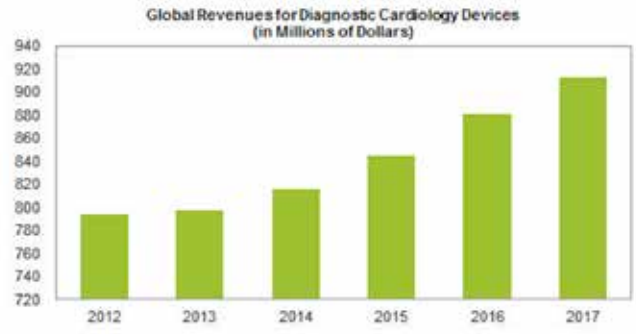
Source: I-S Technology, January 2014

Global Wearable Market Forecast



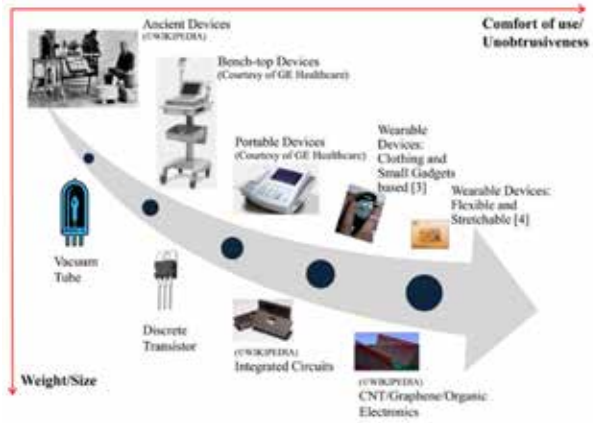
Source: Cisco VNI Mobile, 2014

Global Diagnostic Cardiology Devices



Source: IHS Inc., February 2014

The Evolving of ECG Devices



Source: Y. Zheng, et. al. "Unobtrusive Sensing and Wearable Devices for Health Informatics", IEEE Transactions on Biomedical Engineering, Vol.61, No.5, May 2014.

ECG Devices

- Existing ECG devices are bulky, short battery life, and expensive.
- Wearable devices are mostly single lead.
- Short battery life limits ECG monitoring time – leading to extremely low diagnostic yield of 10-13%

Source: A Schuchert, et.al, "Diagnostic yield of external electrocardiographic loop recorders in patients with recurrent syncope and negative tilt table test", PACE. 2003;26:1837-1840

The Idea ECG Device

- High diagnostic yield
  - Multiple leads
  - Long recording time
  - Good rejection to noises
  - Real-time
- Better user experience
  - Light weight
  - Small size
  - Non-intrusive
  - Low cost
  - Data security
  - Easy to use

Source: D. Kim, et al. "Epidermal Electronics", Science, 333, 838, 2011

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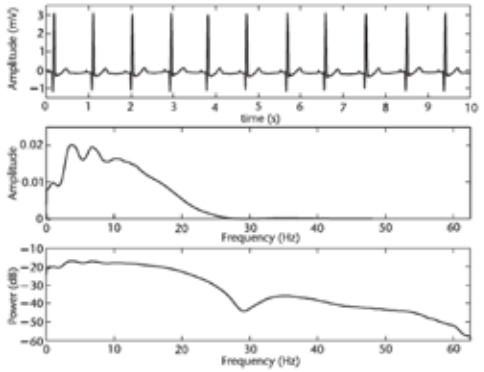
ECG Signal Characteristics

Frequency: 0.01 ~ 1000 Hz



Source: G.D. Clifford et. al., "Advanced Methods and Tools for ECG Data Analysis, Artech House, 2006..

ECG System-on-Chip Requirements

- Analog frontend
  - noise vs. power
- ADC: uniform vs. non-uniform
  - Nyquist ADC or level-crossing
  - Fixed sampling rate or variable one
- Data: transmission vs. signal processing
  - Lossless data compression
  - Feature extraction: QRS, HRV, A-Fib
- Wireless: continuous vs. duty-cycle
  - Narrow band or ultra wideband
  - SRAM or flash

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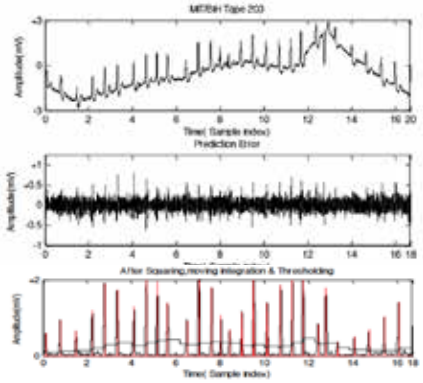
Joint QRS Detection & Compression

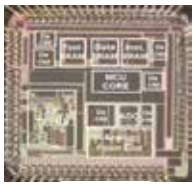
- Lossless compression
- Compression ratio of 2.28
- QRS detection accuracy of 99%
- 490 nW @1.8V in 0.35 μm CMOS

