

# Affordable Healthcare Technology: Scalable ECG



UNIVERSITY OF  
**OXFORD**

**Dr. Gari D. Clifford**

University Lecturer

Director: Centre for Doctoral Training in Healthcare Innovation

Institute of Biomedical Engineering

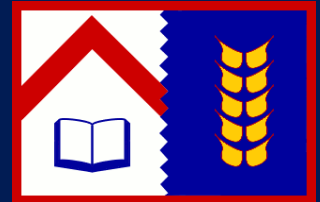
Department of Engineering Science

Director: Centre for Affordable Healthcare Technology, Kellogg College

Sleep, Circadian Rhythm & Neuroscience Institute (SCNi)

Interim Director & James Martin Fellow of Affordable

Healthcare Technology George Institute for Global Health



# Four focus areas of research



- AI4D – Artificial Intelligence for Development
  - Affordable Healthcare in Low & Middle Income Countries
  - Scalable technologies to billions without access to healthcare
  - Big data & crowd sourcing for automated healthcare
  - Machine learning and signal processing on the phone



- Machine learning in Intensive Care
  - ‘The Internet of Things’

- Sleep & Circadian Rhythms
  - Mental Health monitoring through smart phones



- Perinatal monitoring
  - Spin out company form MIT & Tufts in 2008
  - CTO (Mindchild Medical)
  - FDA approved fetal monitor in 2012



# General Design: Smart Phones, Dumb Sensors, Big Data



# Example mHealth products

1. <\$10 Blood pressure monitor
2. Sleep apnea screening app
3. Mental health monitoring app
4. Jet lag app
5. Electronic stethoscope app
6. Perinatal Screening with low cost ultrasound and pulse oximeter
7. BabeeMon – a low cost neonatal monitor
8. CVD risk screening and lifestyle app
9. ECG screening app for rhythm
10. Telespiro – a low cost spirometer for COPD and asthma
11. Sana Mobile – an end-to-end mHealth medical record system
12. Drug-Drug interaction app
13. Smart Water – intelligent water pumps for Africa



# BP mCuff



engineeringworldhealth

1<sup>st</sup> prize in the annual  
Engineering World Health  
Design Competition

**DELL**  
**SOCIAL**  
**INNOVATION**  
**CHALLENGE**

Best Innovation  
Leveraging Technology  
Award in the  
International Dell Social  
Innovation Challenge



- \$1 pressure sensor, plugs into \$1 pressure cuff
- USB for communication and power
- Plugs directly into phone
- Phone does all the calculations, checks quality
- Checks posture and teaches user
- Uploads data direct to medical record

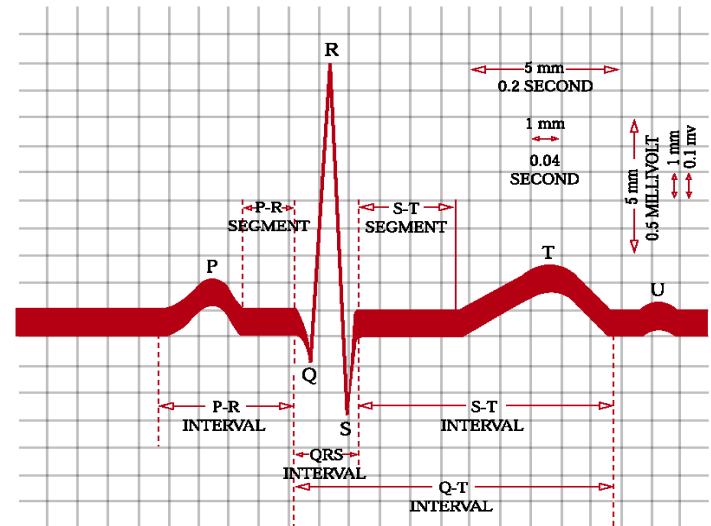
# What is the (clinical) point of ECG?

## Pros

- Accurate rhythm detector
- Ischemia (ST changes)
- Adverse drug effects (long QT)

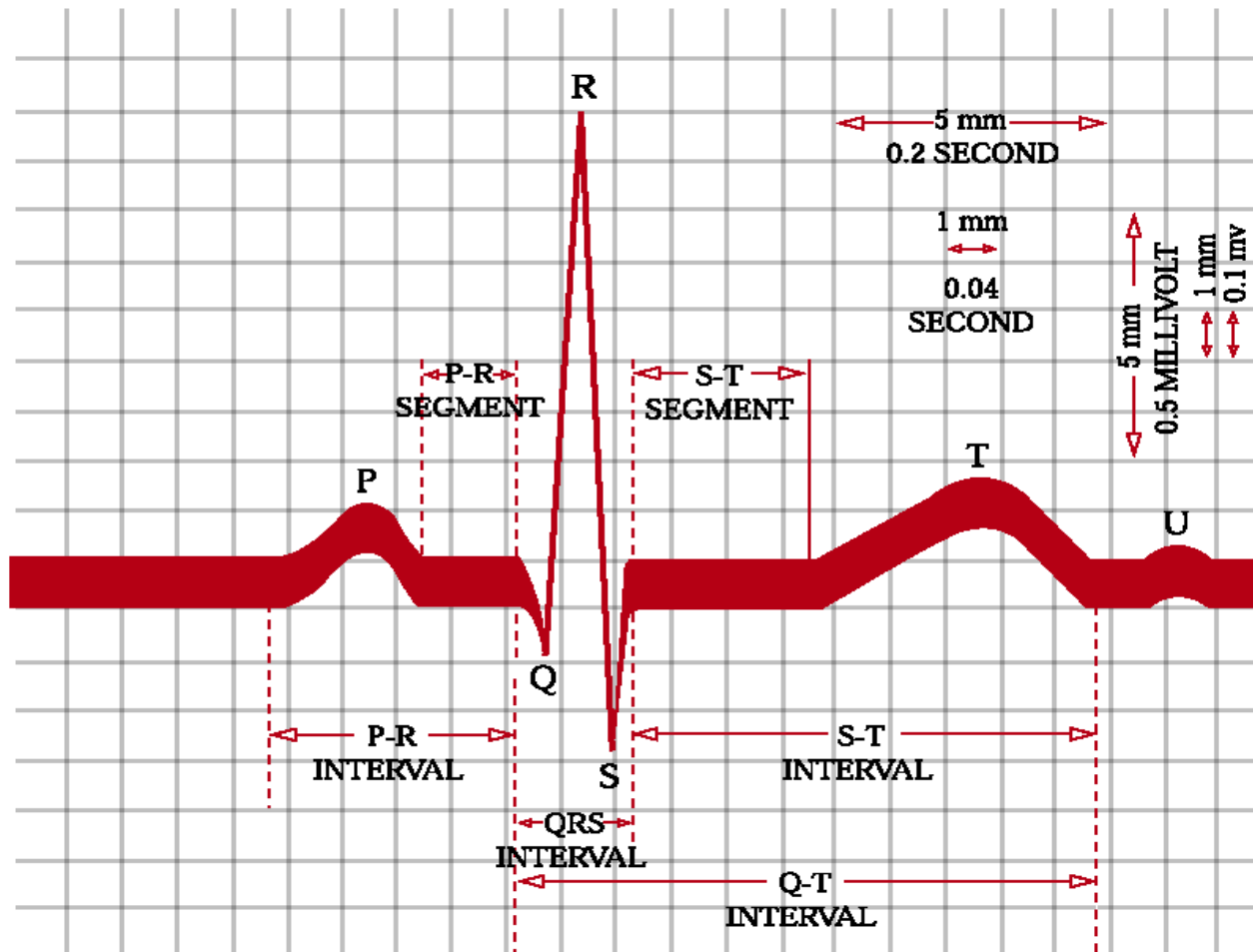
## Cons:

- Skin prep and accurate multilead placement needed for subtle features
  - E.g., ST analysis requires at least 5 precordial leads
- Current algorithms: High Se, Low Sp
  - They need an expert to filter and with P:D of 50k:1 ...!



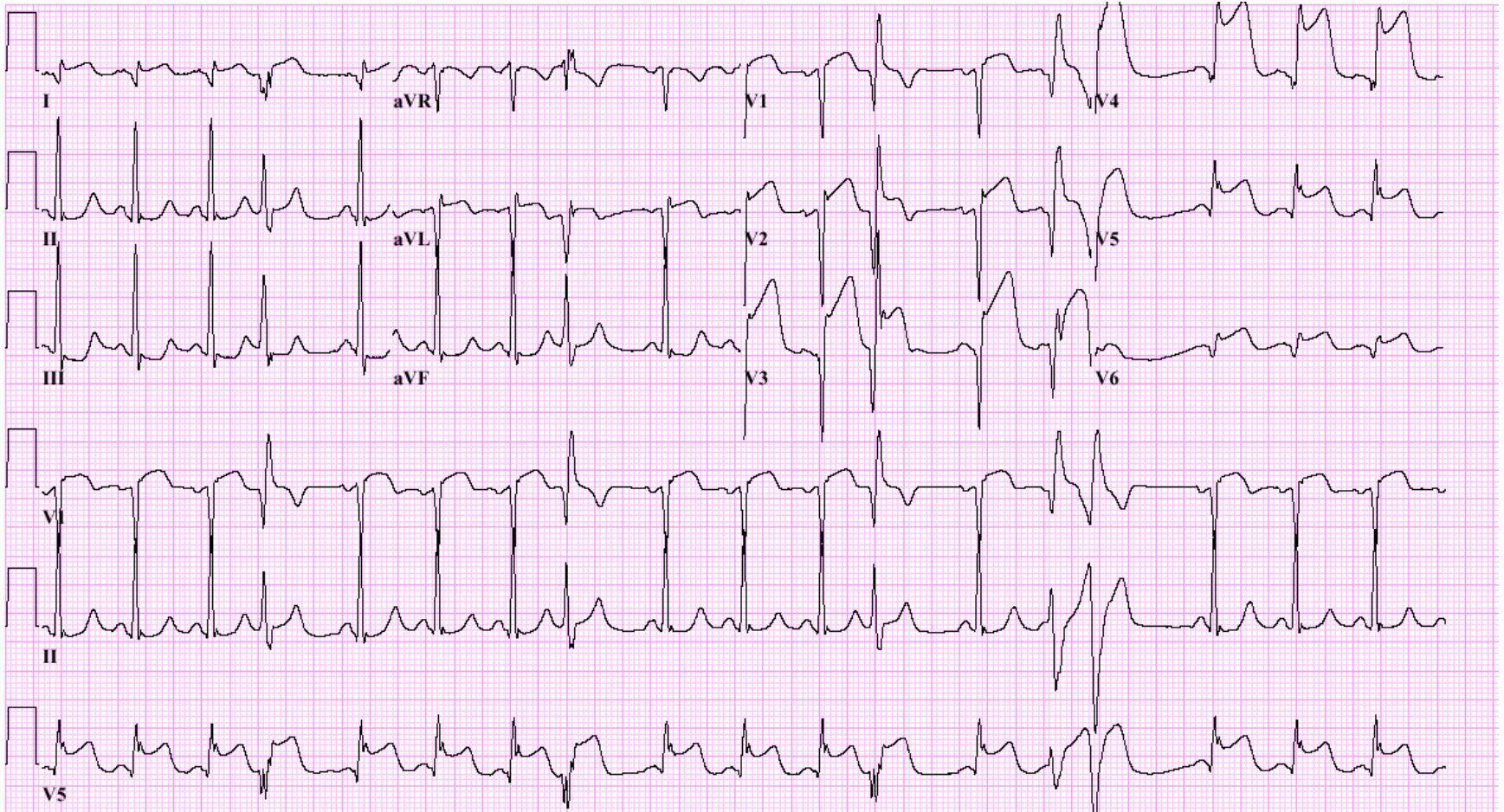
Recording Conventions, Waveform Nomenclature, and Normal Values for the Electrocardiogram.

# Typical ECG signal



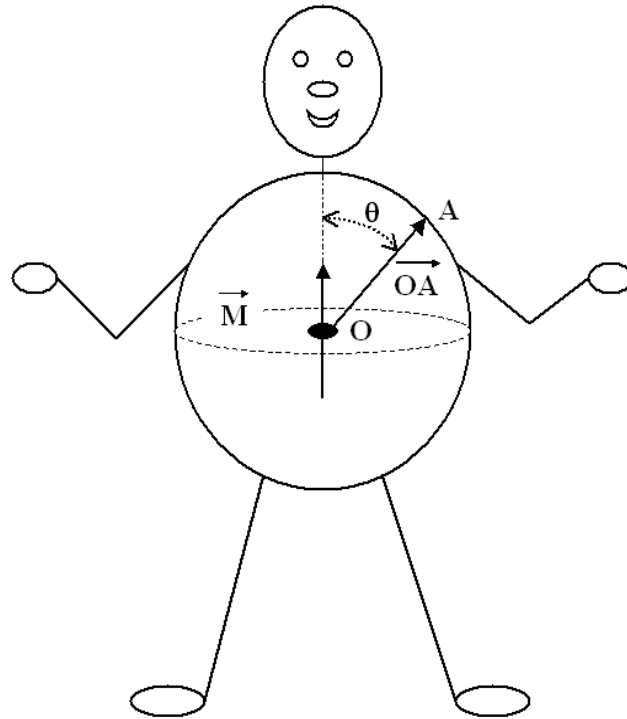
Recording Conventions, Waveform Nomenclature, and Normal Values for the Electrocardiogram.

# Typical 12 ECG signal



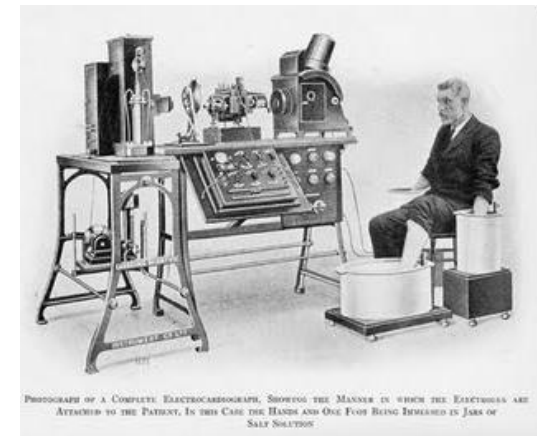


# The Dipole Model



The Idealized Spherical Torso with the Centrally Located Cardiac Source (Simple dipole model)

# Clinical Lead Placement



- Einthoven Limb Leads (bipolar):

The Einthoven *limb leads* (standard leads) are defined in the following way:

Lead I:  $V_I = \Phi_L - \Phi_R$

Lead II:  $V_{II} = \Phi_F - \Phi_R$

Lead III:  $V_{III} = \Phi_F - \Phi_L$

where  $V_I$  = the voltage of Lead I

$V_{II}$  = the voltage of Lead II

$V_{III}$  = the voltage of Lead III

$\Phi_L$  = potential at the left arm

$\Phi_R$  = potential at the right arm

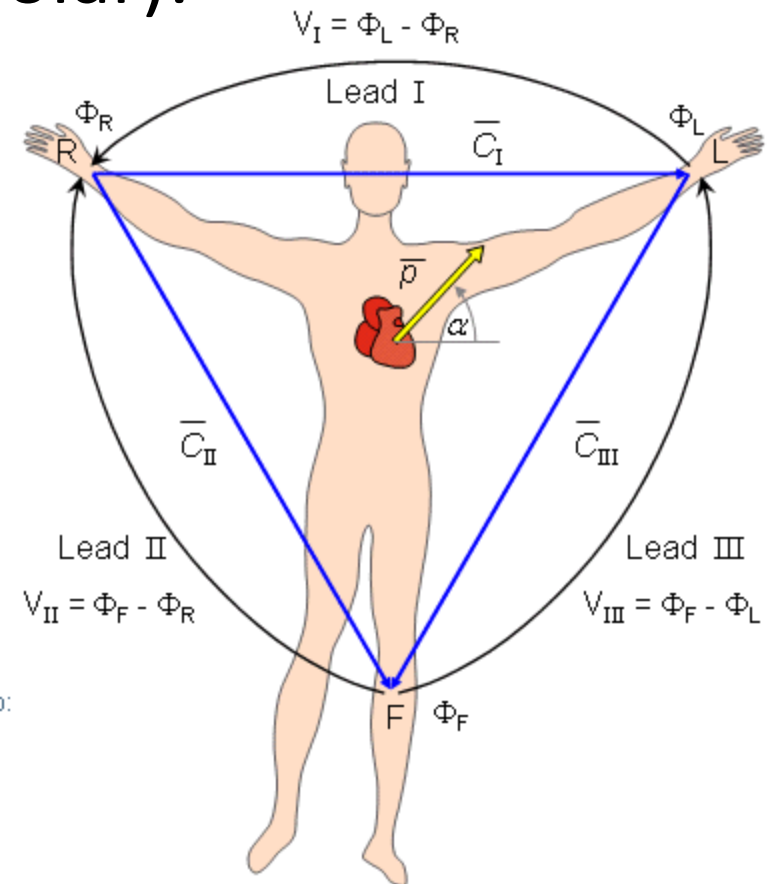
$\Phi_F$  = potential at the left foot

(The left arm, right arm, and left leg (foot) are also represented with symbols LA, RA, and LL, respectively.)

According to Kirchhoff's law these lead voltages have the following relationship:

$$V_I + V_{III} = V_{II}$$

hence only two of these three leads are independent.



# Precordial leads

- Unipolar – measured with respect to ref
  - So an artifact on ref lead affects all leads!

The location of these leads is as follows:

V<sub>1</sub>: on the fourth intercostal space at the right sternal margin

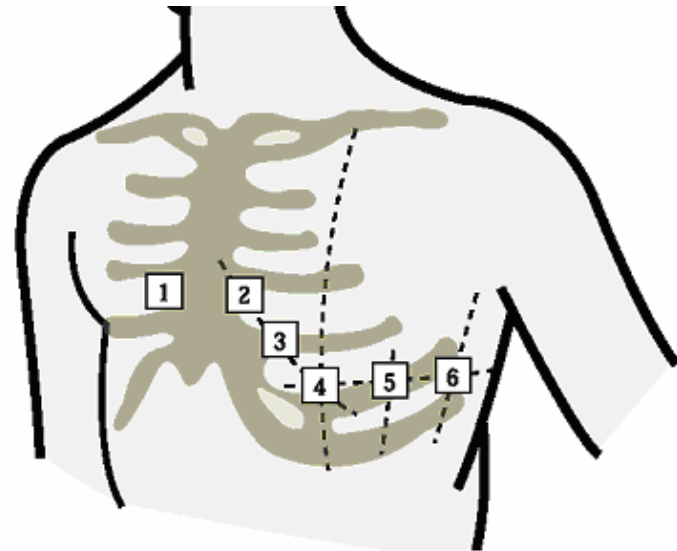
V<sub>2</sub>: on the fourth intercostal space at the left sternal margin

V<sub>3</sub>: midway between leads V<sub>2</sub> and V<sub>4</sub>

V<sub>4</sub>: on the fifth intercostal space at the midclavicular line

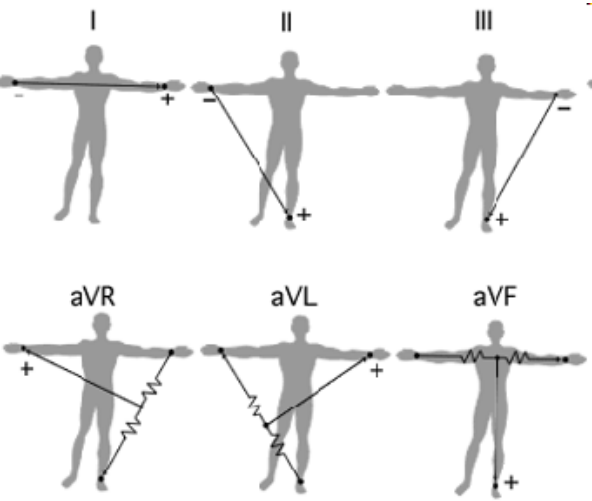
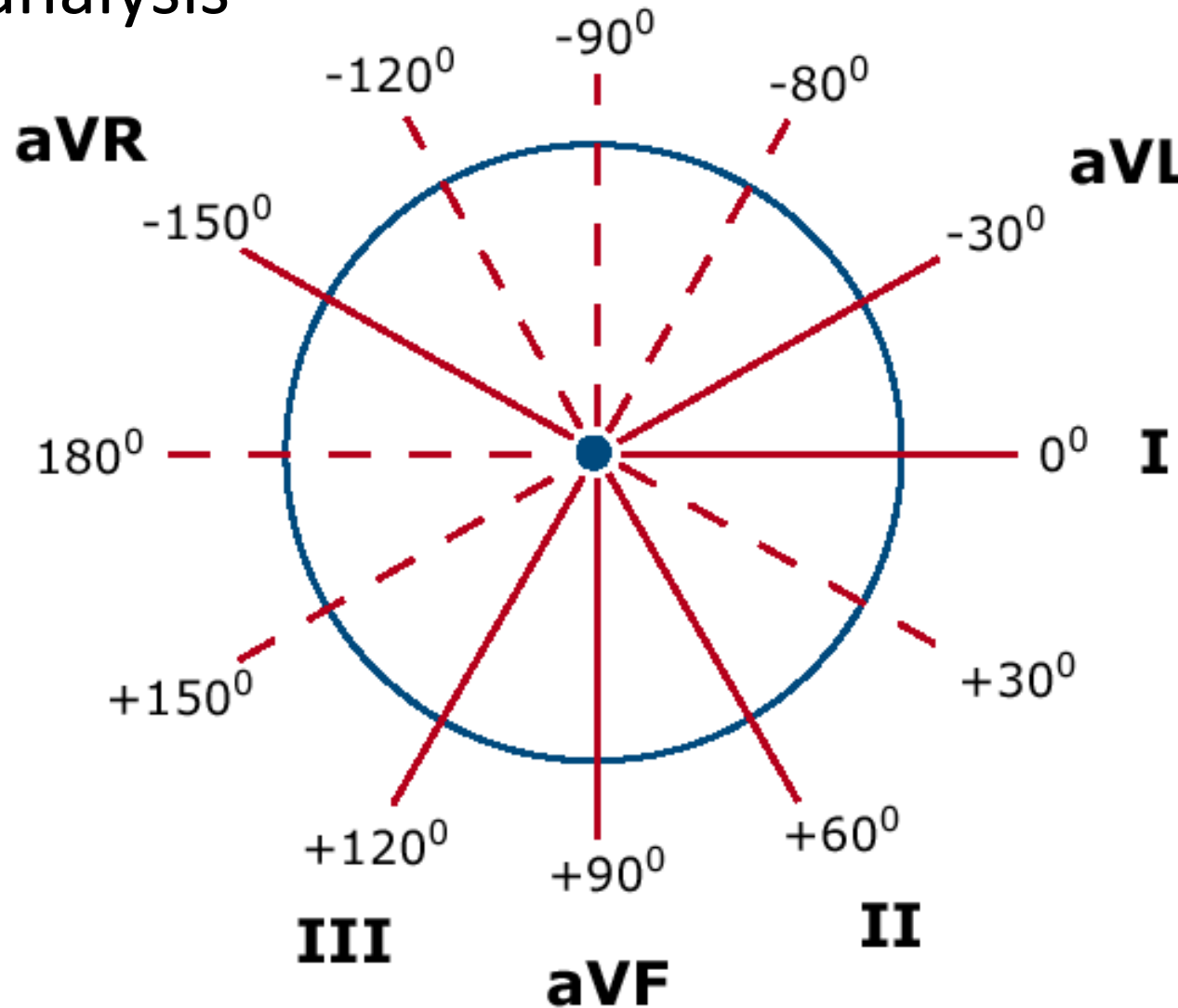
V<sub>5</sub>: on the anterior axillary line at the horizontal level of lead V<sub>4</sub>