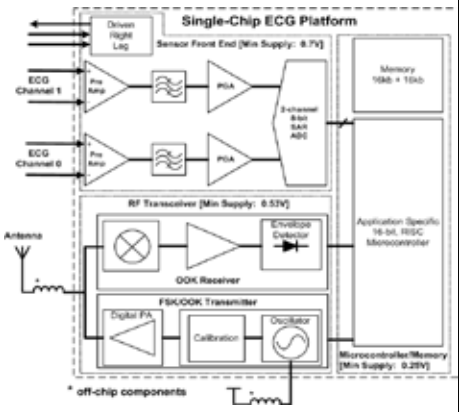


"A Joint QRS Detection and Data Compression Scheme for Wearable Sensors", IEEE Transactions on Biomedical Engineering, 2014

Wireless ECG SoC

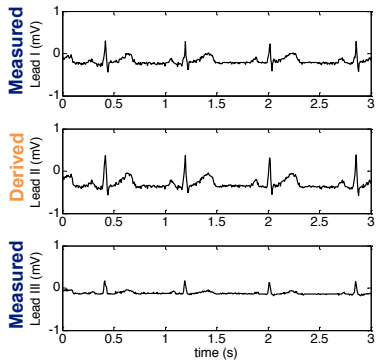
- Single chip ECG solution.
- Lowest power @17.4μW
- 3-lead ECG for better recording

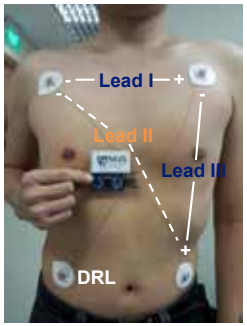




*M. Khayatzadeh, WS Liew, X Zhang, J Tan, and Y Lian, "A 0.7-V 17.4-μW 3-Lead Wireless ECG SoC", *IEEE Transactions on Biomedical Circuits and Systems*, Vol.7, No.5, pp.583-592, Oct. 2013.

Real ECG Recording





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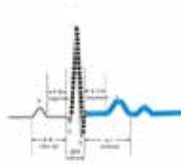
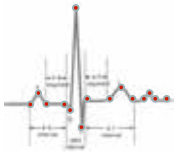
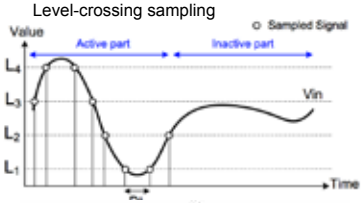
ADC – Nonuniform Sampling

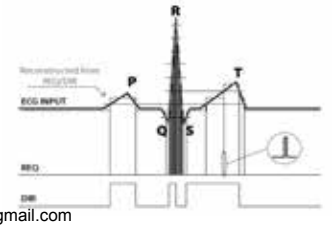


Nyquist sampling method



Adaptive level-cross





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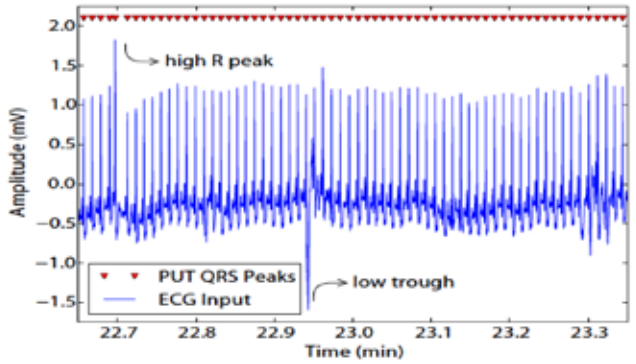
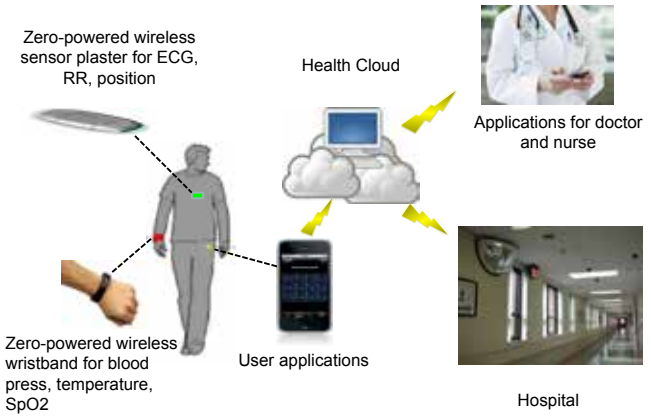
LC-ADC Based QRS Detection



"A 300-mV 220-nW Event-Driven ADC With Real-Time QRS Detection for Wearable ECG Sensors", IEEE Transactions on Biomedical Circuits, 2014

On-going Research Program



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Conclusions

- Building zero-powered wireless body sensor network is possible, but very challenging
- Novel low power system architecture is a must for zero-powered devices
- Innovations in energy harvesting is the key to success
- Flexible circuit and low cost are important for user acceptance

Prof. Yong LIAN, Email: eleliany@gmail.com

Thank You!

Interested in our research

Contact: Prof. Lian Yong

Email: eleliany@gmail.com