V<sub>6</sub>: on the midaxillary line at the horizontal level of lead V<sub>4</sub>



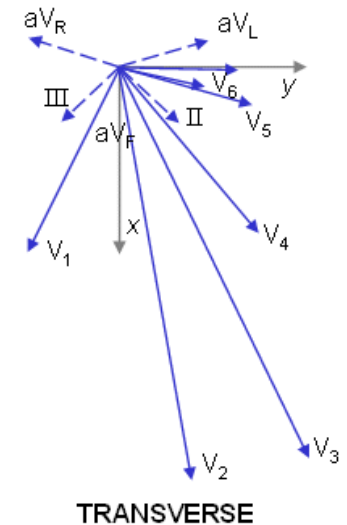
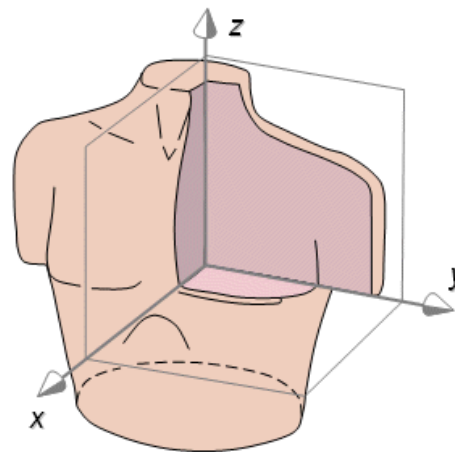
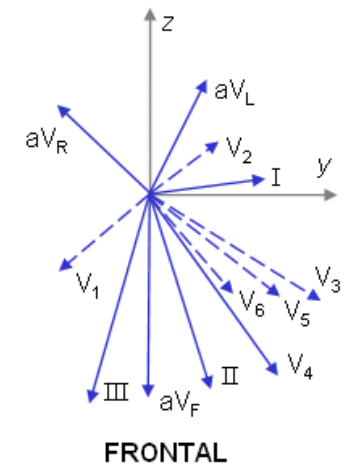
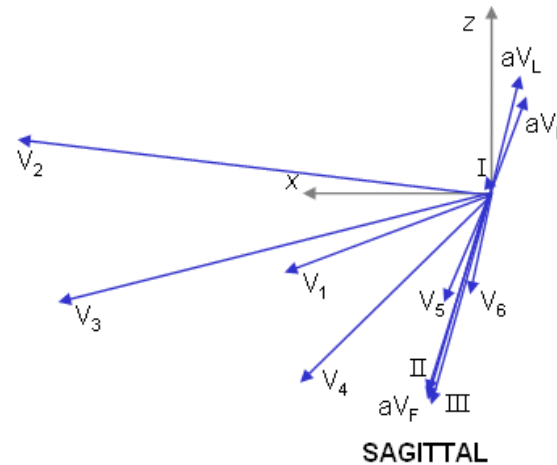
# Frontal Plane Leads

- Useful for axis analysis
- Bipolar



# 12 Lead ECG

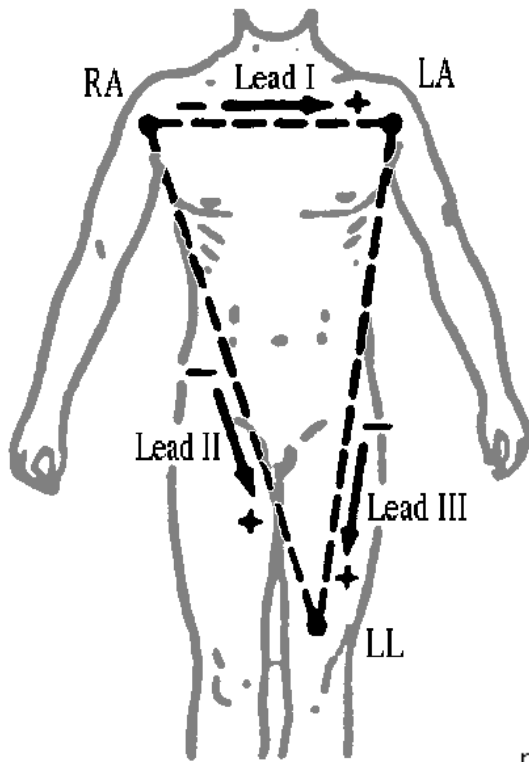
- 12 clinical leads
- Spatial oversampling
- To identify localized issues
- Can approximate them all from a VCG (X-Y-Z) with Dower Transform



# Typical 12 ECG signal

- Dipole model is just an approximation
- Near field effects -> must spatially oversample
  - E.g. Ischemia on left side of heart does not show up on leads located near right side
- Lead choice depends on what you are looking for!
- Prior is important!
- 12 lead if you have no idea what you are looking for (or where)
  - But watch out for FP: “A healthy person is someone who has had no tests performed on them”
- Single lead (or two/three for SQI) is suitable for rhythm

# Electrode placement for this lab

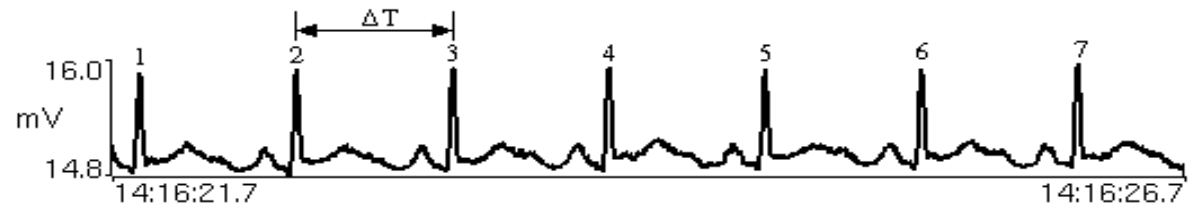


$$V_I = (\text{potential at LA}) - (\text{potential at RA})$$

$$V_{II} = (\text{potential at LL}) - (\text{potential at RA})$$

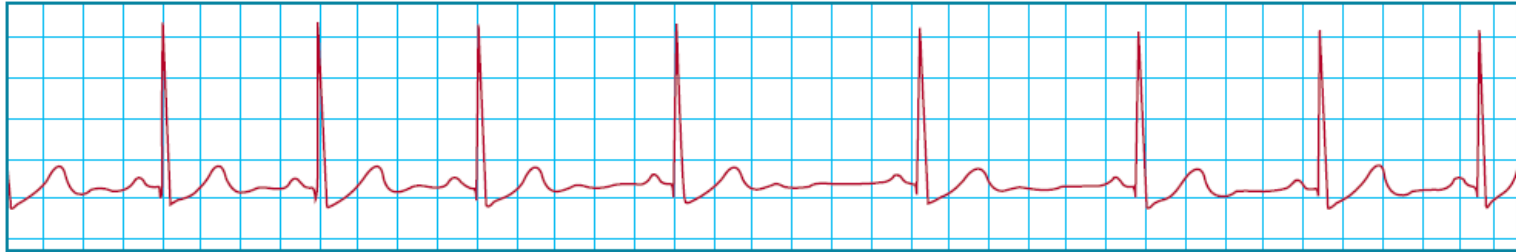
$$V_{III} = (\text{potential at LL}) - (\text{potential at LA})$$

The right leg (RL) is usually the ground

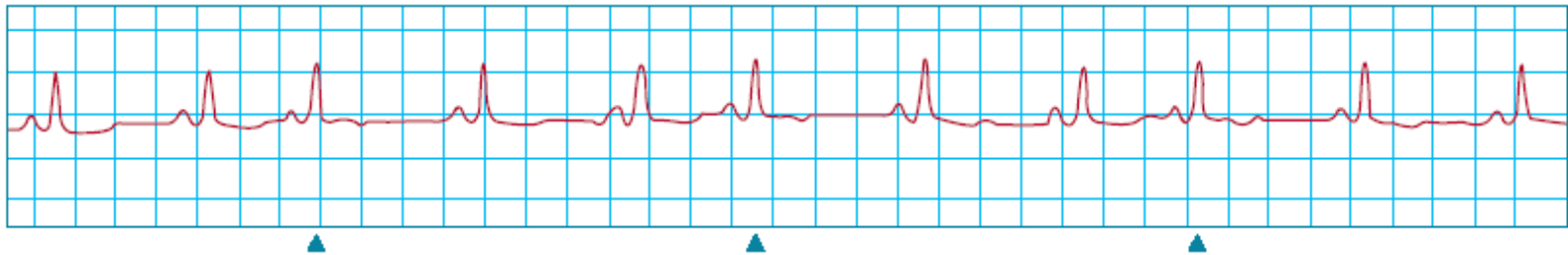


# Rhythm strips

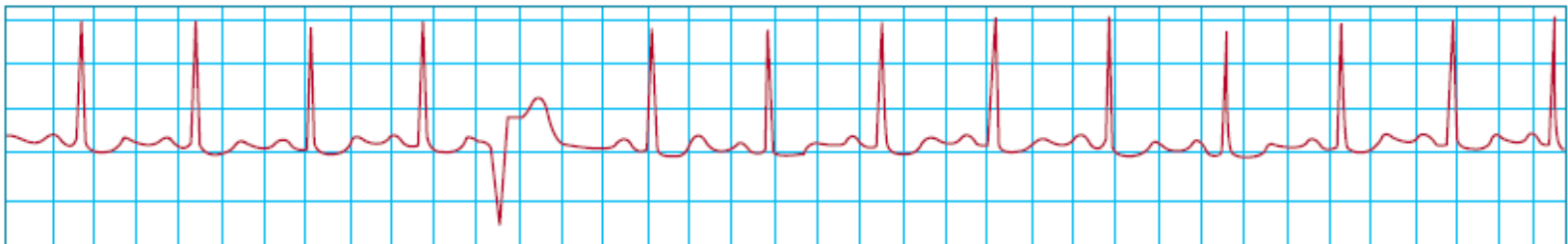
**Sinus Arrhythmia**



**Atrial Premature Contractions**



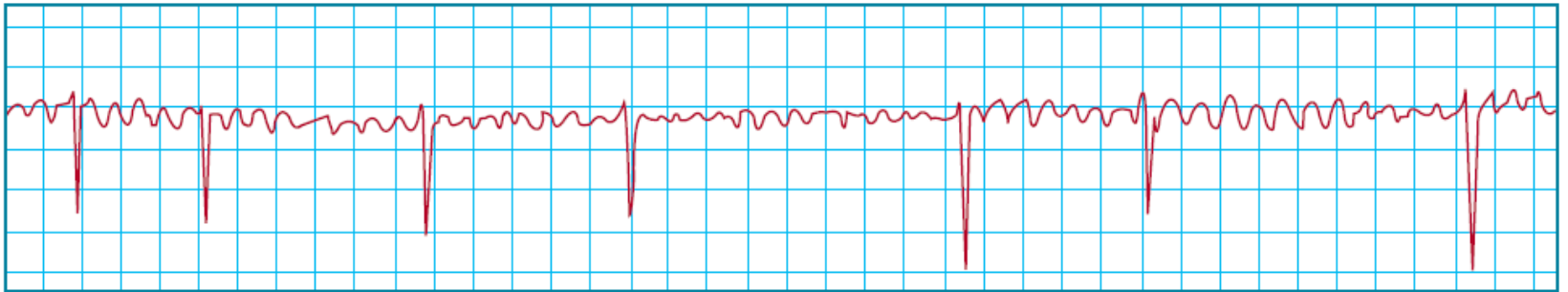
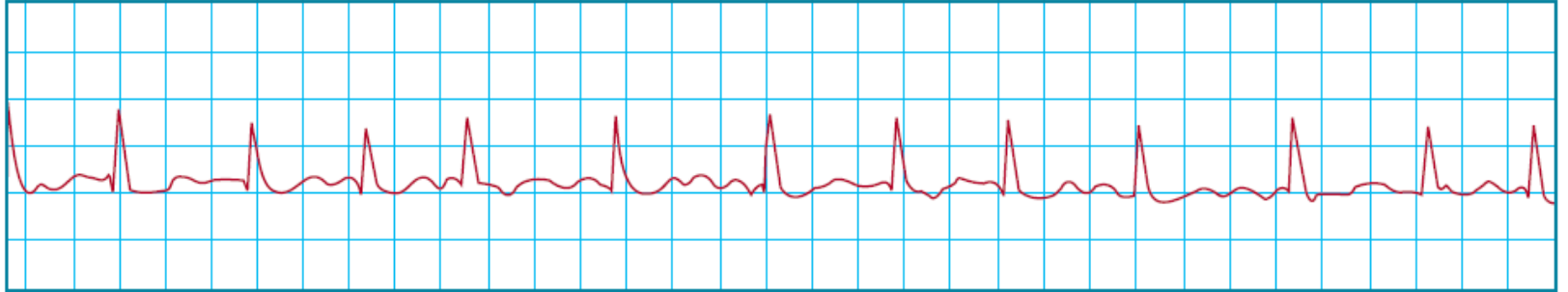
**Ventricular Premature Contractions**



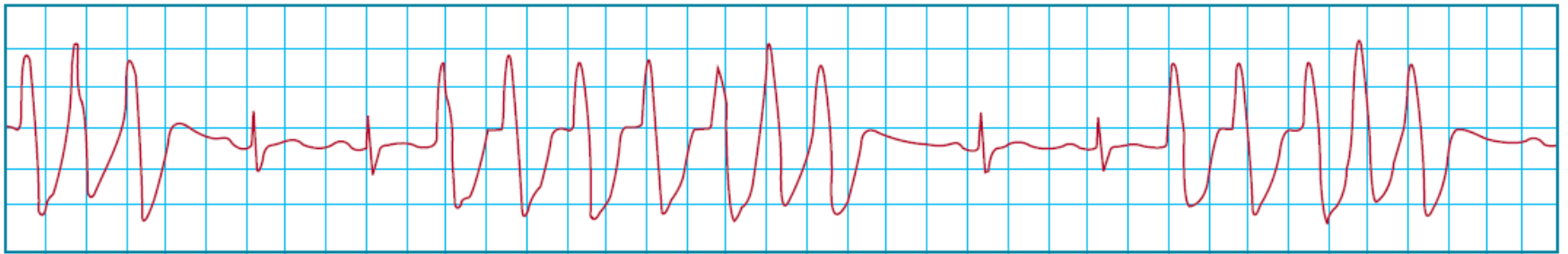


# Rhythm strips

Atrial Fibrillation (2 examples)



Non-sustained VT



# Rhythm Strips

## Three Examples of Ventricular Fibrillation

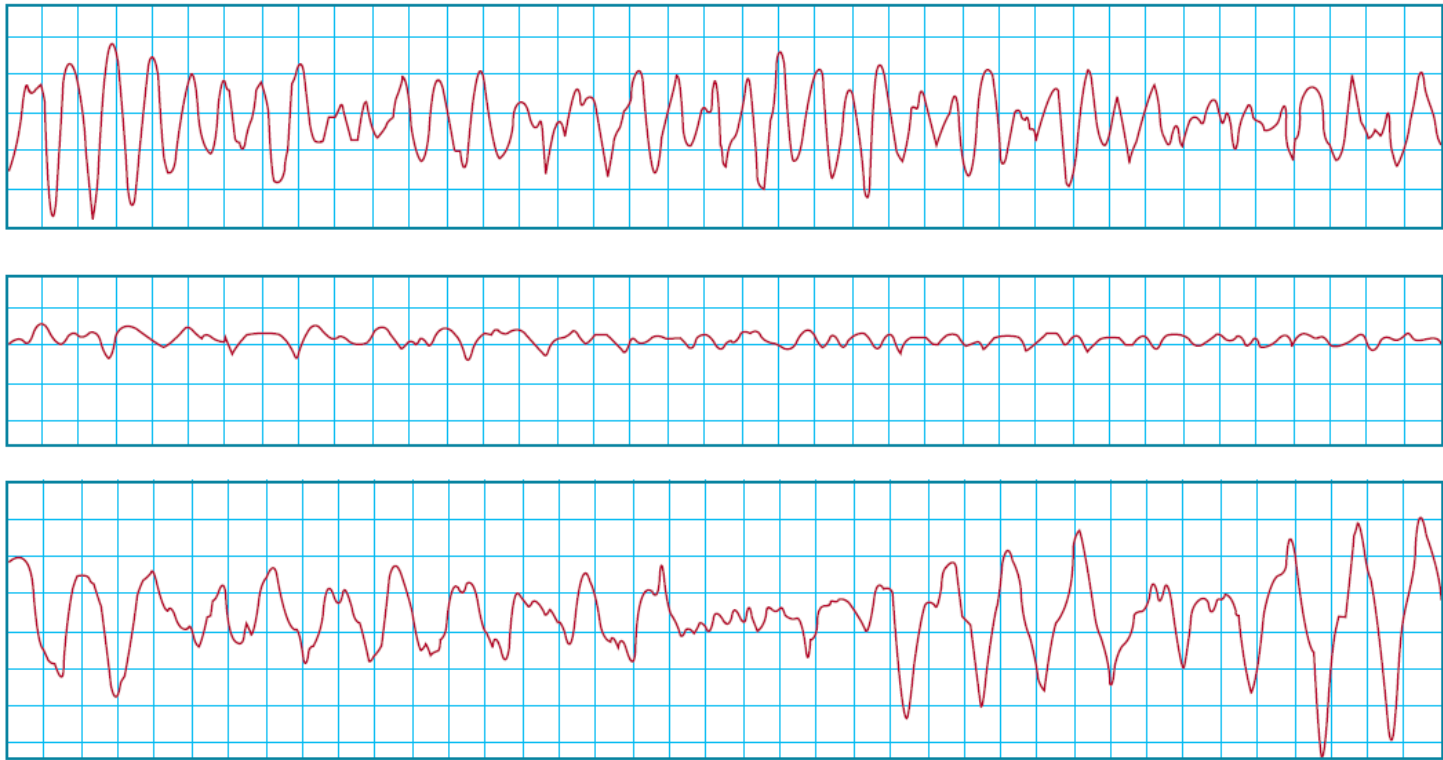
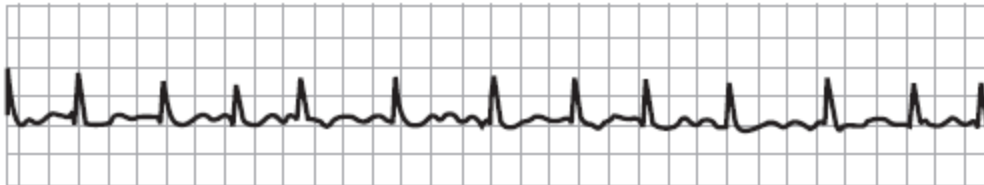
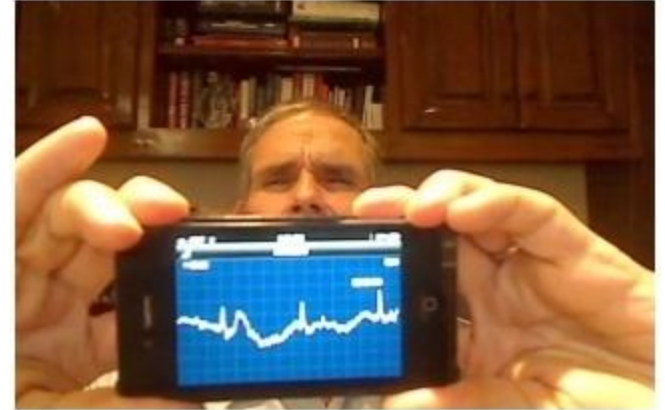


Figure by MIT OCW.

# Look at current mHealth examples

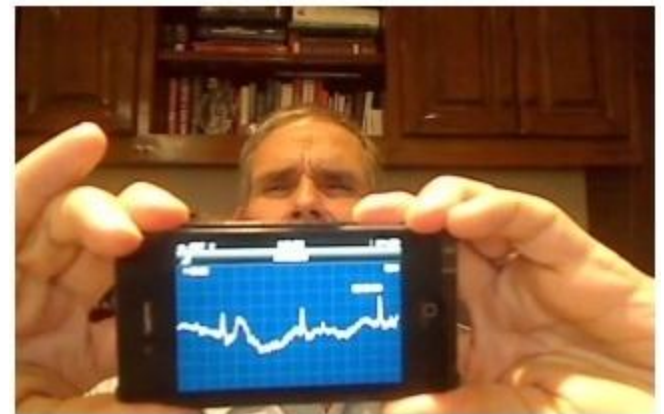
- iCore gets a lot of press:
- But can it deliver?



Patient with Atrial Fibrillation – untreated leads to increase p(death)

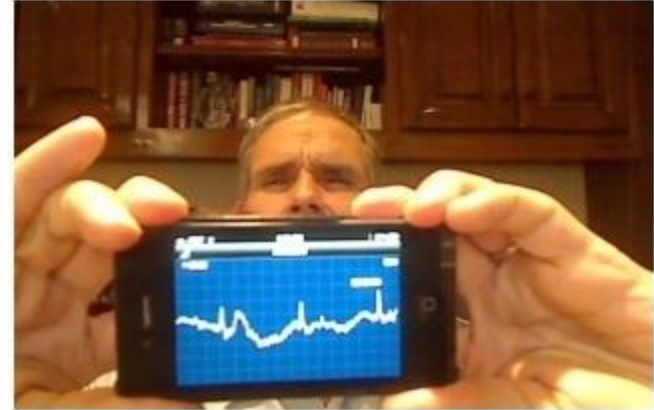
# Design pluses

- Uses RF technology to pair phone with device
- Can store and transmit data afterwards
  - Although only by email – needs to be integrated into EMR which will record all doctor activity
- Can be used rapidly – you are likely to carry it
- Could be shipped with phone



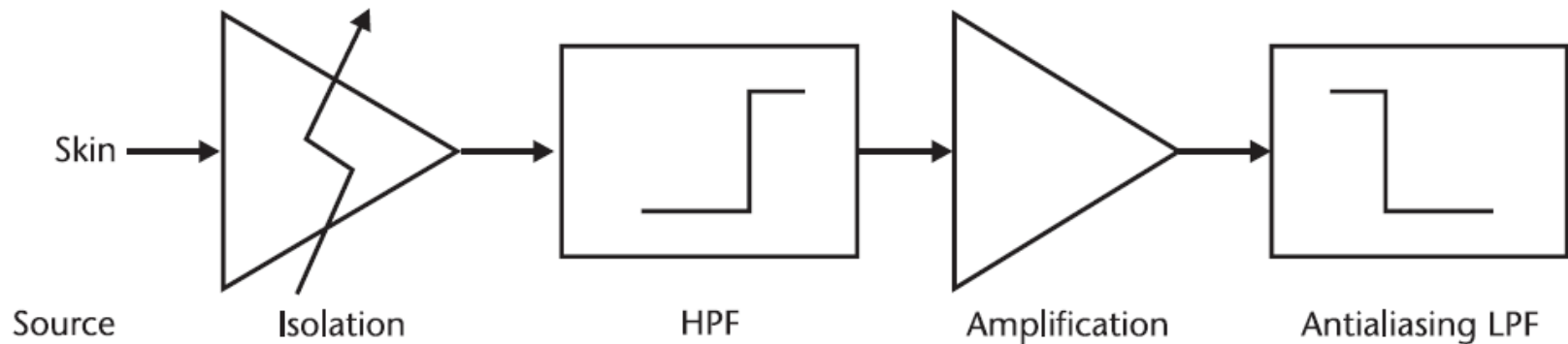
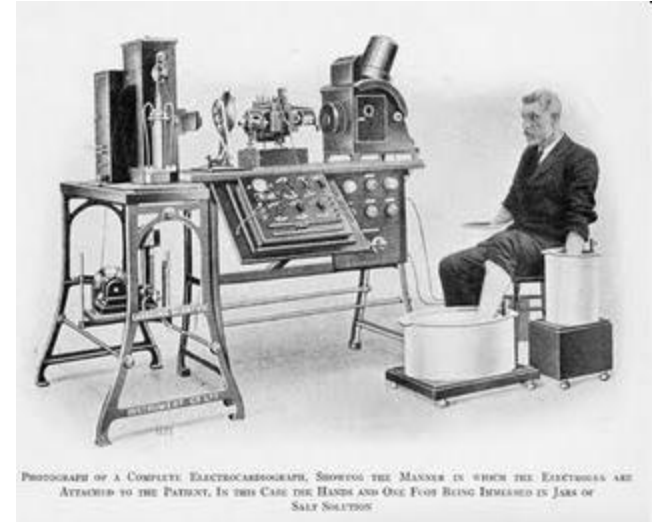
# Design flaws

- Expensive attachment
- Not integrated (?)
- Expensive phone required
- Requires its own battery source
- Wrong operational modality (noisy lead to lots of false positives (and negatives))
- Requires expert user – no different from any other ECG – just a smaller screen
- Expert annotations not captured
- No in-built intelligence / user feedback



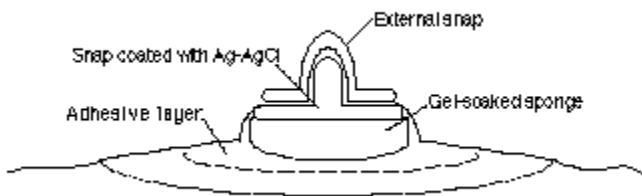
# General system design

- Defib protection
- Isolation
- Filtering
- Amplification
- Anti-alias filtering
- Digitization
- Signal processing



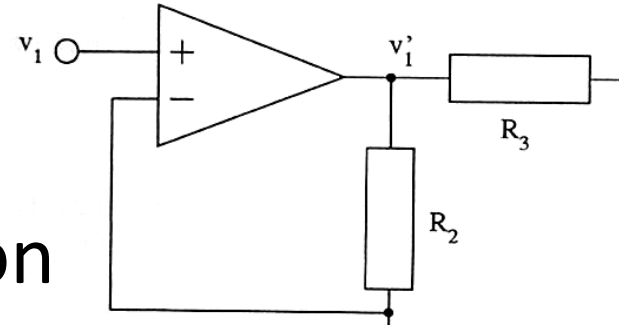
# Recording the ECG – electrode choice

- To record ECG - a transducer capable of converting the ionic potentials generated within the body into electronic potentials is required
- Such a transducer is a pair of electrodes and are:
  - Polarisable (which behave as capacitors)
  - Non-polarisable (which behave as resistors)
  - Both; common electrodes lie between these two extremes
- Most commonly used: *silver-silver chloride* electrode, which is closer to a non-polarisable electrode.
- Think about supply chains – these go off quick and are expensive



# ECG Amplification

- Problems in ECG amplification



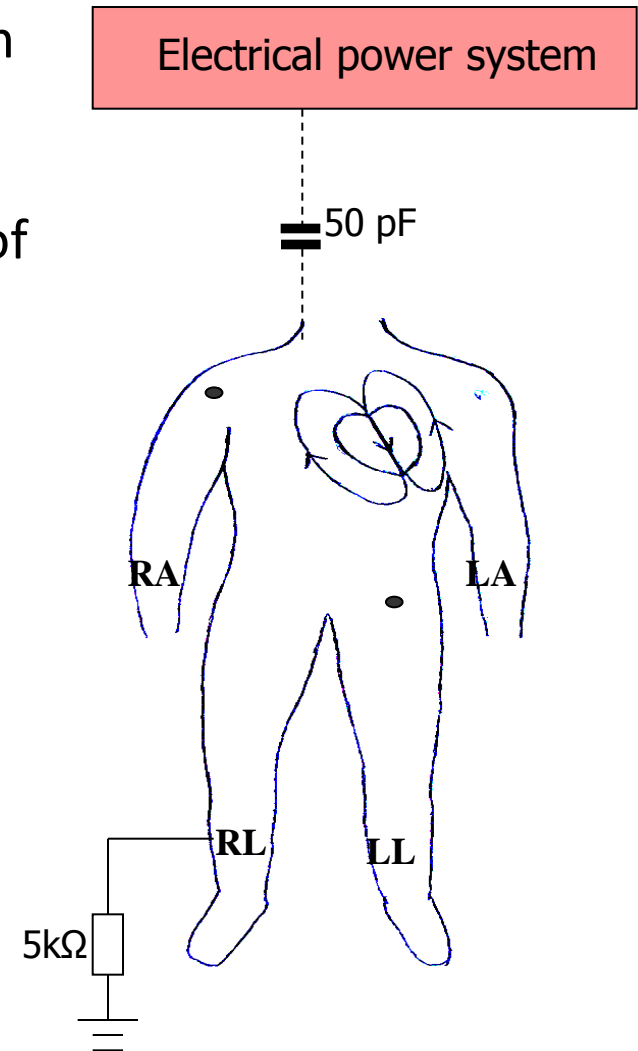
- The signal is small (typical ECG peak value  $\sim 1\text{mV}$ ) so amplification is needed
- Interference is usually larger amplitude than the signal itself



# 1<sup>st</sup> Problem: Electric Field Interference

- Capacitance between power lines and system couples current into the patient
- This capacitance varies but it is of the order of 50pF (this corresponds to  $64\text{M}\Omega$  at 50Hz ... recall  $X_c=1/\omega C$  )
- If the right leg is connected to the common ground of the amplifier with a contact impedance of  $5\text{k}\Omega$ , the mains potential will appear as a  $\sim 20\text{mV}$  noise input.

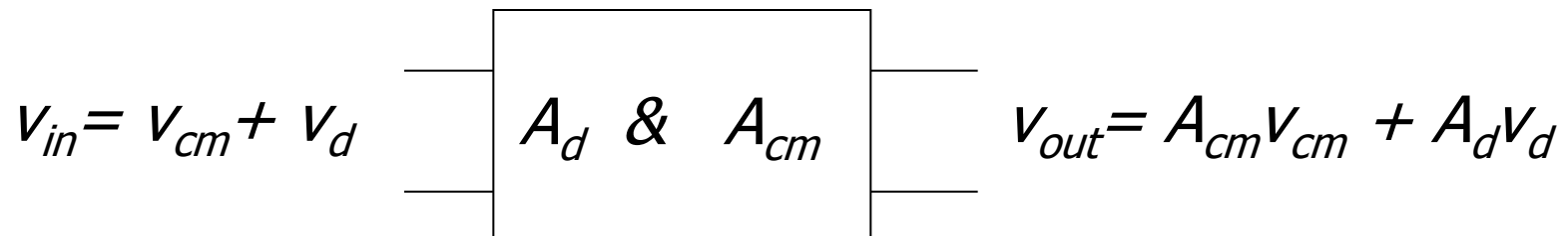
the 50 Hz interference is common to both measuring electrodes!  
(common mode signals)



# The solution

- The ECG is measured as a *differential* signal.
- The 50/60Hz noise, however, is common to all the electrodes.
  - It appears equally at the Right Arm and Left Arm terminals.
- Rejection therefore depends on the use of a *differential amplifier* in the input stage of the ECG machine.
- The amount of rejection depends on the ability of the amplifier to reject *common-mode* voltages.

# Common Mode Rejection Ratio (CMRR)

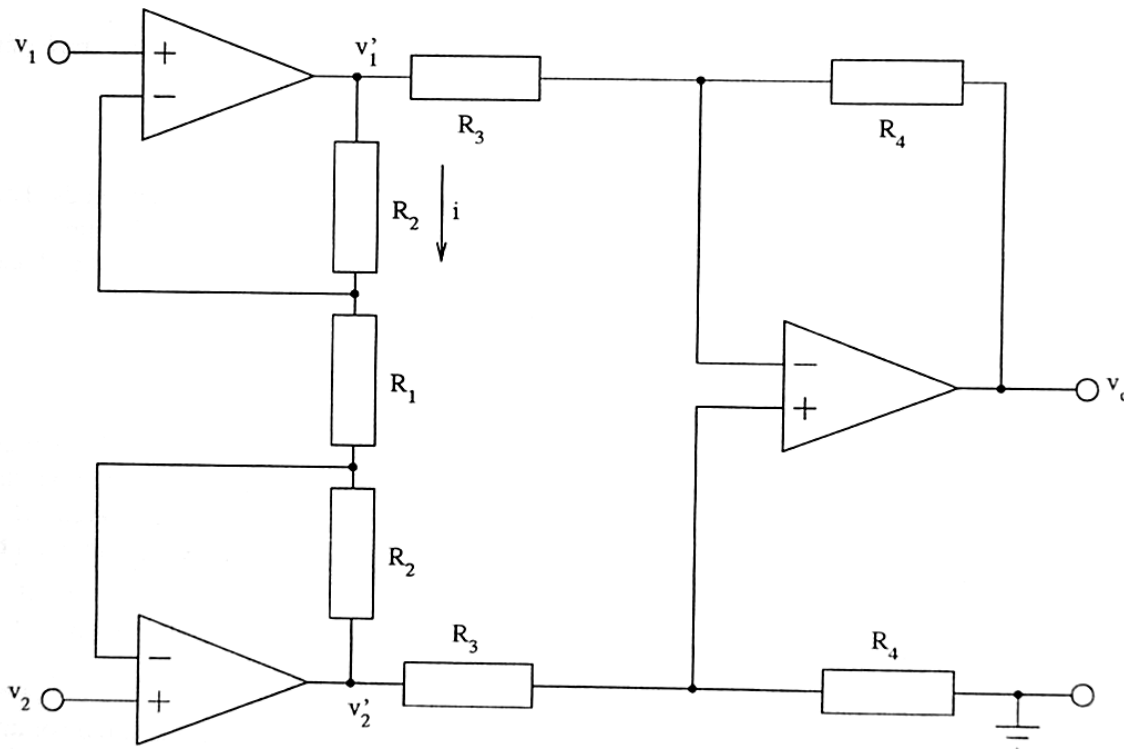


$$CMRR = A_d / A_{cm}$$

*(ratio of differential gain to common mode gain)*

*Often expressed in power:  $CMRR = 10\log_{10}(A_d/A_{cm})^2$*

# Three Op-Amp Differential Amplifier



$$i = \frac{v_1' - v_2}{R_2} = \frac{v_1 - v_2}{R_1} = \frac{v_2 - v_2'}{R_2}$$

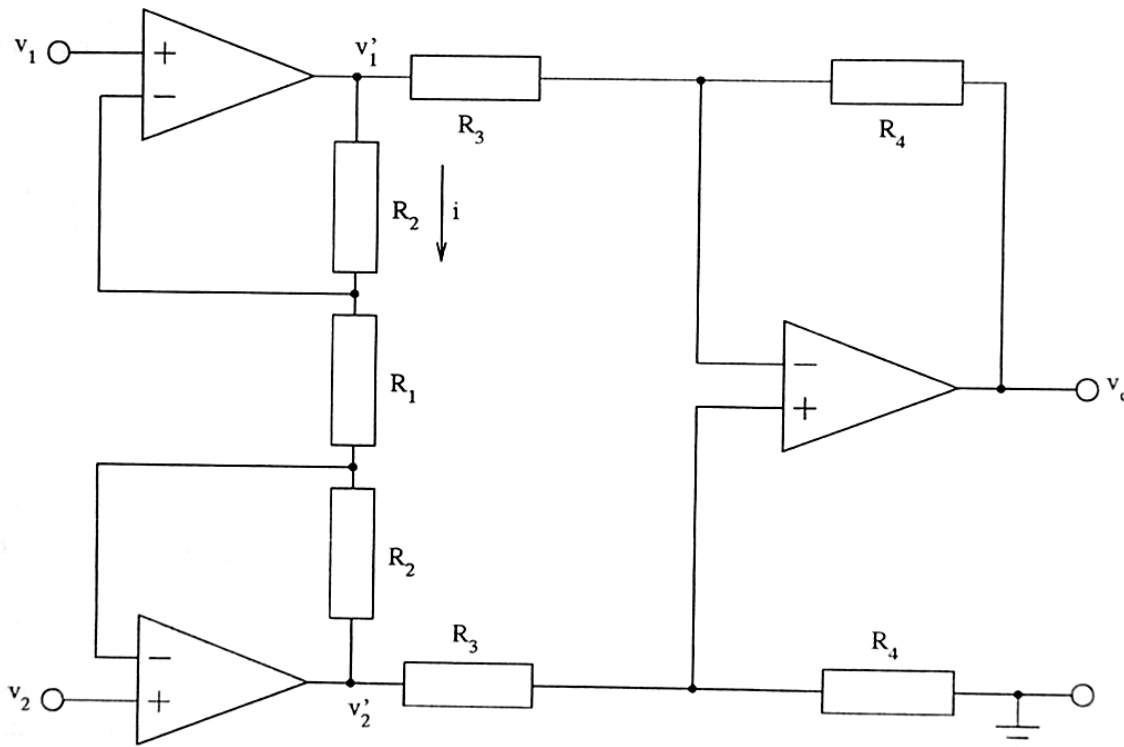
$$v_1' = \left(1 + \frac{R_2}{R_1}\right)v_1 - \frac{R_2}{R_1}v_2$$

$$v_2' = \left(1 + \frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1$$

$$v_2' - v_1' = (v_2 - v_1) \left(1 + \frac{2R_2}{R_1}\right)$$

$$A_{d1} = 1 + \frac{2R_2}{R_1}$$

# Three Op-Amp Differential Amplifier



$$i = \frac{v_1' - v_2'}{R_2} = \frac{v_1 - v_2}{R_1} = \frac{v_2 - v_2'}{R_2}$$

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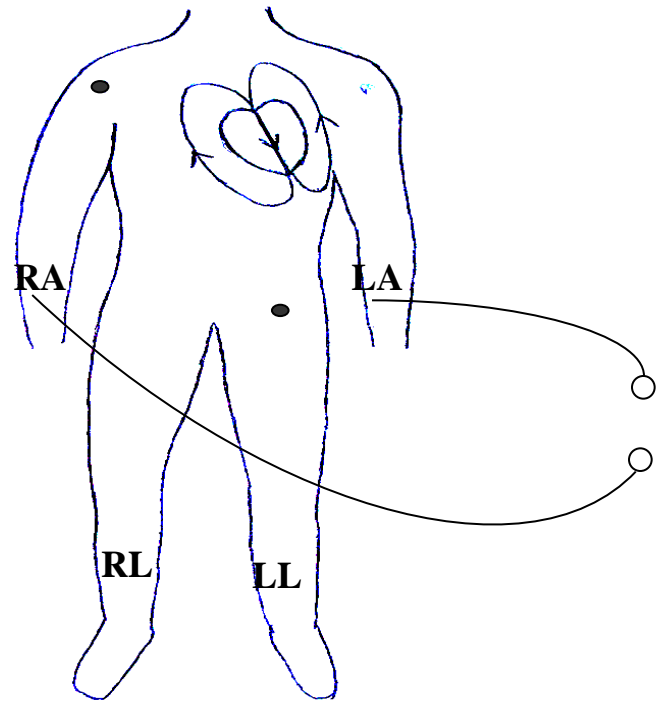
$$v_2' - v_1' = (v_2 - v_1)\left(1 + \frac{2R_2}{R_1}\right)$$

- Need to make CMRR as high as possible

$$\text{CMRR} = \frac{\mathbf{A}_{d1} \cdot \mathbf{A}_{d2}}{\mathbf{A}_{cm1} \cdot \mathbf{A}_{cm2}}$$

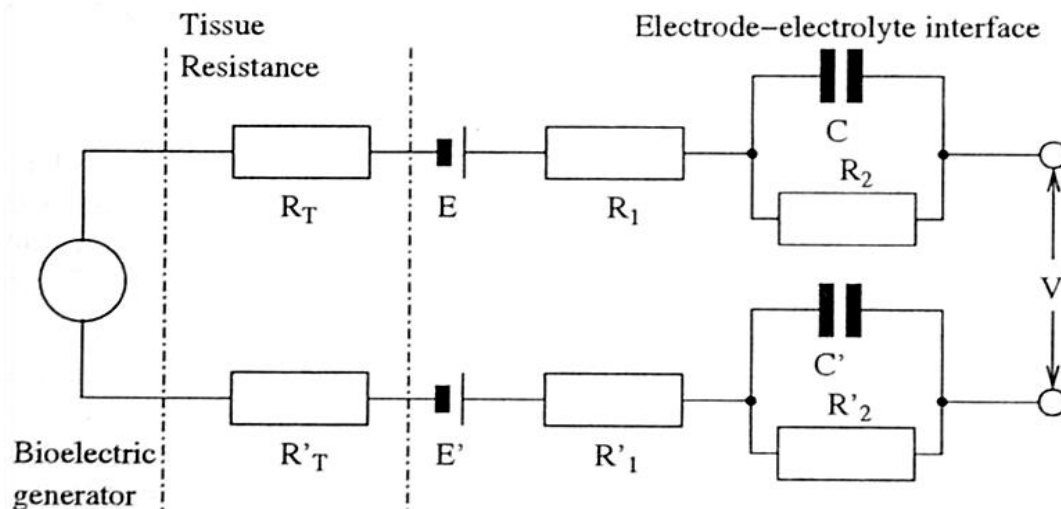
## 2<sup>nd</sup> problem: Magnetic Induction

- Current in magnetic fields induces voltage in the loop formed by patient leads
- The solution is to minimise the coil area (e.g. by twisting the lead wires together)
- The noise is now common to both inputs and is cancelled at differential amplifier
- Twisted pair cabling minimises cross talk in communication lines



# 3<sup>rd</sup> problem: Source impedance unbalance

- If the contact impedances are not balanced (i.e. the same), then the body's common-mode voltage will be higher at one input to the amplifier than the other.



# 3<sup>rd</sup> problem:

## Source impedance unbalance

- If the contact impedances are not balanced (i.e. the same), then the body's common-mode voltage will be higher at one input to the amplifier than the other.
- Hence, a fraction of the common-mode voltage will be seen as a differential signal.
- So make sure you use the same electrodes & wires (and same age of electrodes/wires) on each electrode



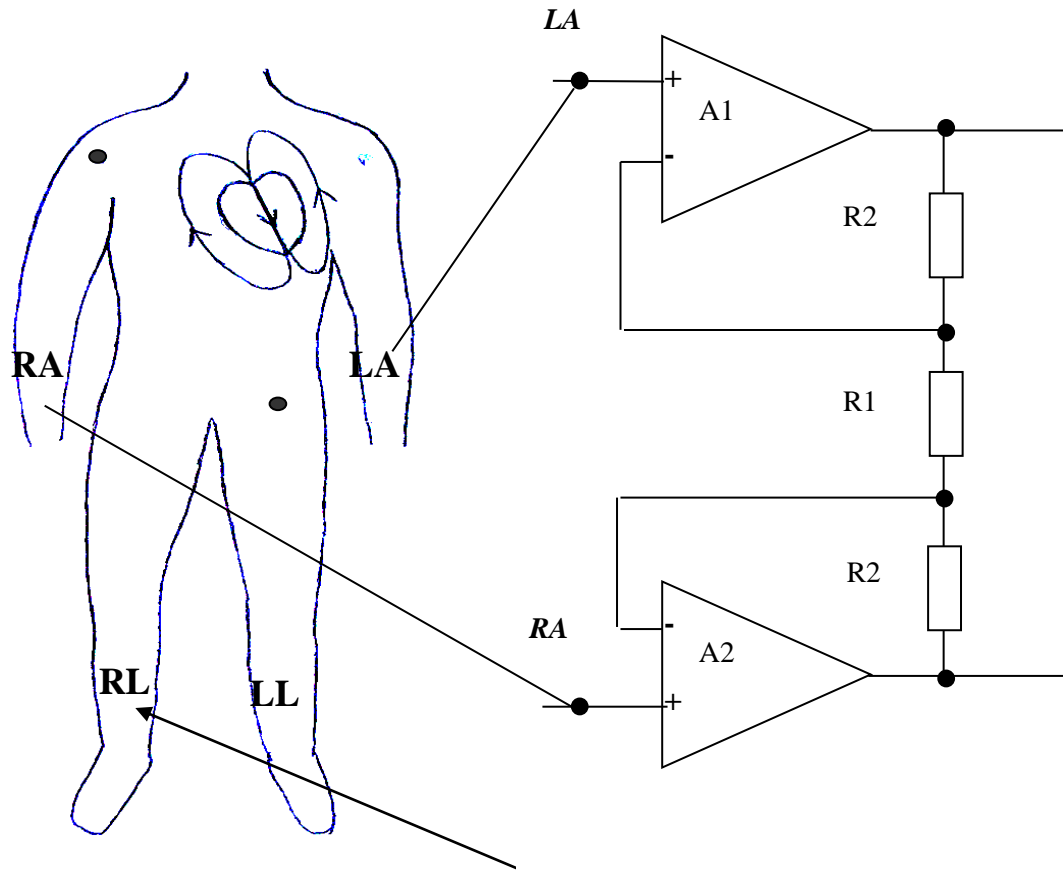
# Summary

- Output from the differential amplifier consists of three components:
  - The *desired* output (ECG)
  - *Unwanted* common-mode signal because the common-mode rejection is not infinite
  - *Unwanted* component of common-mode signal (appearing as pseudo-differential signal at the input) due to contact impedance imbalance

# Driven right-leg circuitry

- The common-mode voltage can be controlled using a *Driven Right-Leg Circuit*.
- A small current ( $<1\mu\text{A}$ ) is injected into the patient to equal the displacement currents flowing in the body.

# Driven right-leg circuitry

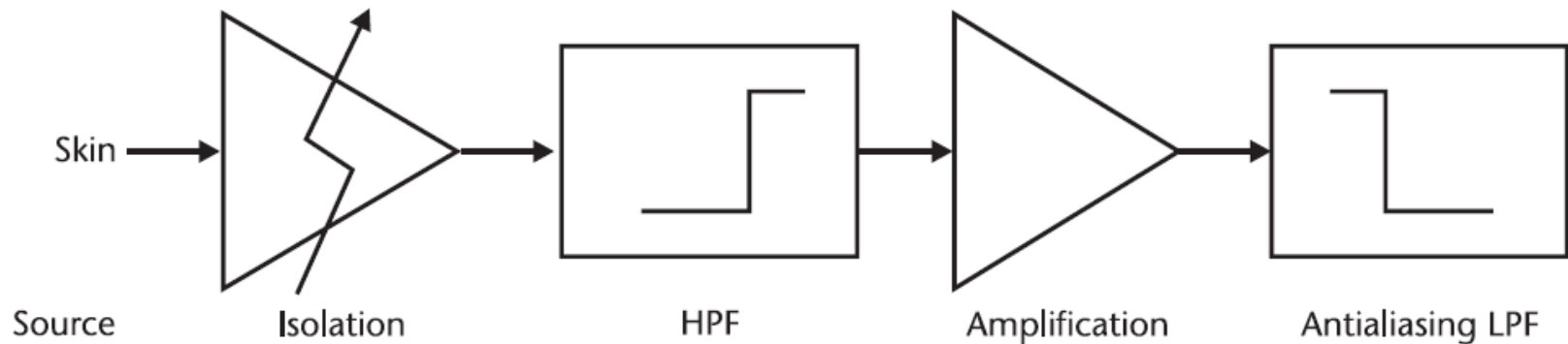
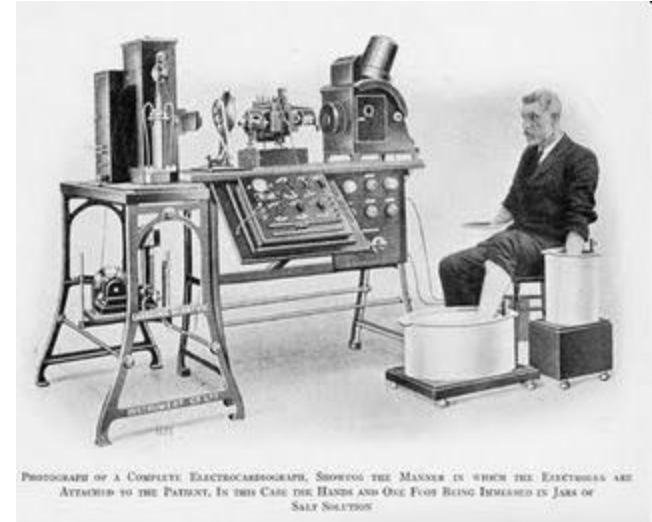


# Driven right-leg circuitry

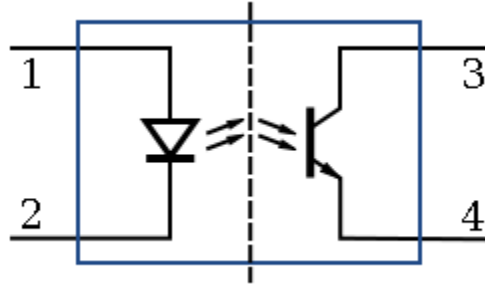
- The common-mode voltage can be controlled using a *Driven right-leg circuit*.
- A small current ( $<1\mu\text{A}$ ) is injected into the patient to equal the displacement currents flowing in the body.
- The body acts as a summing junction in a feedback loop and the common-mode voltage is driven to a low value.
- This also improves patient safety ( $R_o$  is v. large).
  - If an abnormally high voltage appears between the patient and ground the auxiliary op-amp in the right leg circuit saturates.
  - Effectively ungrounds the patient ... the amplifier can no longer drive the right leg.
  - The resistance  $R_o$  between the patient and ground is usually several  $\text{M}\Omega$  - protects patient.  
e.g. With a  $5\text{ M}\Omega$  resistor and a supply voltage of  $10\text{V}$ , amplifier will saturate @  $I \sim 2\ \mu\text{A}$ .)

# Other patient protection

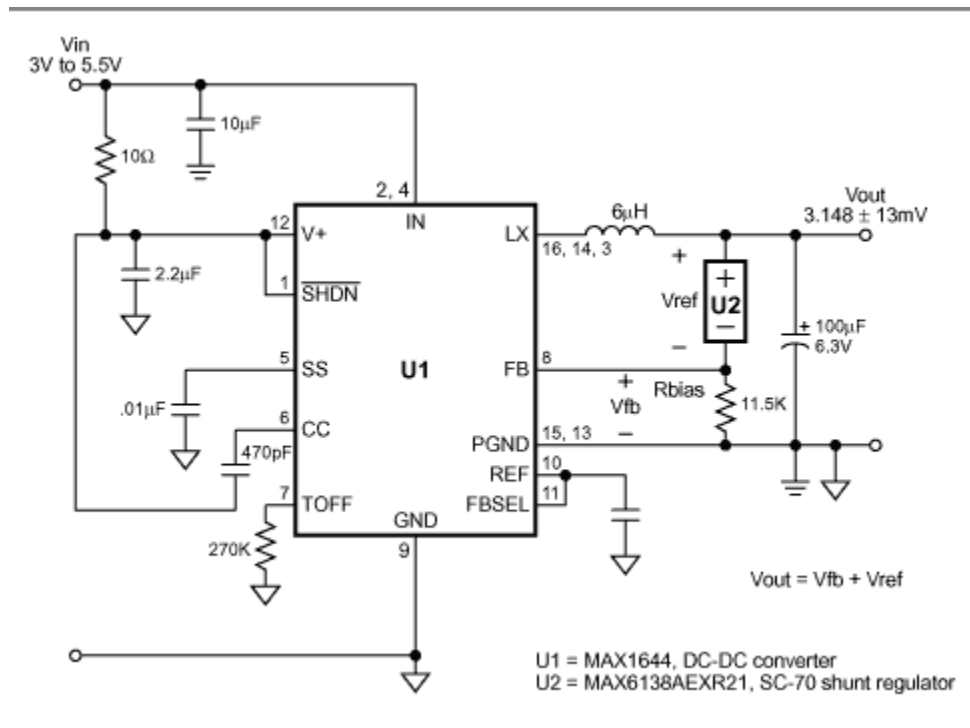
- Defib protection
- **Isolation**
- Filtering
- Amplification
- Anti-alias filtering
- Digitization



# Patient Isolation



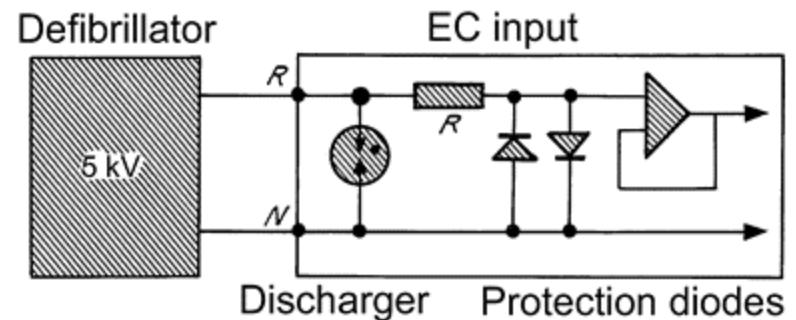
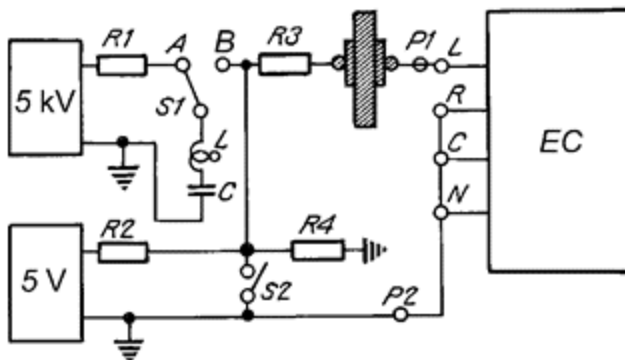
- Opto-isolators



- DC-DC Converters

# Static defibrillation protection

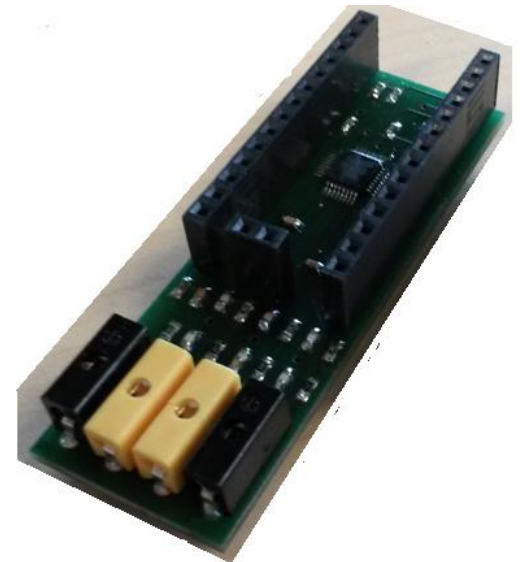
- For use in medical situations, the ECG must be able to recover from a 5kV, 100A impulse (defibrillation)
- Use large inductors and diodes



# Hardware design – analogue front end

- Filters –  $>0.01 <100\text{Hz}$  (check electrodes work in this bandwidth)
  - 0.5-40 Hz: ‘monitoring’ bandwidth
  - 0.05-100 for diagnostic ECG
  - $\geq 0.05$  Hz for ischemia
  - $\geq 0.1$  Hz for QT
- Representation (8, 10, 12, 16, 24 bit)?
  - Each of these will use up storage
  - But more bits  $\Rightarrow$  fewer filters, better amplitude resolution
  - Also think about gain on amplifier
- Sampling frequency?
  - QRS detection 100-256HZ
  - QT, HRV 500-1000Hz
- Isolation?
  - Battery / Bluetooth? Think about trade-offs
- Differential amplifier choice?
  - Don’t waste time ... Use the TI ADS1292

<http://www.ti.com/lit/ds/symlink/ads1292.pdf>

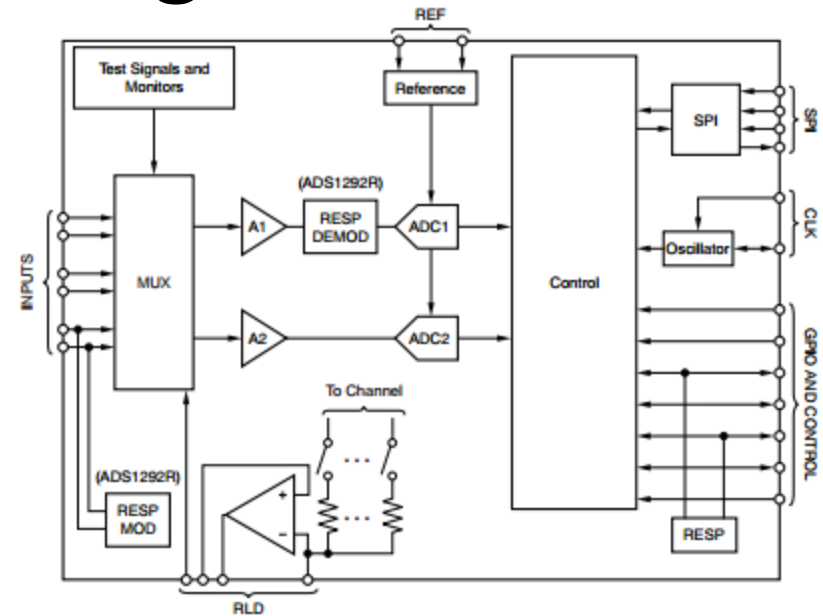




# Hardware design – analogue front end

## TI ADS1292 (~\$3)

- Programmable Gain: 1:12
- CMRR -105 dB
- Leads: Unipolar or Bipolar
- Component power supplies regulated:
  - Analog: 2.7 V to 5.25 V
  - Digital: 1.7 V to 3.6 V
- 3MHz EM interference filter
- Antialiasing filter before ADC at 8.6kHz
- Operates at data rates up to 8 kSPS.
- Built-In Right Leg Drive Amplifier
- Lead-Off detection can be implemented
- Fully integrated respiration impedance measurement (ADS1292R)
- Built-In Oscillator and Reference
- Flexible Power-Down, Standby Mode
- Operating Temperature Range:  $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$
- Thin flat pack: 5-mm  $\times$  5-mm, 32-pin



<http://www.ti.com/lit/ds/symlink/ads1292.pdf>

**Note: NO ISOLATION!** ... Just RL driven circuitry

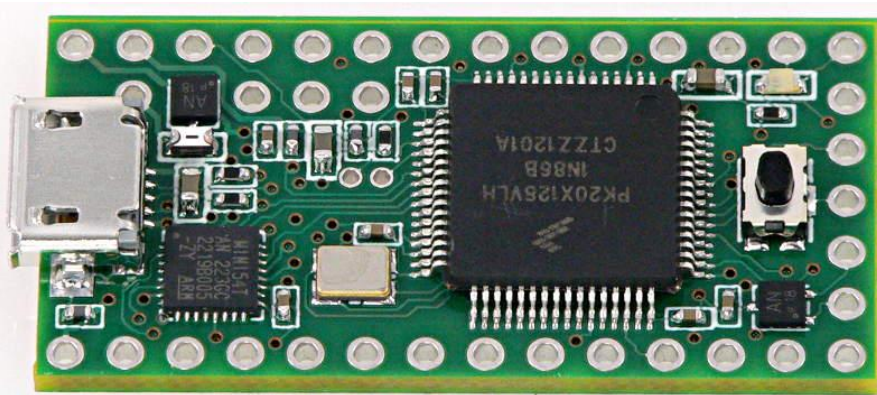
# Incomplete Isolation!!!

- IMPORTANT

- This package does not have full medical grade isolation
- **Do not** connect the mains to the device and the device to the patient
- Put PCs/laptops/tablets/phones on battery mode when a live subject is connected to your device
- Avoid USB splitting cables
- ToDo (Future fun) -Design a battery pack to interface with the USB port
- Save data to flash/microSD card or transfer out via USB cable or Bluetooth to phone

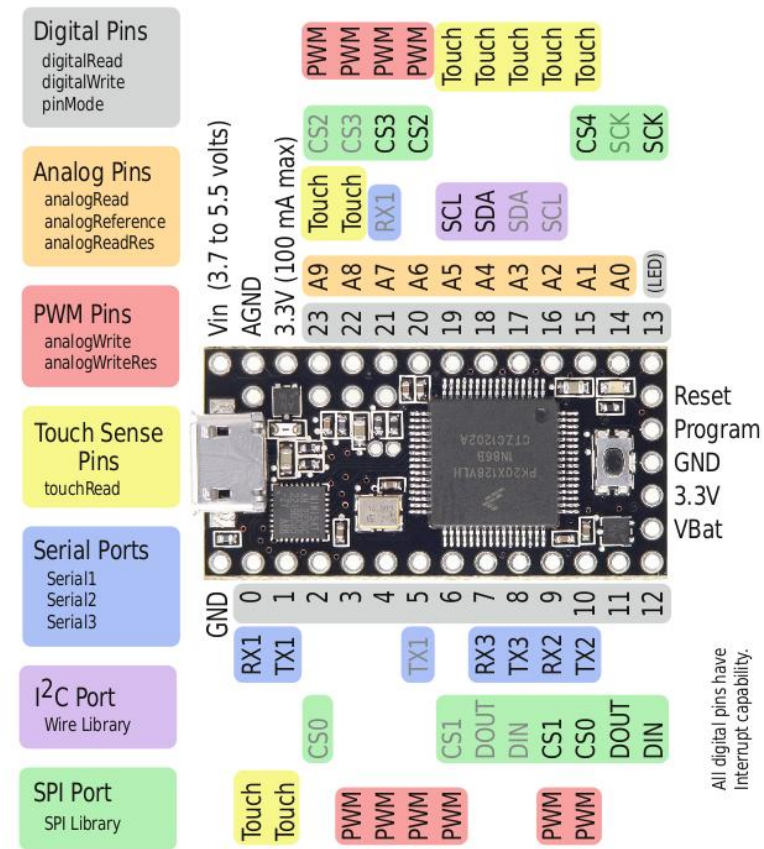
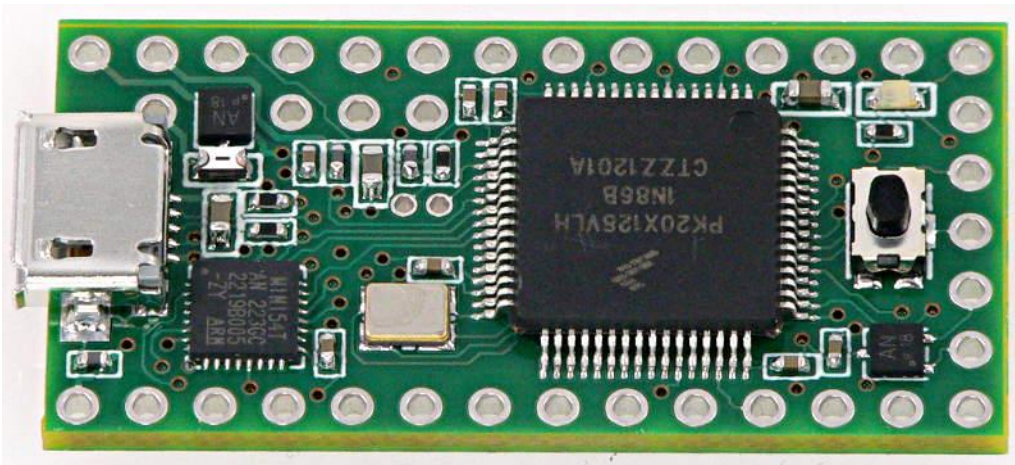
# Hardware design – DSP

- Where do you want to do the processing?
  - On the phone? – use simple low cost processor that serialises
  - Onboard (e.g. New FDA guidelines on mHealth)?
  - In the cloud?

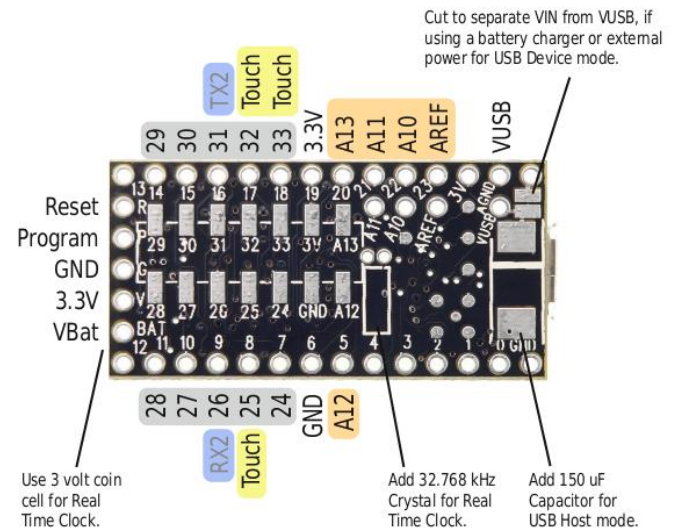


# Digital board

- Teensy 3.0
  - 48 MHz ARM Chipset
  - 16k RAM
  - C or Arduino instructions
  - Use *teensyduino* software

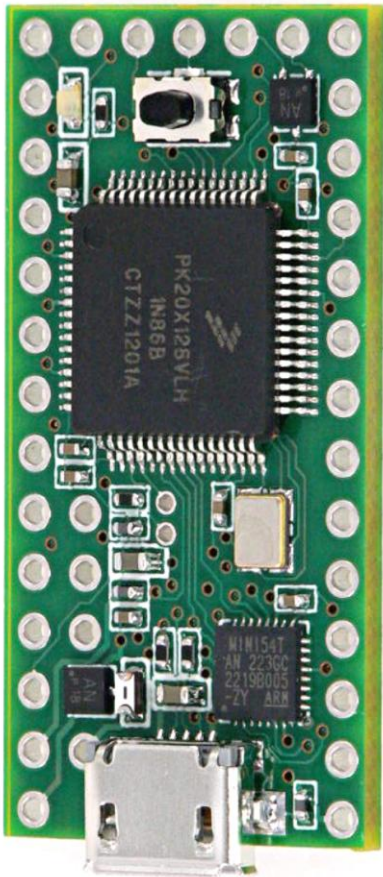


All digital pins have interrupt capability.



# Digital board

- Teensy 3.0: ARM CPU



Specification	Teensy 2.0	Teensy++ 2.0	Teensy 3.0
	ATMEGA32U4	AT90USB128	MK20DX128
Processor	8 bit AVR	8 bit AVR	32 bit ARM Cortex-M4
	16 MHz	16 MHz	48 MHz
Flash Memory	32256	130048	131072
RAM Memory	2560	8192	16384
EEPROM	1024	4096	2048
I/O	25, 5 Volt	46, 5 Volt	34, 3.3 Volt
Analog In	12	8	12
PWM	7	9	10
UART,I2C,SPI	1,1,1	1,1,1	3,1,1
Price	<u>\$16</u>	<u>\$24</u>	<u>\$19</u>

# Parts List

1 x ADS1292R TQFP32

<http://www.digikey.com/product-detail/en/ADS1292RIPBSR/296-30389-1-ND/3188671>

1 x Teensy 3.0

<https://www.pjrc.com/store/teensy3.html>

2 x 14-Pins 2.54mm pitch

[https://www.pjrc.com/store/header\\_14x1.html](https://www.pjrc.com/store/header_14x1.html)

2 x 14-Socket 2.54mm pitch

[https://www.pjrc.com/store/socket\\_14x1.html](https://www.pjrc.com/store/socket_14x1.html)

1 x 2-Socket 2.54mm pitch

[https://www.pjrc.com/store/socket\\_12x1.html](https://www.pjrc.com/store/socket_12x1.html) (can be split)

1 x 2-Pins 2.54mm pitch

[https://www.pjrc.com/store/header\\_12x1.html](https://www.pjrc.com/store/header_12x1.html) (can be split)

4 x Banana Socket 2mm

<http://docs-europe.electrocomponents.com/webdocs/01b6/0900766b801b63e4.pdf>

1 microUSB data/power cable (mail full size to mail micro)

--Resistors (SMD)--

3 x 22.1K 0603

8 x 10k 0603

2 x 100k 0603

1 x 1M 0603

--Capacitors (SMD)--

6 x 47p 0603

3 x 4.7n 0603

2 x 1u 0603

1 x 0.1u 0603

1 x 10u 1206

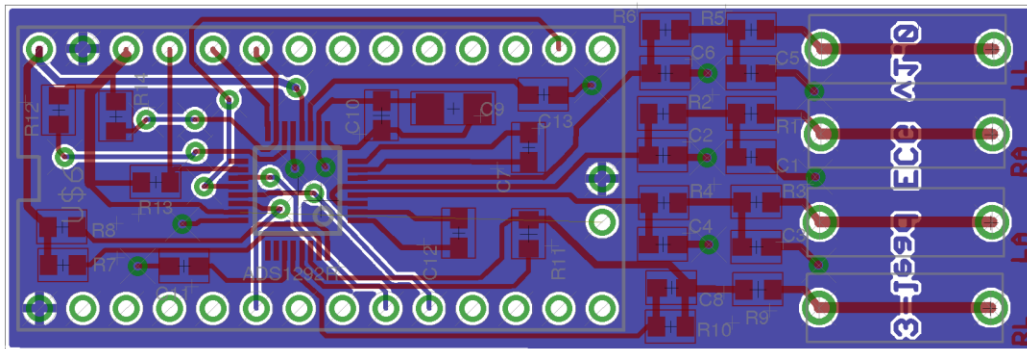
--ECG electrodes--

4 x Leads with 2mm banana plugs

4 x Crocodile clips with 2mm banana plug sockets

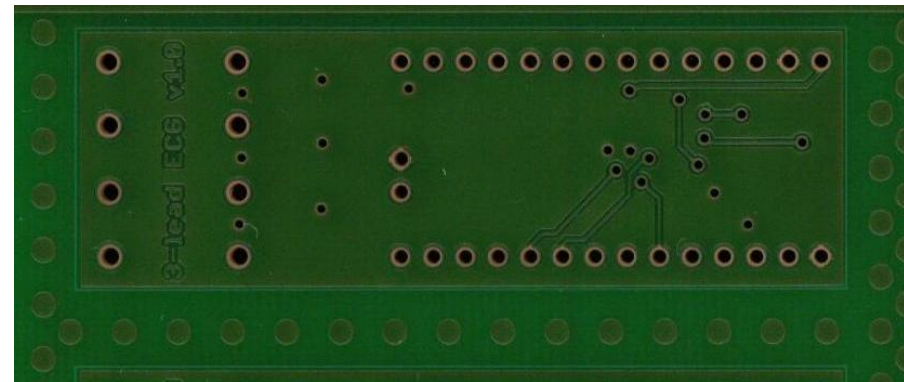
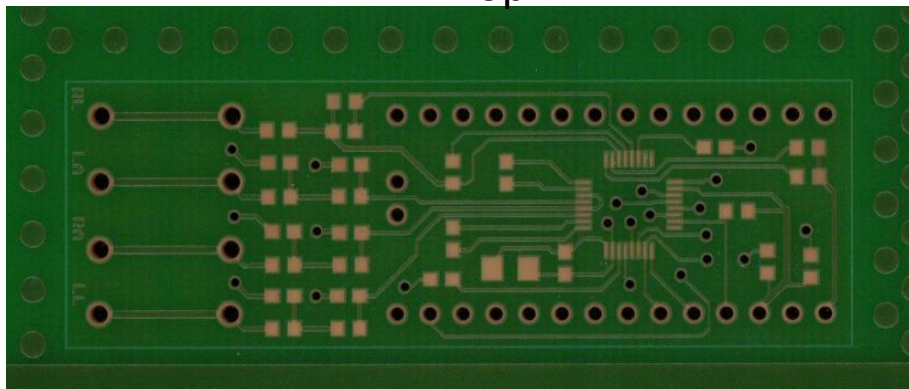
# Assembling PCB

- Eagle design:  
ecg.scd & ecg.brd



Top

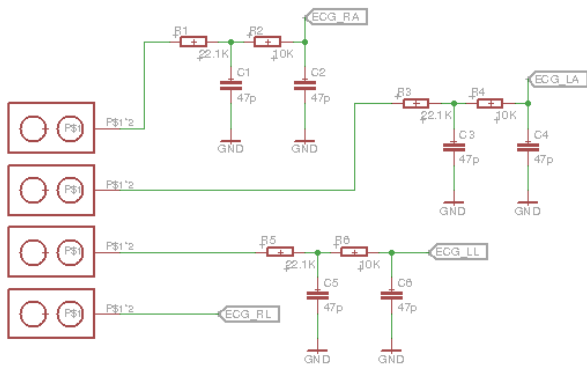
bottom



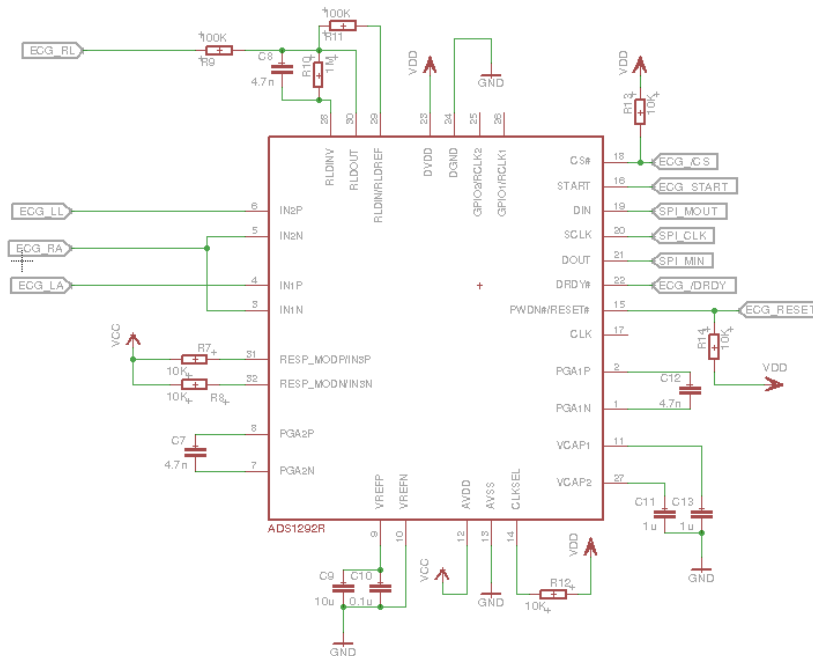
# Assembling PCB

- Eagle design: ecg.scd & ecg.brd

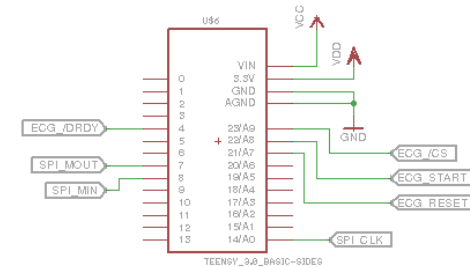
3-lead ECG connector



ECG front end



Teensy 3.0

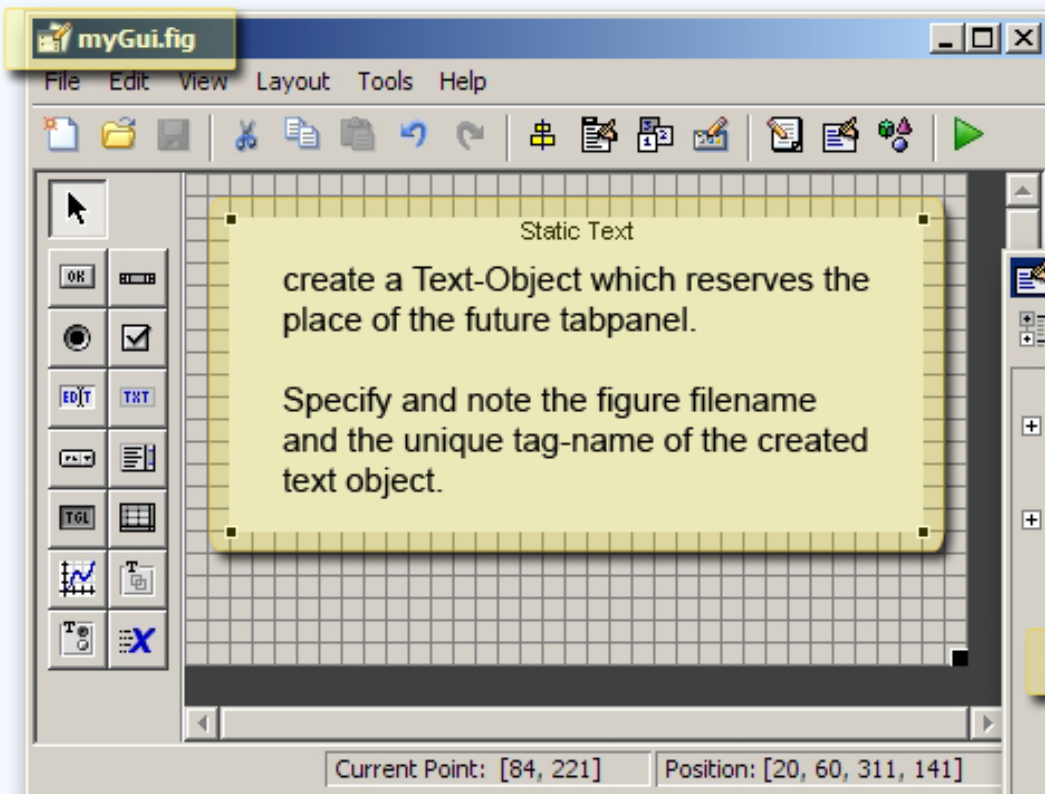




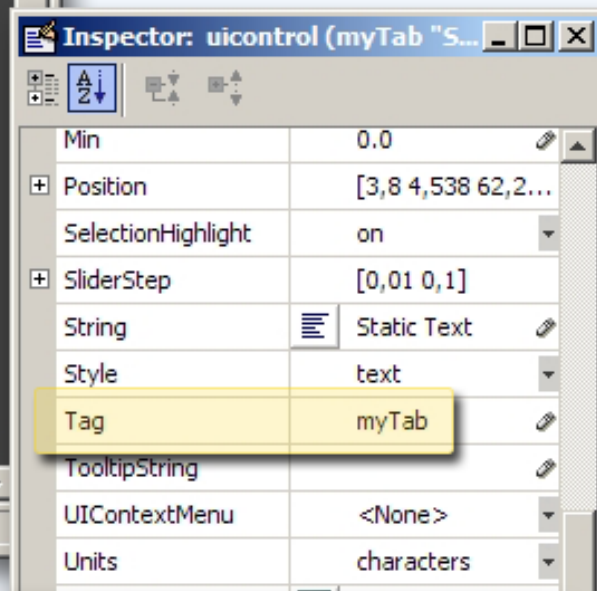
# Getting the boards to talk

- 1- Download and install the Arduino software: <http://arduino.cc/en/main/software>
- 2- Download and install the Teensyduino plugin  
<http://www.pjrc.com/teensy/teensyduino.html>
- 3- Load the .ino file (source code) e.g. `ecg_ads1292.ino` which is a test file.  
You can do it by "File-->Open" from the arduino software and it will create a folder for the project.
- 4- Select the right device (teensy 3.0) by going to "Tools -->boards-->Teensy 3.0".
- 5- Compile: You have 5 icons on the top left of the arduino interface. The check mark (verify) compiles the code.
- 6- Load the code into the teensy: With the teensy connected through USB, go to "Tools-->Serial Port-->" and select the serial port that corresponds to the Teensy. Finally, the arrow icon next to the compilation check mark works to upload the code into the teensy.
- 7- Open the Matlab interface and follow the instructions (i.e. select the "serial port" that corresponds to the Teensy, and start the acquisition).

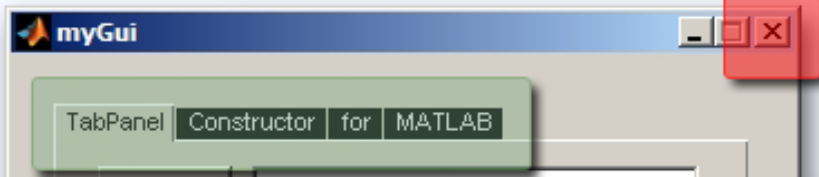
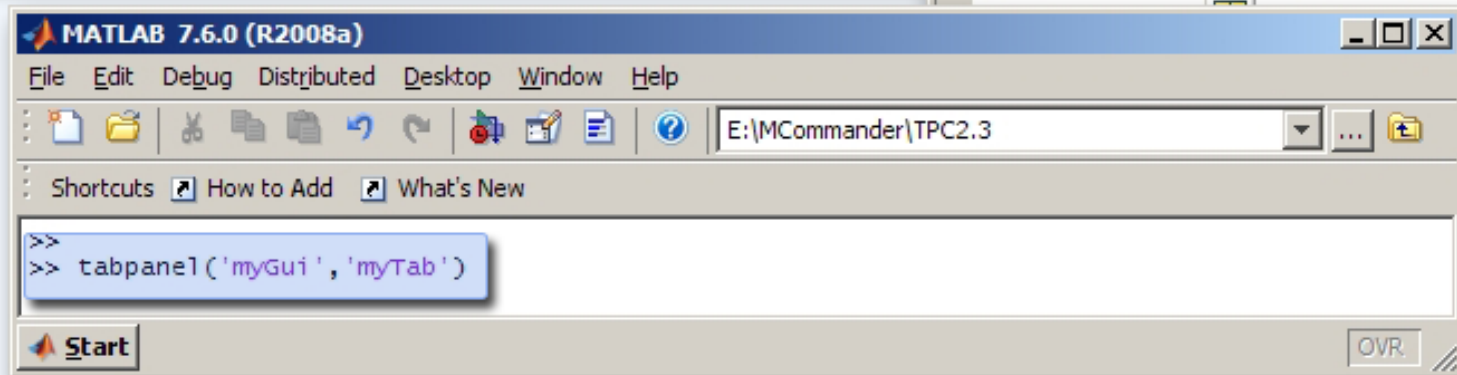
Software available at [www.mit.edu/~gari/CODE\\_ECG\\_lab/](http://www.mit.edu/~gari/CODE_ECG_lab/)



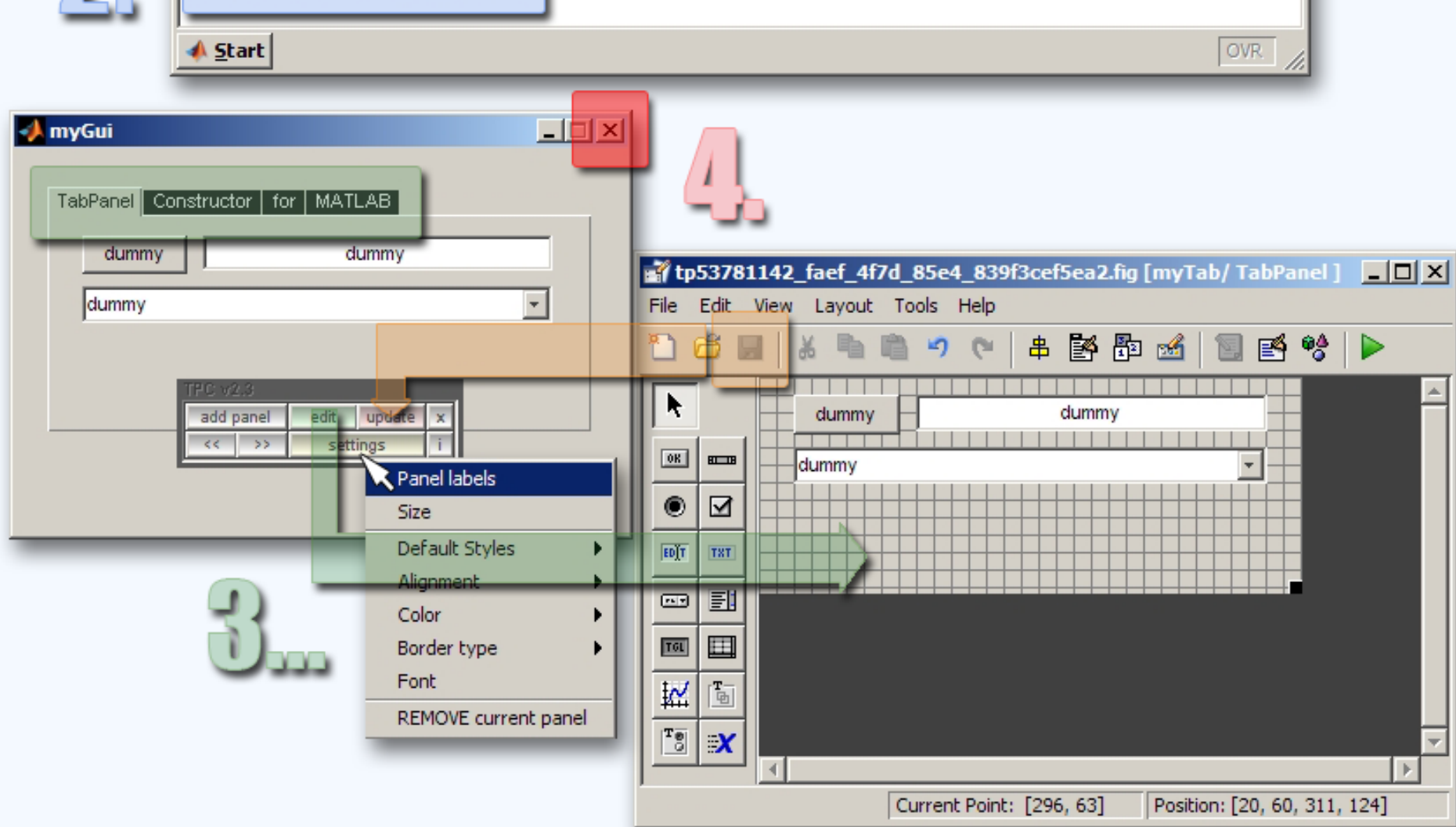
1.



2.



4.



Do you want to edit the tabpanel later?  
 >> **tabpanel ('myGui','myTab')**

Do you want to delete tabpanel from figure?  
 >> **tabpanel ('myGui','myTab','delete')**

# Output: Int to mV?

Output is a 2 col file (2 ECG leads) of 24 bit unsigned integers. 0V =  $2^{23}$  bits

## Offset

The conversion of the differential inputs are in signed integers.

They go from 800000h ( $\leq -V_{ref}$ ), to 7FFFFFFh ( $\geq V_{ref}$ ).

The value 000000h should correspond to 0V difference between inputs

## Gain

The Gain in bits/mV is =  $\text{GainSetting} * (2^{23} - 1) / V_{ref}$  (bits/mV),

where GainSetting is the setting in the Chip (1x, 2x, 6x, etc),

and  $V_{ref} = 2.42\text{V}$ .

So, for a gain = 1, there are 3466366 bits/mV.

We are not setting any offset to the signal, but there can be an offset in the channel due to noise and other factors. We can measure this and compensate for it.

There is an option in the chip to short-circuit the inputs and measure that voltage.

If that is different from 0, we can record this and subtract it from the actual gain.

# Analysis software: QRS detection

## PanT\_light\_ascii.c

- gcc PandT\_light\_ascii.c -lm -o gqrs
- Reads 2 column file
- Writes out several files:
  - Mxxxch0.bpf .slp .sqr .tav .fid
  - See README.txt

## Syntax:

gqrs ecg\_file.txt #columns gain(bits per mV) representation(in bits)

e.g.

gqrs ecg\_example\_256Hz\_24bits.txt 2 838860 24

## Output:

R-peak\_time R\_amplitude S\_amplitude RS\_amplitude

Software at [www.mit.edu/~gari/CODE/ECG\\_lab](http://www.mit.edu/~gari/CODE/ECG_lab)

# PandT\_light\_ascii.c

ecg\_example\_256Hz\_24bits.txt

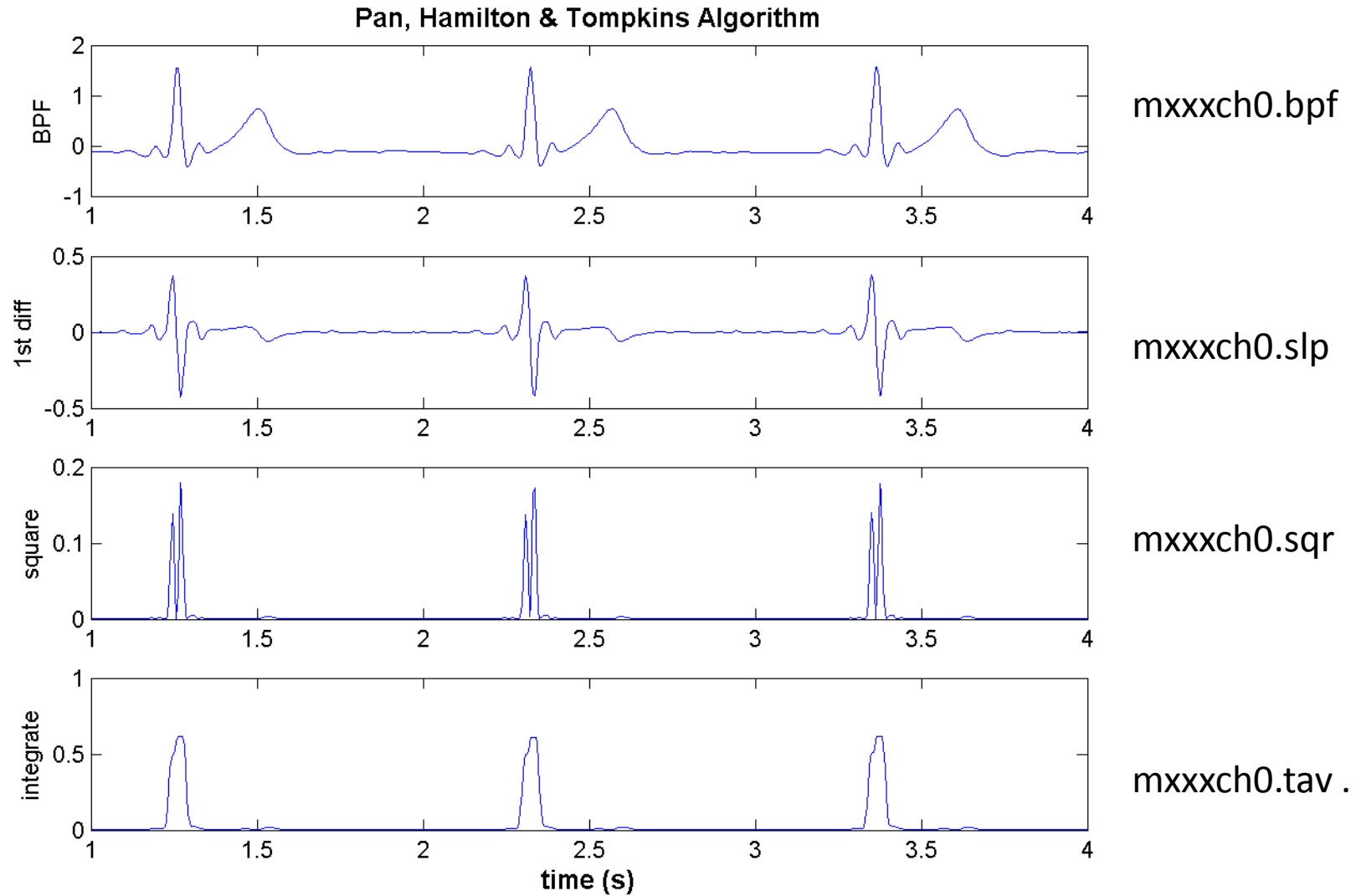
A 2 column 24 bit unsigned int file of ECG data similar to that which will be extracted from the DSP board.

PandT\_light\_ascii.c

A QRS detector which reads 2 column 24 bit unsigned integer ascii files. (Note that the baseline is computed from the representation as  $2^{(NB-1)}$  where NB=number of bits in the representation.)

You can edit the samp\_freq variable to be 250 with almost no effect – as I have already done. Be sure to downsample correctly in the hardware by averaging every 4 samples

# Modern QRS detection



# I have two (or more) ECG leads!

- The QRS detector is only operating on one lead
- What do I do with 2 leads?
  - Compare them to see which one you trust
  - Measure signal quality on them and choose the best one
  - Weight them together?
  - Better to have three (then a majority vote is easy)
- See <https://code.google.com/p/ipm-ecg-analysis/>



# Signal Quality

- Basic SQI provided

<https://code.google.com/p/ipm-ecg-analysis/>

- Optimise threshold for ignoring data and telling user the system is not working
- Also look at electrode impedance (See TI chip)

# Rhythm Detection

- Basic AF detector provided

<https://code.google.com/p/ipm-ecg-analysis/>

- Current published detectors do not generalise well
- We have developed an SVM-based detector which provides >98% accuracy across a range of databases
- Accuracy depends on quality of QRS detector and noise levels!

# Test kit

- Phantom ECG:

[http://www.ms-gmbh.de/en/phantom\\_start.htm](http://www.ms-gmbh.de/en/phantom_start.htm)



# Test databases

- Standard databases: [www.physionet.org](http://www.physionet.org)
  - NSRDB
  - AFDB
  - MITBIH Arrhythmia Database
- All of these are too clean. Use
  - NSTDB
  - Data collected using your device
- Must still report results on above databases!

# Now the lab

Suggestion:

- Break into groups of three or four & parallelize:
  1. Hardware construction and testing/debugging and electrode choices & battery pack(?)
  2. Hardware communication between boards, checking formats, and files I/O, Bluetooth(?)
  3. Signal processing, feature extraction
  4. *Visualisation (Phones, cloud services etc)*

# Hardware Construction

- i. Check that output is giving a reliable signal on analog side – use test signals, try a phantom ECG.
- ii. Were all parts soldered on correctly? – check diagrams & photos.
- iii. Test out various electrode types.
- iv. Add impedance pneumogram(?)
- v. Check lead off detection
- vi. Check temperature sensing

# Hardware Comms

- i. Check that output from analog board is reaching digital board.
- ii. Use test scripts to communicate with digital board and write data to PC
- iii. Can you sense temperature on teensy?
- iv. Can you pass through data on lead off detection?

# Signal processing

- i. Test out QRS detector on sample data
- ii. Visualise all the steps in the filters
- iii. Design quicker filters with shorter buffers?
- iv. Put data in fewer buffers (merge slp, sqr & tav)
- v. Take data from Teensy and test gain & offset



# Visualization

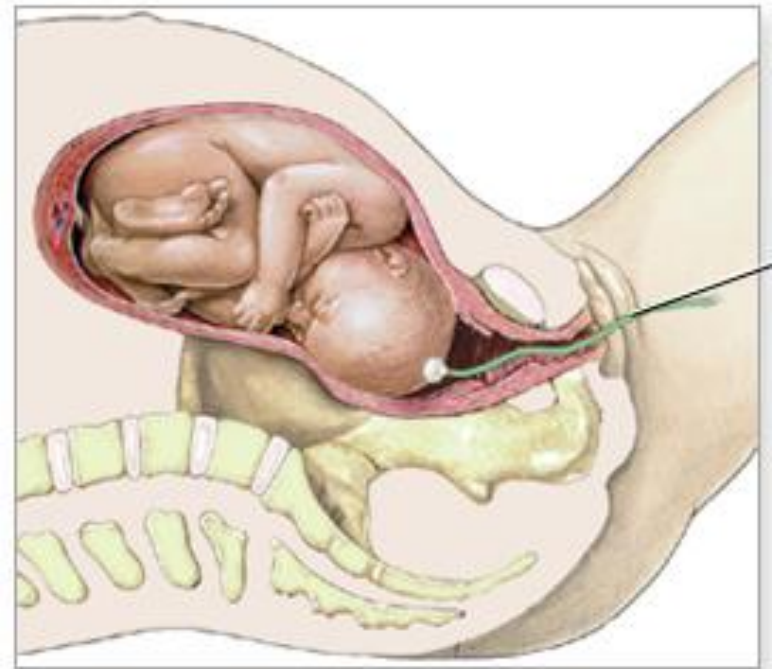
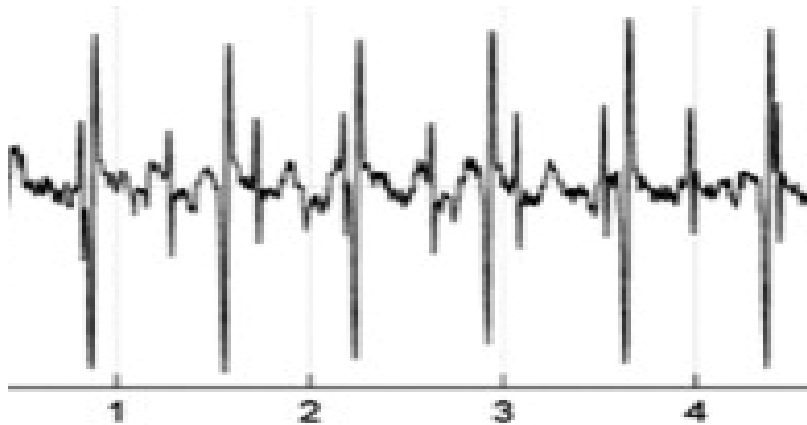
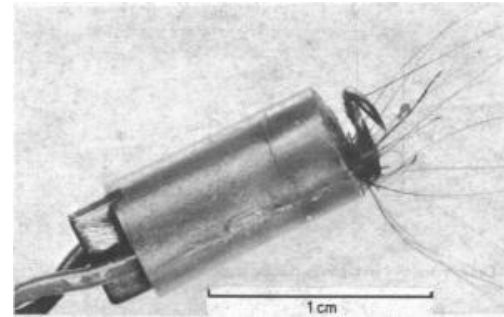
- i. Build Matlab interface to read data in real time
- ii. Adapt our Java code to visualise data on teensy and run on phone/PC/tablet
- iii. Copy Java code for SQI & AF detection and put on-board?

# OK – go for it

- [www.mit.edu/~gari/CODE/ECG\\_lab/](http://www.mit.edu/~gari/CODE/ECG_lab/)
- <https://code.google.com/p/ipm-ecg-analysis/>

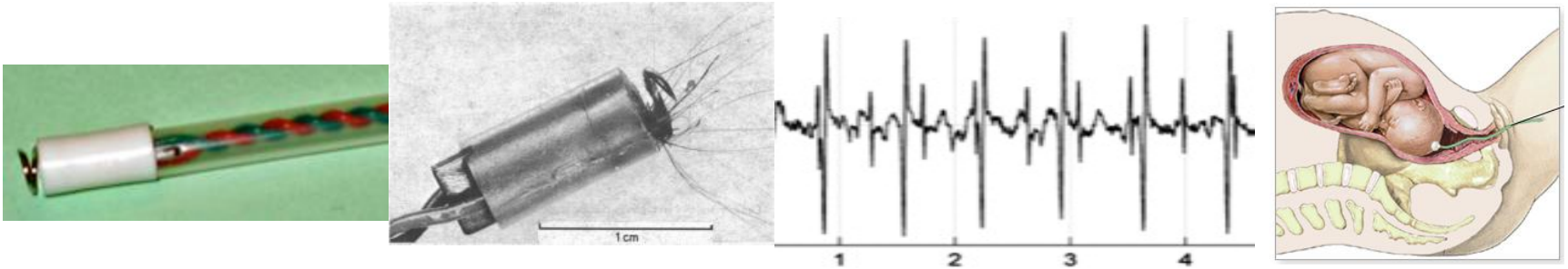


# Diagnostic uses of ECG



# Diagnostic uses of ECG

- Foetal monitoring (both before birth & during)



- Patient monitoring in Ambulance, Intensive Care Unit or Coronary Care Unit
  - S-T segment elevation to diagnose heart attacks
  - Evidence of cardiac muscle damage (infarct)
- Detection of precursors to heart attacks:
  - Abnormal heart beats (e.g. many ectopic beats, TWA)
  - Abnormal heart rhythms

# Use of ECG in CCU

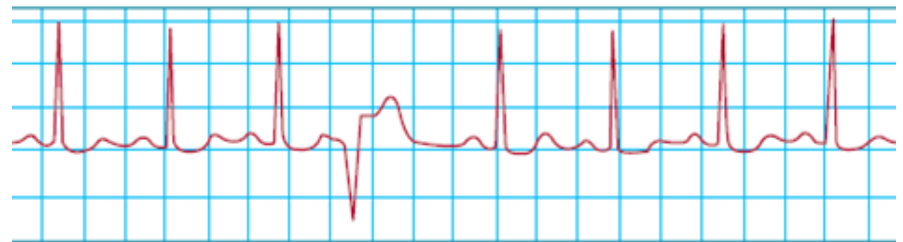
- The ECG is highly informative in the diagnosis of a heart attack (*Myocardial Infarct*). Insufficient blood supply to the cardiac cells due to a blockage in the coronary arteries (*ischaemic heart condition*) causes S-T segment elevation.



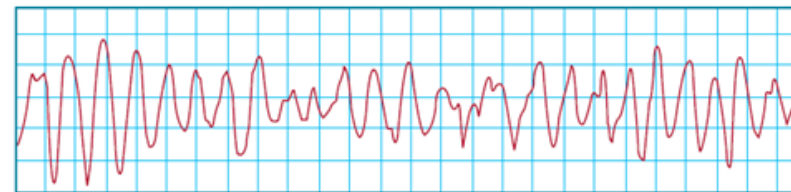
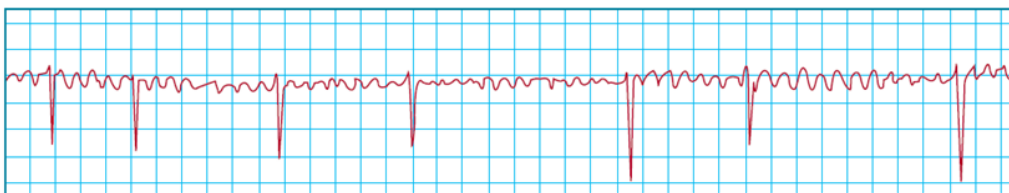
- Following the heart attack, cardiac muscle damage (infarct) generally leads to a loss of amplitude in the ECG.

# ECG abnormalities (possible precursors to heart attacks)

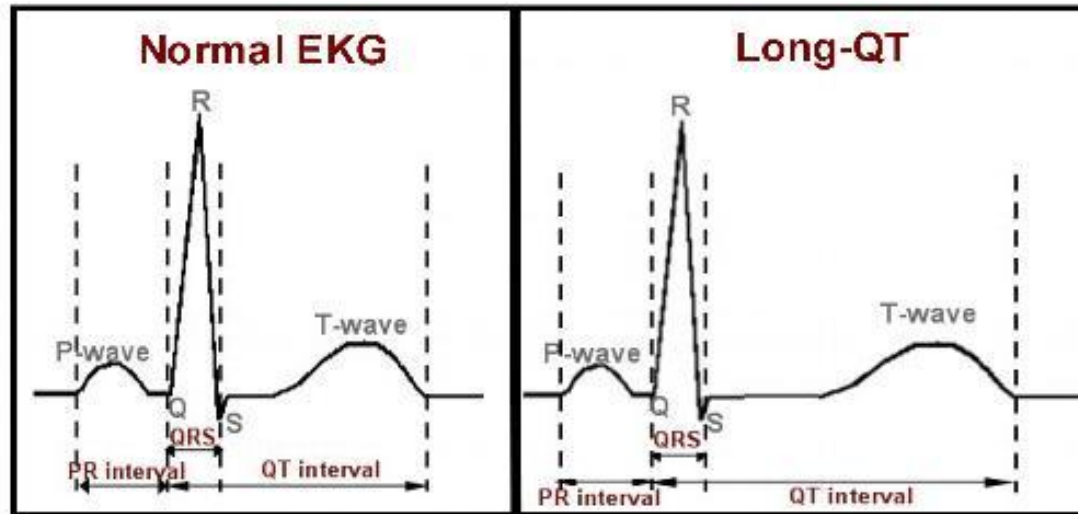
- Analysis of the ECG can provide early warning of potential problems.
- Ectopic beats originate somewhere other than the Sino-Atrial (SA) node and often have different shapes (*morphologies*).



- Abnormal heart rates (*arrhythmias*) can be treated.

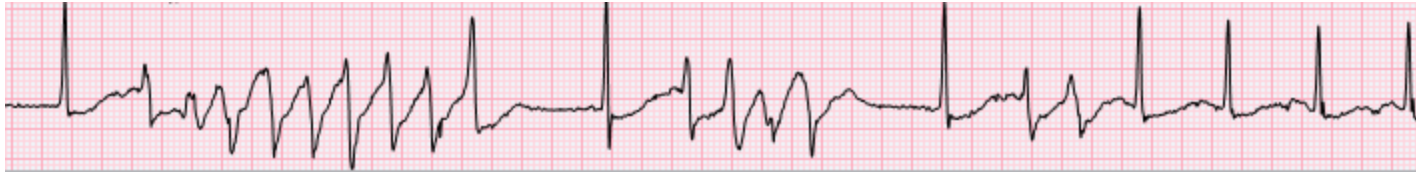


# Other intervals in ECG analysis



- The most important interval in the ECG is the QT interval
- A longer than normal QT interval is a good indicator of long QT syndrome (LQTS)

# Q-T interval measurement



- LQTS is a potentially fatal condition that renders sufferers vulnerable to an arrhythmia known as *torsade de pointes*.
- When this rhythm occurs the heart is unable to beat effectively and the blood flow to the brain falls dramatically.
- The result is a sudden loss of consciousness and possible cardiac death.



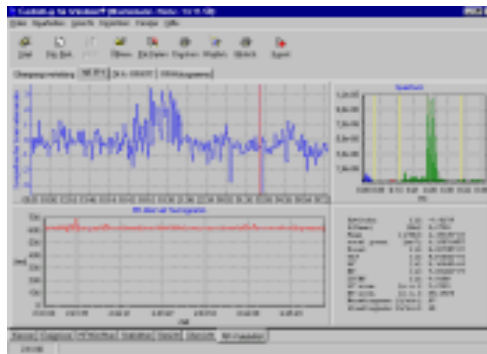
# Detecting ECG abnormalities

- Two methods are in common use:
  - Ambulatory monitoring
  - Exercise stress ECGs



# Ambulatory ECG monitoring

- ECG monitored for 24 hours.
- Results printed out:
  - 24-hour summary detailing the heart rate and segment changes over the period of the test.
  - Detailed information on ECG recorded at the time of a significant event (e.g. arrhythmia).



# Analysis of ECG waveform

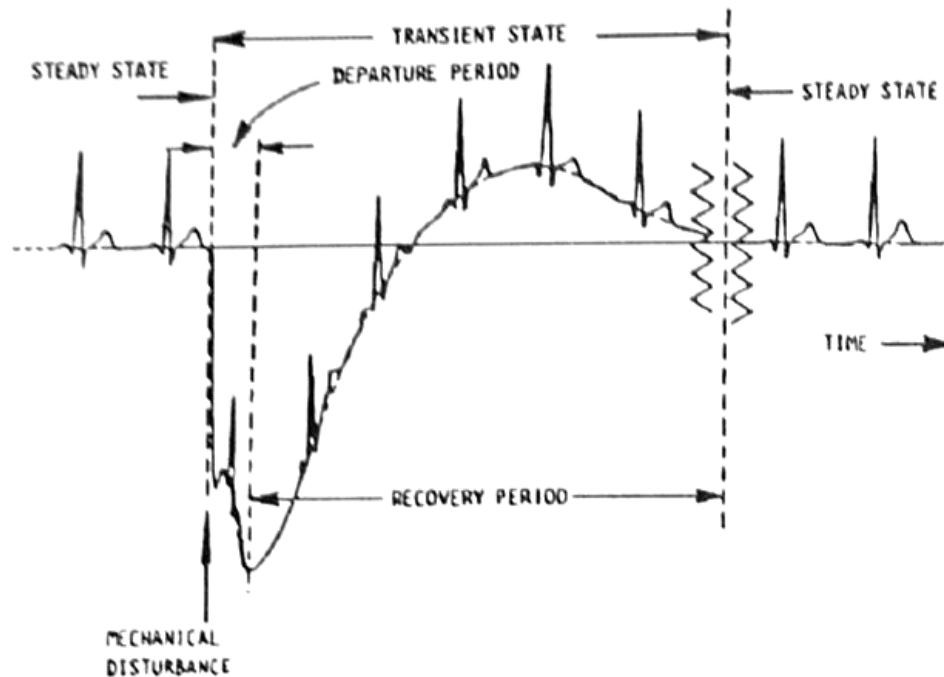
- Diagnostic information can be obtained by analysis of the amplitude and *relative timing* of the various segments.
- The simplest interval to measure is the R-R interval (from which the heart rate is derived).
- Two types of heart rate meters:
  - Averaging heart rate meter
  - Beat-to-beat heart rate meter

# Heart Rate Meters

- Heart rate is usually given in beats per minute (BPM).
- The easiest way to obtain this is to count an identifying feature in the ECG which occurs once per heart beat.
- The most obvious such feature is the QRS complex which is a sharp spike.
- Both averaging and beat-to-beat devices need to perform this detection.

# QRS detection

- There are 4 main problems in detecting the QRS complex in ECG traces:
  - Artefacts due to electrode motion



# QRS detection

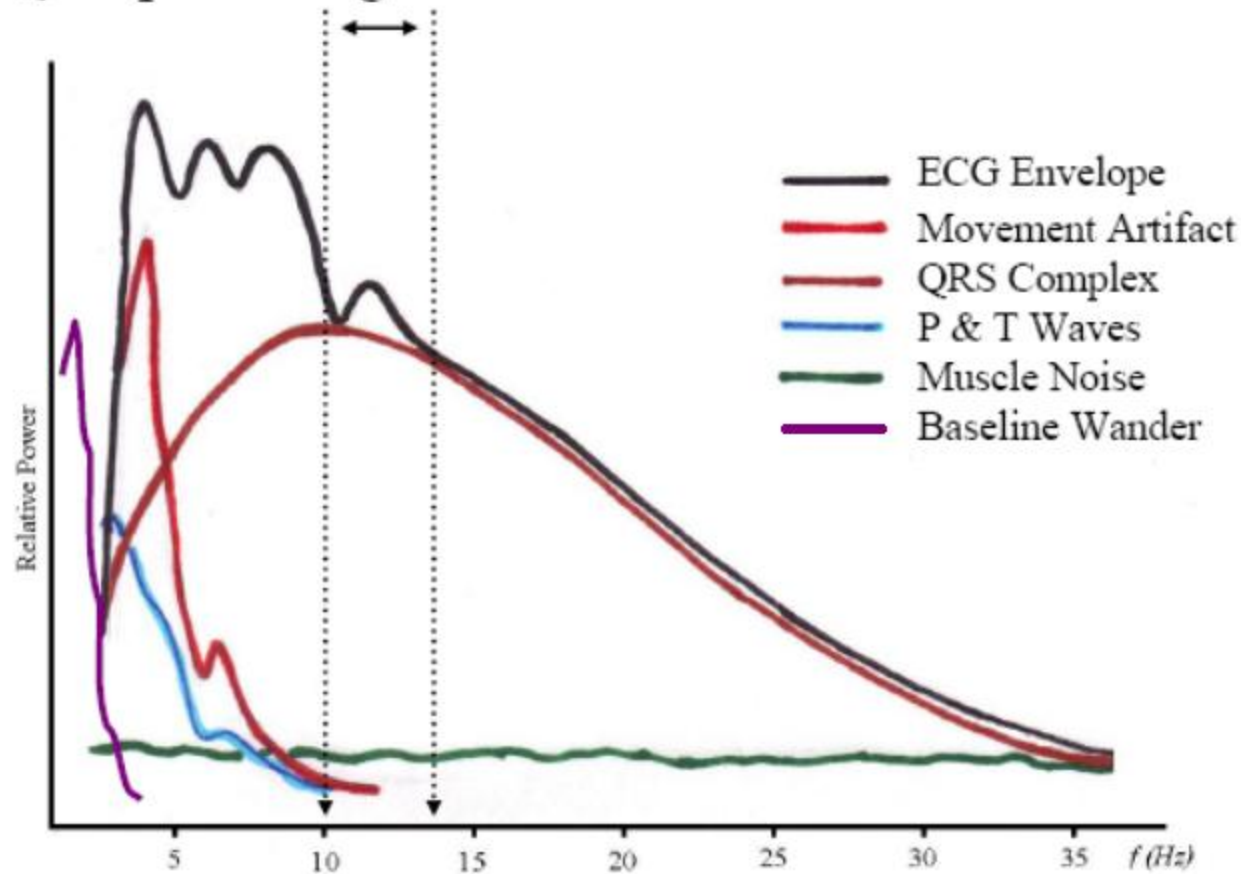
- There are 4 main problems in detecting the QRS complex in ECG traces:
  - Artefacts due to electrode motion
  - Baseline wander (mostly caused by breathing and torso movements)
  - Muscle artefact (broadband)
  - T-waves with high-amplitude content

# QRS detection

- The solution to these problems is to use a band-pass filter to remove:
  - Low-frequency changes such as baseline wander
  - High-frequency changes e.g. movement/muscle artefact
- Most of the frequencies in the QRS complex are around 5-20 Hz.
- A pass-band of 10 – 40 Hz is therefore appropriate....  
Why?

# ECG spectral properties

QRS power region

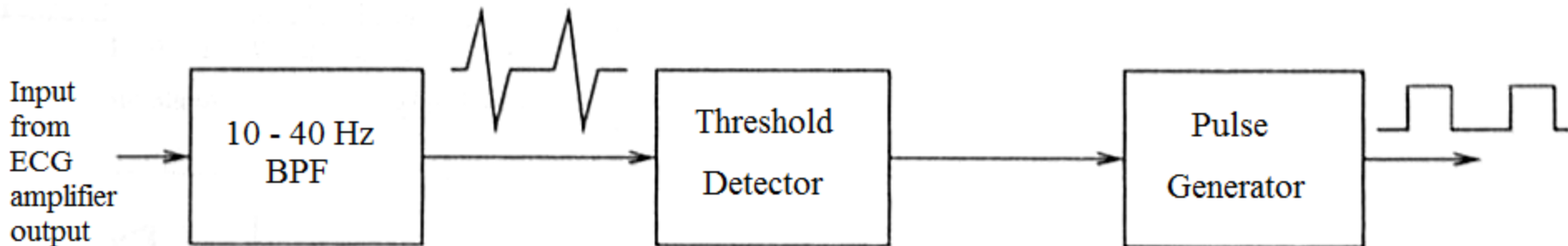


- Look at the signal below 10Hz .. Why do we want to remove it?



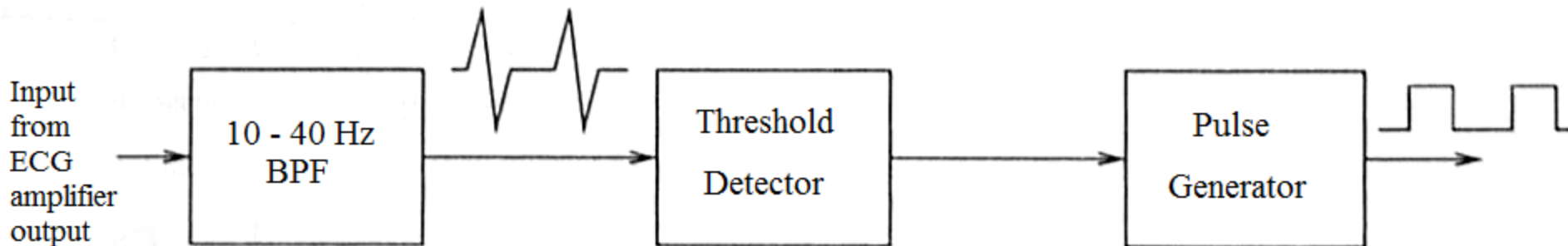
# QRS detection

- Once the “non-QRS” sections of the ECG have been attenuated, the QRS complex can be detected with a threshold detector.



# R-Wave pulse generator

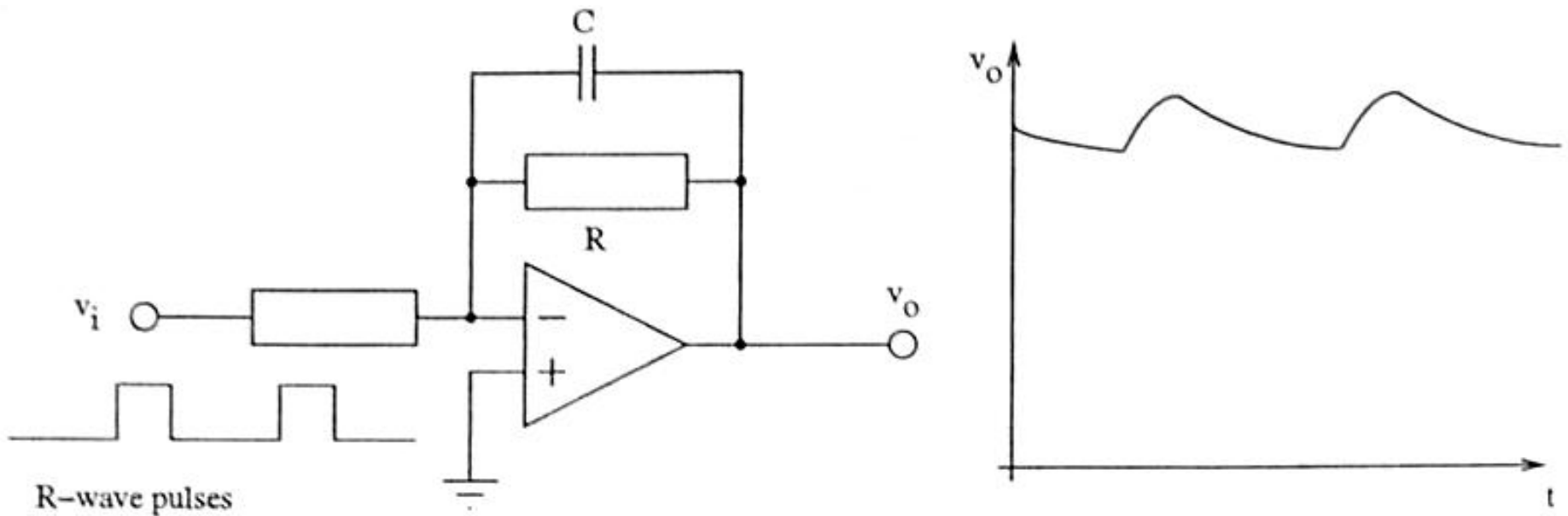
- This should trigger a pulse generator so that a short pulse of a fixed duration is generated once (and only once) for each QRS complex.



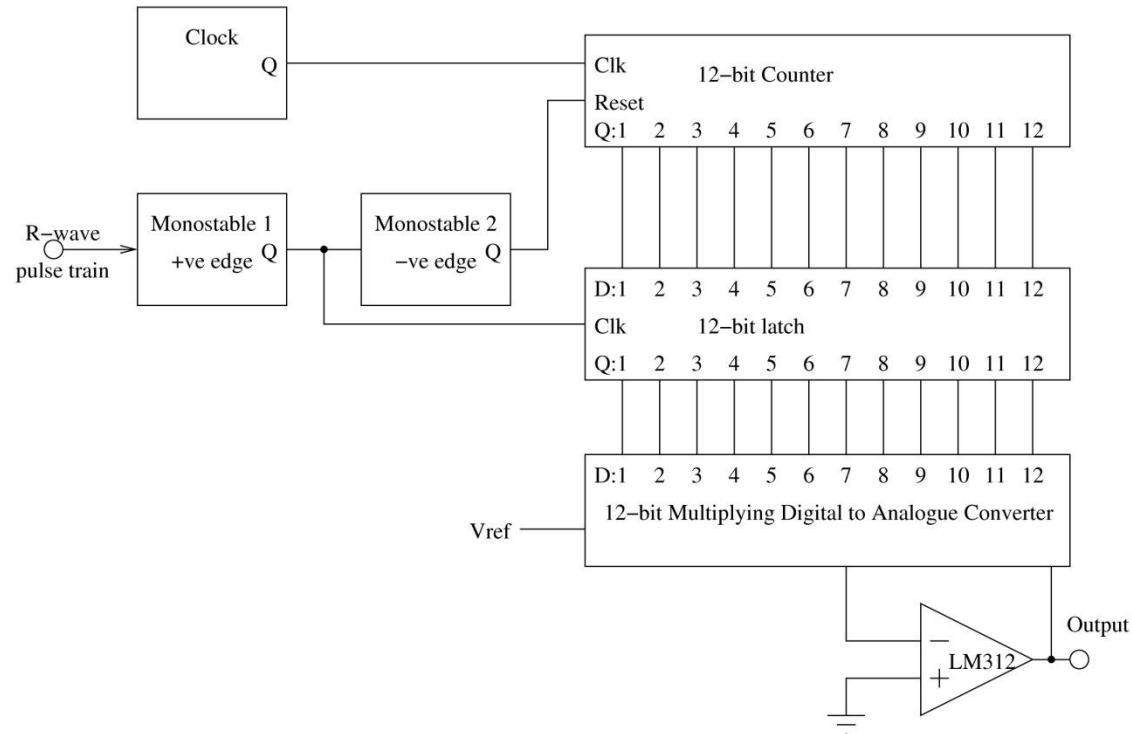
# Averaging heart rate meter

- The “average power” of the pulse train from the pulse generator circuit will be indicative of the Heart Rate.
- This can be determined using a “leaky integrator” (a form of low-pass filter).
- The time-constant of the R-C circuit should be several beats long to minimise output ripple.

# Averaging heart rate meter



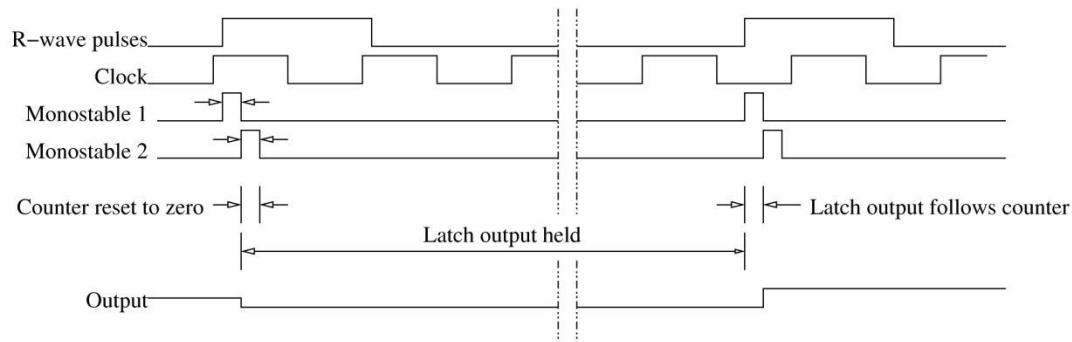
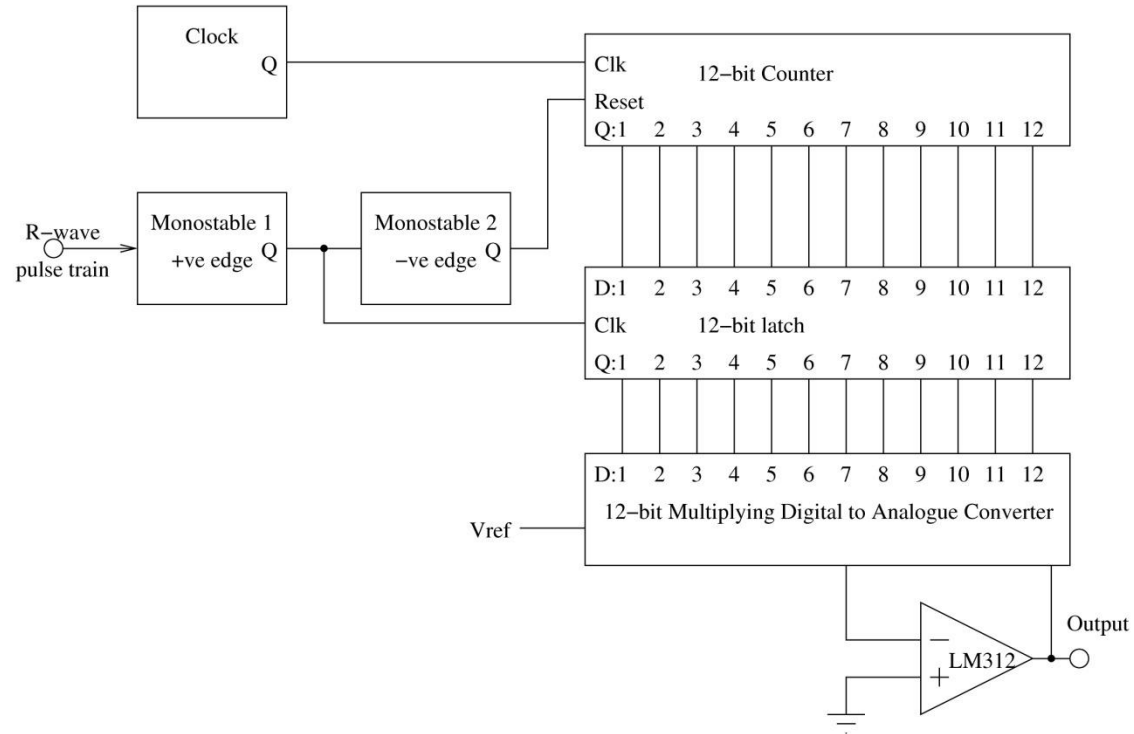
# Beat-to-beat heart rate meter



This is best achieved using a digital circuit which:

- Counts the time between consecutive QRS complexes
- Inverts this in order to obtain a heart rate (rather than interval)

# Beat-to-beat heart rate meter



# Heart rate variability

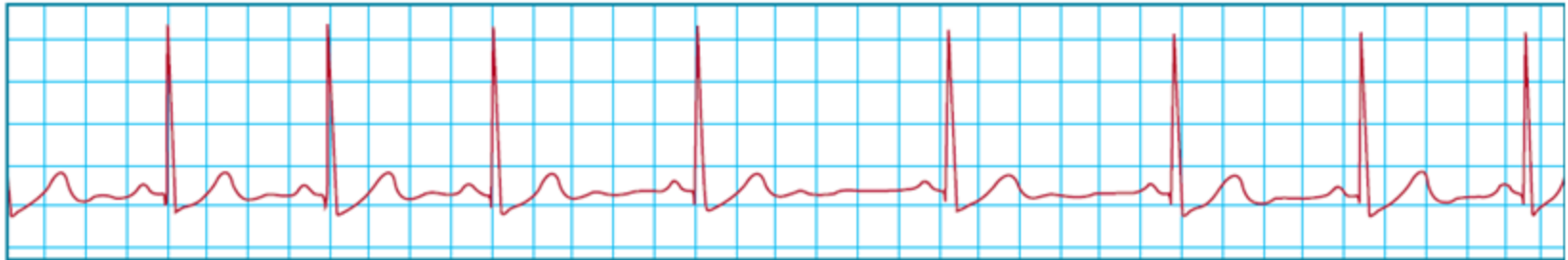


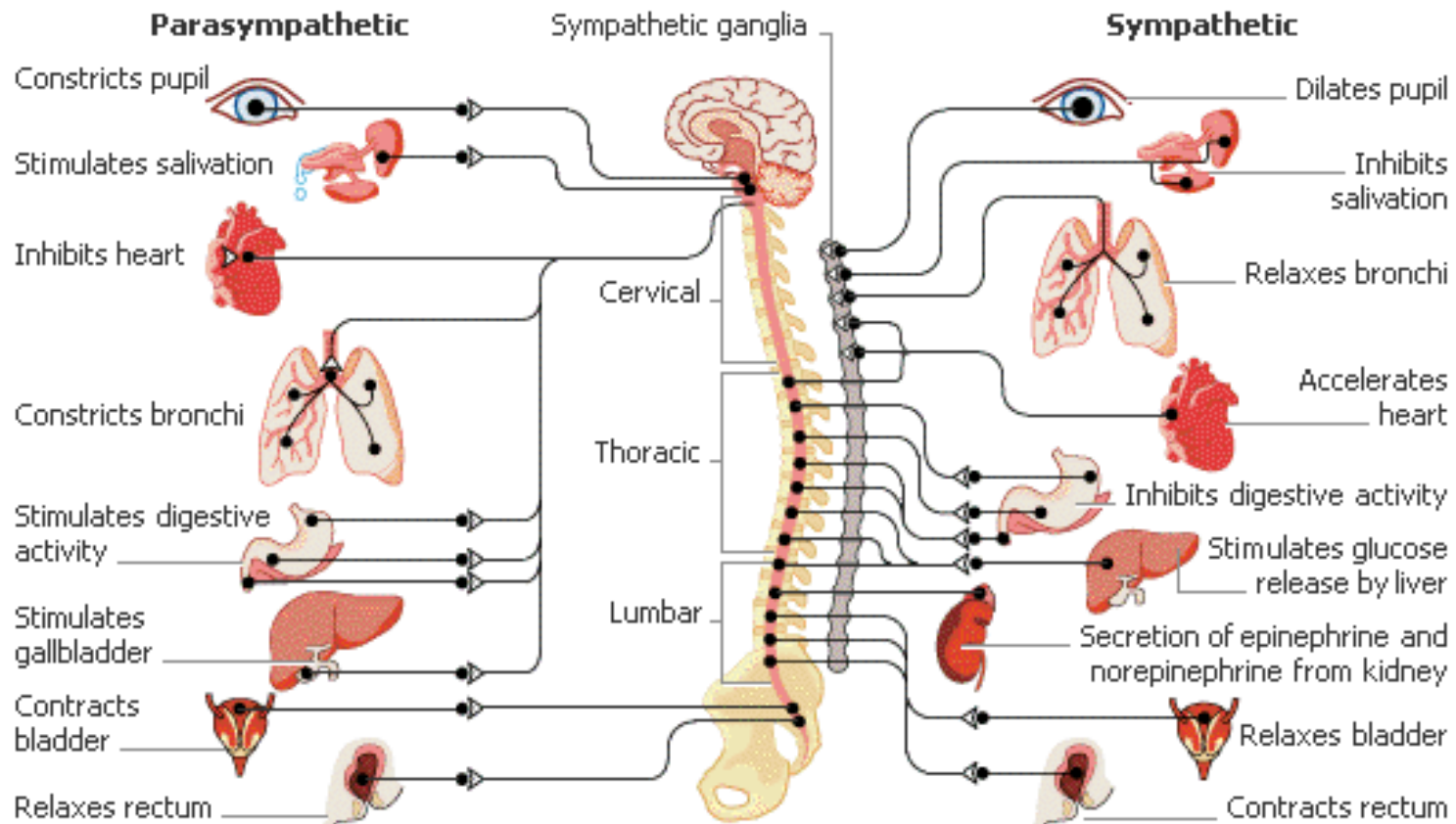
Figure by MIT OCW

- Under resting conditions, the heart rate of a healthy individual is *not* constant. (Notice compressions and rarefactions above)
- During expiration, the vagus nerve is stimulated, which slows down the heart rate (the right vagus innervates the sinoatrial node).
- During inspiration, the vagus nerve is not stimulated.
- This gives rise to a phenomenon known as respiratory sinus arrhythmia (RSA); cardio-acceleration during inspiration, cardio-deceleration during expiration.

# Autonomic Regulation

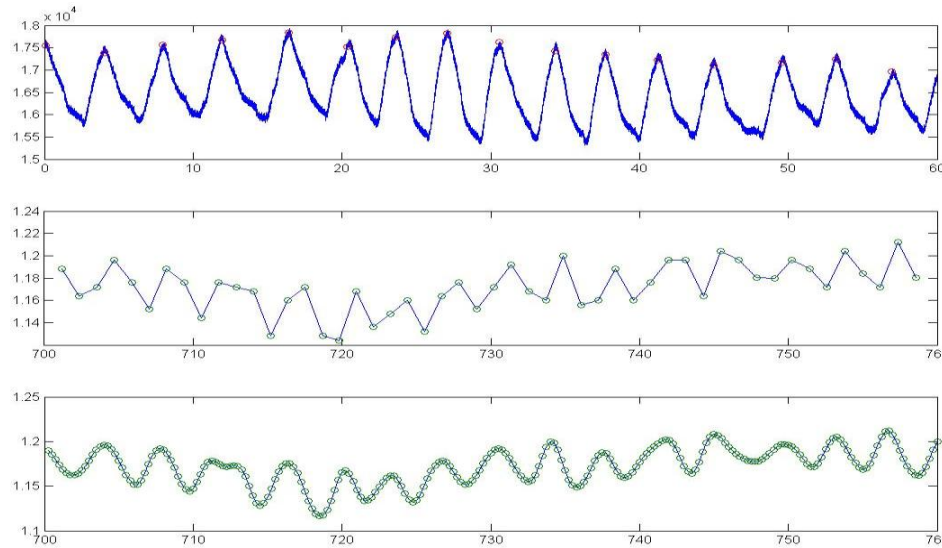
## *Rest & Digest*

## *Fight & Flight*



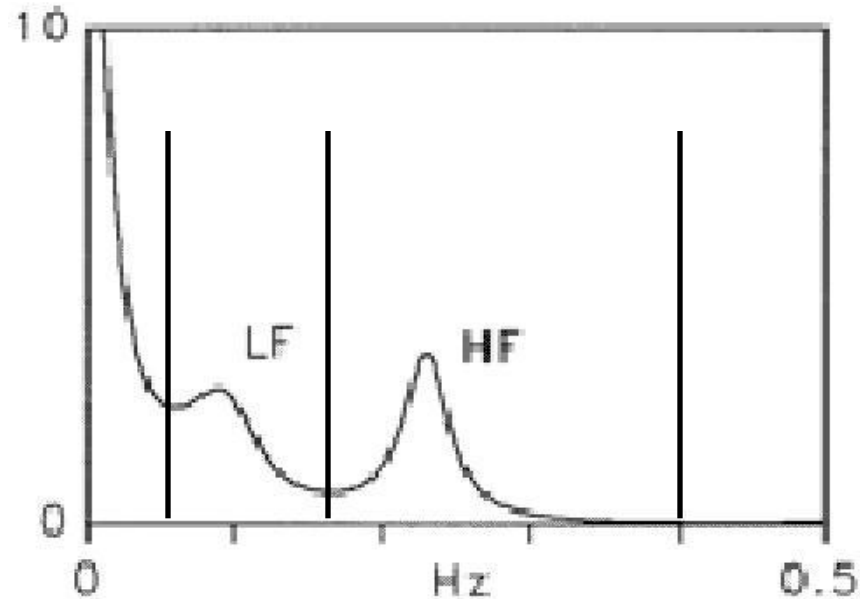


# Heart rate variability



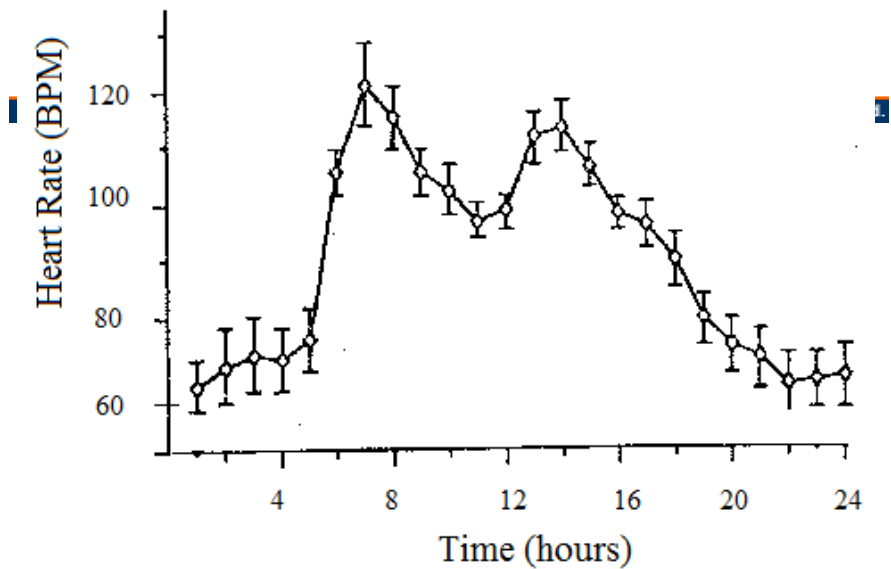
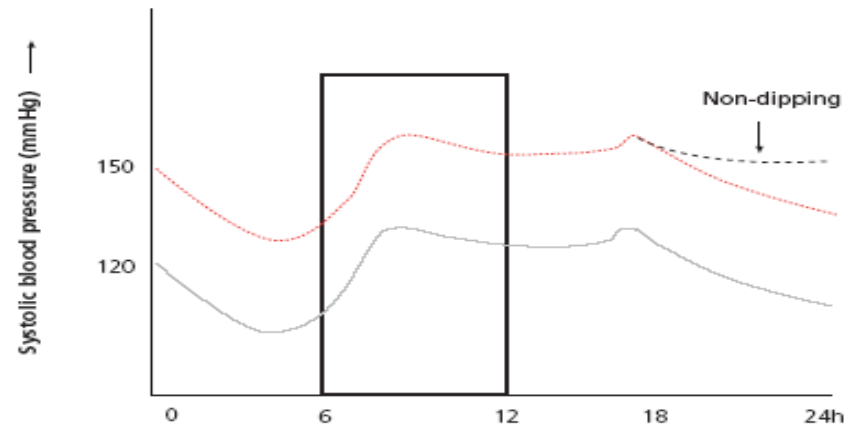
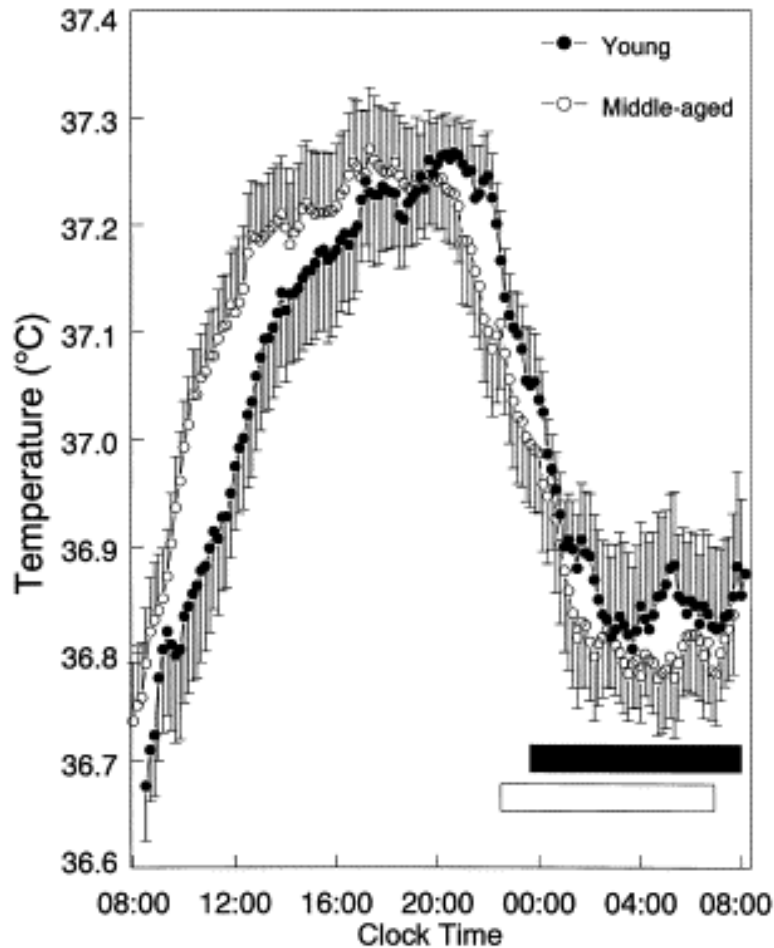
- Upper trace: respiration rate from electrical impedance plethysmography – see next lecture.
- Middle trace: beat-to-beat R-R interval.
- Lower trace: R-R interval series re-sampled at 4Hz and cubic spline fitted to time series (smoothing).

# The sympathovagal balance:



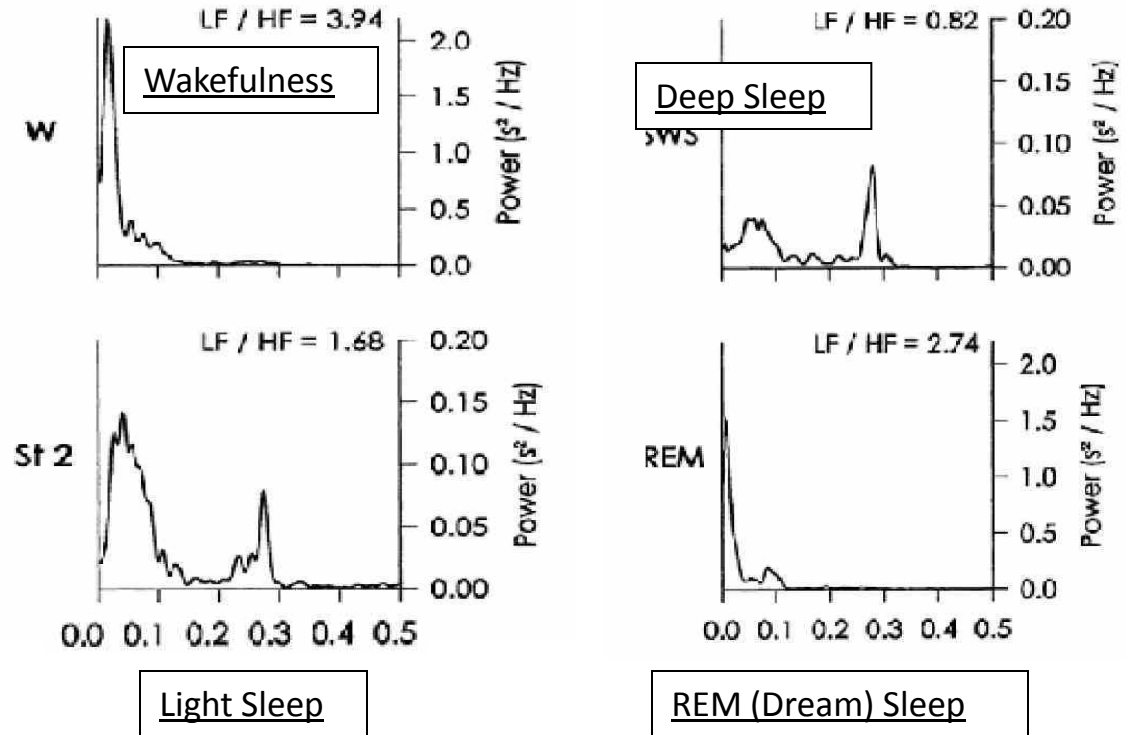
- Ratio of LF power to HF power in PSD of heart rate time series is thought to reflect sympathovagal balance

# The circadian rhythm



# HRV and sleep state

- HRV is also circadian
- Autonomic balance changes over 24 hours
- Significantly in different sleep cycles
- Also changes based on disease.

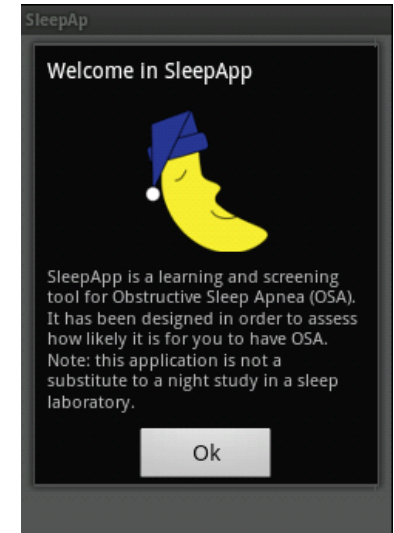
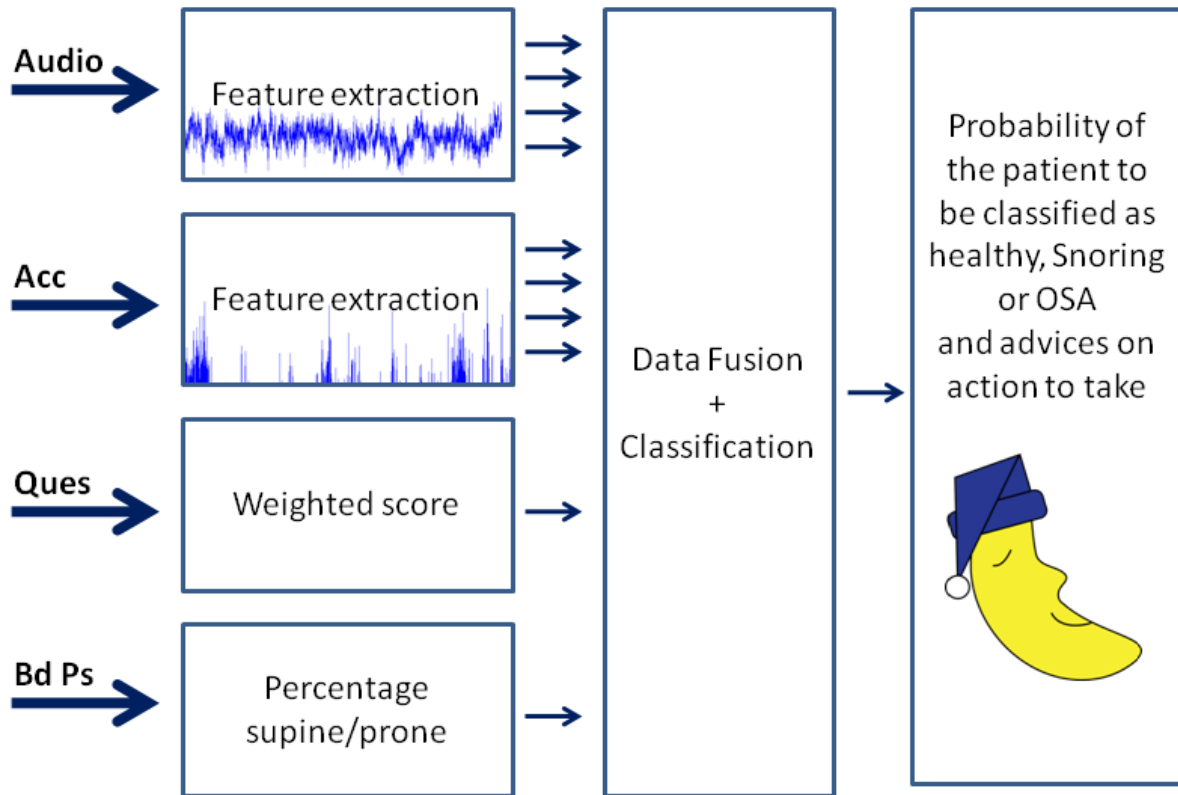


- HR & HRV are not specific enough to identify sleep stages
- So what is ...?

# Sleep Apnea Screening on a Mobile Phone



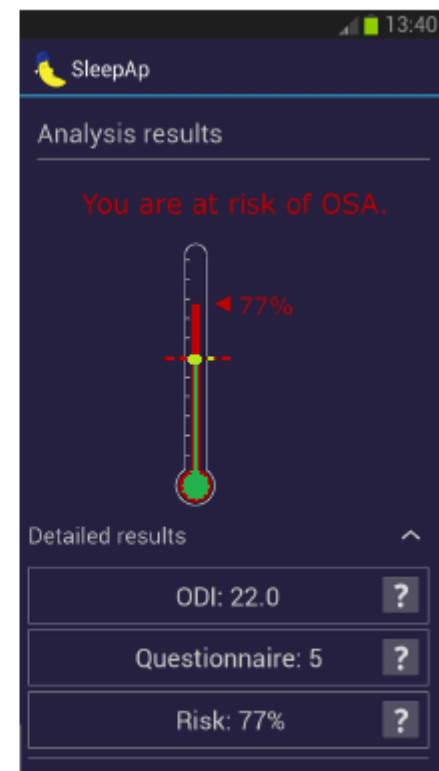
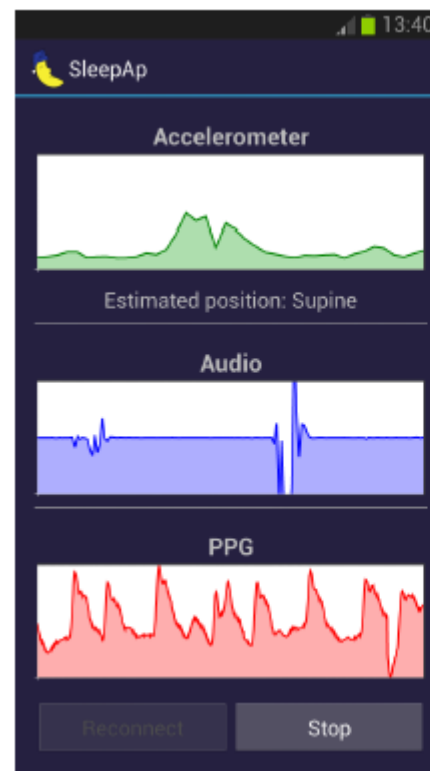
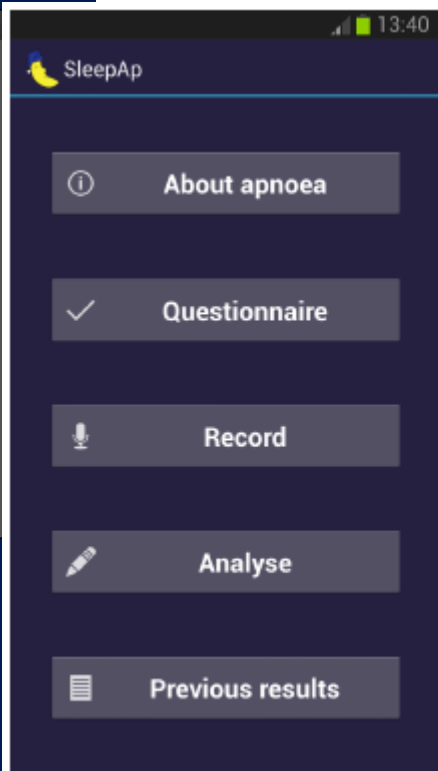
## Identify P(treatable sleep apnea requiring treatment)



Block diagram describing the phone application system. Acc: Acceleration, Ques: Questionnaire, Bd Ps: Body Position.

# SleepAp - Android application

- **92% Accuracy, 100% Specificity**



Screenshots SleepAp

# SleepAp - Android application

- **92% Accuracy, 100% Specificity**

Table 1. EXP-1, SVM classification on clinical data: {Normal, Snorer} vs {Mild, Moderate and Severe OSA}

	Training set (735)			Test set (121)		
	Ac	Se	Sp	Ac	Se	Sp
ODI	84.4	80.1	88.6	85.1	80.5	93.2
AU	76.6	69.5	83.7	74.4	70.1	81.8
AC	63.1	60.5	65.8	72.7	74.0	70.5
DE	65.6	64.6	66.6	67.8	63.6	75.0
AU+AC	74.6	65.9	83.2	76.9	66.2	95.5
AU+AC+ODI	85.6	81.5	89.7	<u>88.4</u>	81.8	100

ODI: oxygen desaturation index, AU: audio, AC: actigraphy,  
 DE: demographic, Ac: accuracy, Se: sensitivity, Sp: specificity.

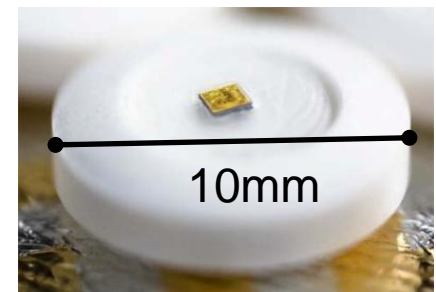
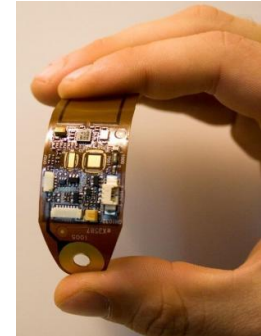
Table 2. EXP-2, SVM classification on clinical data: {Normal, Snorer} vs {Moderate and Severe OSA}

	Training set (646)			Test set (104)		
	Ac	Se	Sp	Ac	Se	Sp
ODI	90.9	87.8	93.2	90.4	83.3	100.0
AU	81.7	68.0	92.1	77.9	66.7	93.2
AC	68.0	44.6	85.6	72.1	53.3	97.7
DE	70.7	63.7	76.1	73.1	61.7	88.6
AU+AC	81.3	71.9	88.3	79.8	70.0	93.2
AU+AC+ODI	91.3	88.1	93.8	<u>92.3</u>	86.7	100.0

# Mental Health Monitoring

**WHO: Depression is predicted to be the single largest burden of health GLOBALLY by 2030**

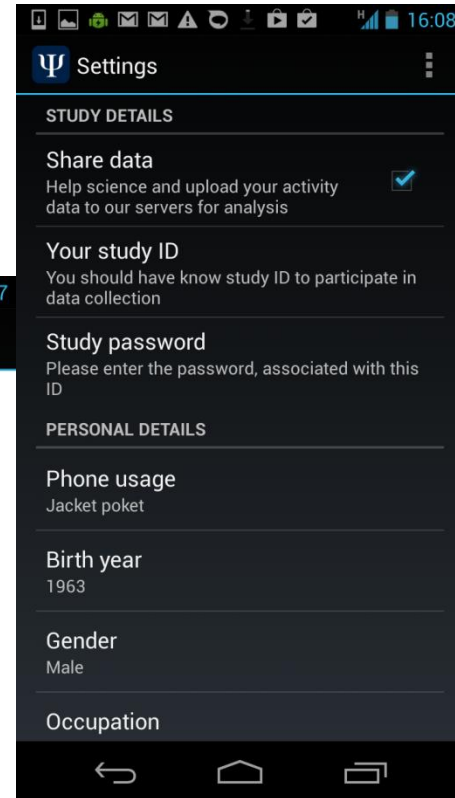
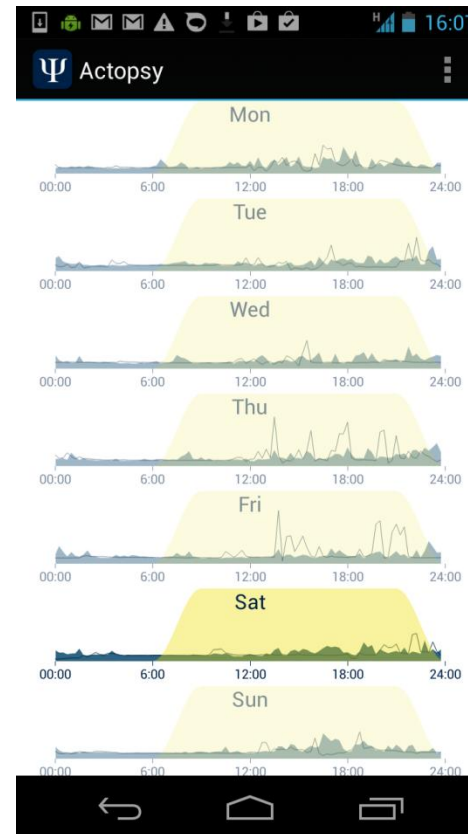
- Monitor Circadian Rhythms: Sleep and activity change with depression and schizophrenia
- Use ECG patches and actigraphy meters –
  - 90% accuracy in differentiating schizophrenics from normal controls
  - Adding physiology increases this to 95%
- Monitor social interaction complexity changes & response times
- Compliance is a key issue –
  - Use chip-on-a-pill





# Mental Health App

- Tracks physical activity every day
- User or doctor can compare to normal behavior
- Monitor social interaction complexity changes & response times to social cues
- Links to smart watches



# Jet Lag App

- Optimizes behavior based on time zone changes, recommending:
  - Avoid light, seek light or sleep

The image displays four sequential screenshots of the JetLag app interface, illustrating how the app's recommendation changes based on user input and time zone settings. Each screenshot shows the departure and arrival details, flight duration, and a circular light exposure chart.

**Screenshot 1 (Leftmost):** Shows the departure screen for 25-08-2013 from Hartsfield Jacks (EDT) to Heathrow (LHR) (GMT+01:00). The flight duration is -1:00 hours and the time zone difference is +5.0 hours. The status is **Sleep**.

**Screenshot 2:** Shows the same flight details but with the option "Use time below instead of system time" unchecked. The status is **Avoid light**.

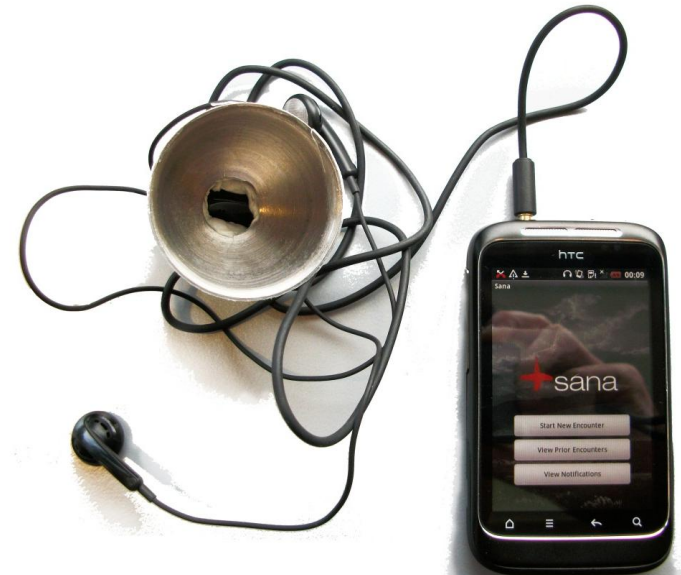
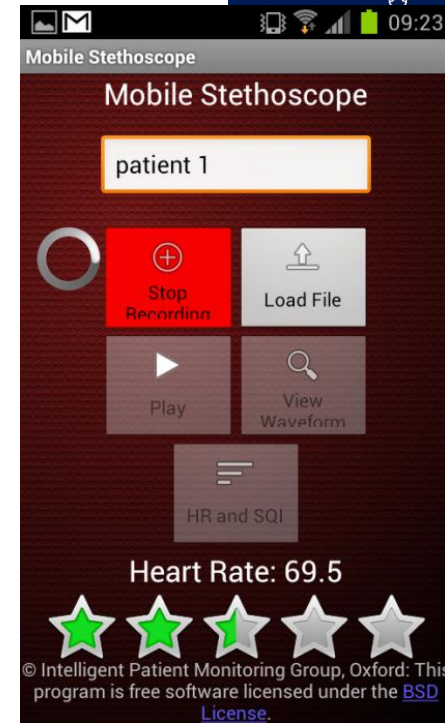
**Screenshot 3:** Shows the same flight details but with the option "Use time below instead of system time" checked. The status is **Seek light**.

**Screenshot 4 (Rightmost):** Shows the same flight details but with the option "Use time below instead of system time" checked and the local time set to 16:39. The status is **Seek light**.

The circular charts in each screenshot represent light exposure recommendations over a 24-hour period. The chart is divided into segments representing different light levels: dark (black), low (grey), medium (white), high (red), and very high (yellow). A green line indicates the recommended light exposure level for the user's current location and time.

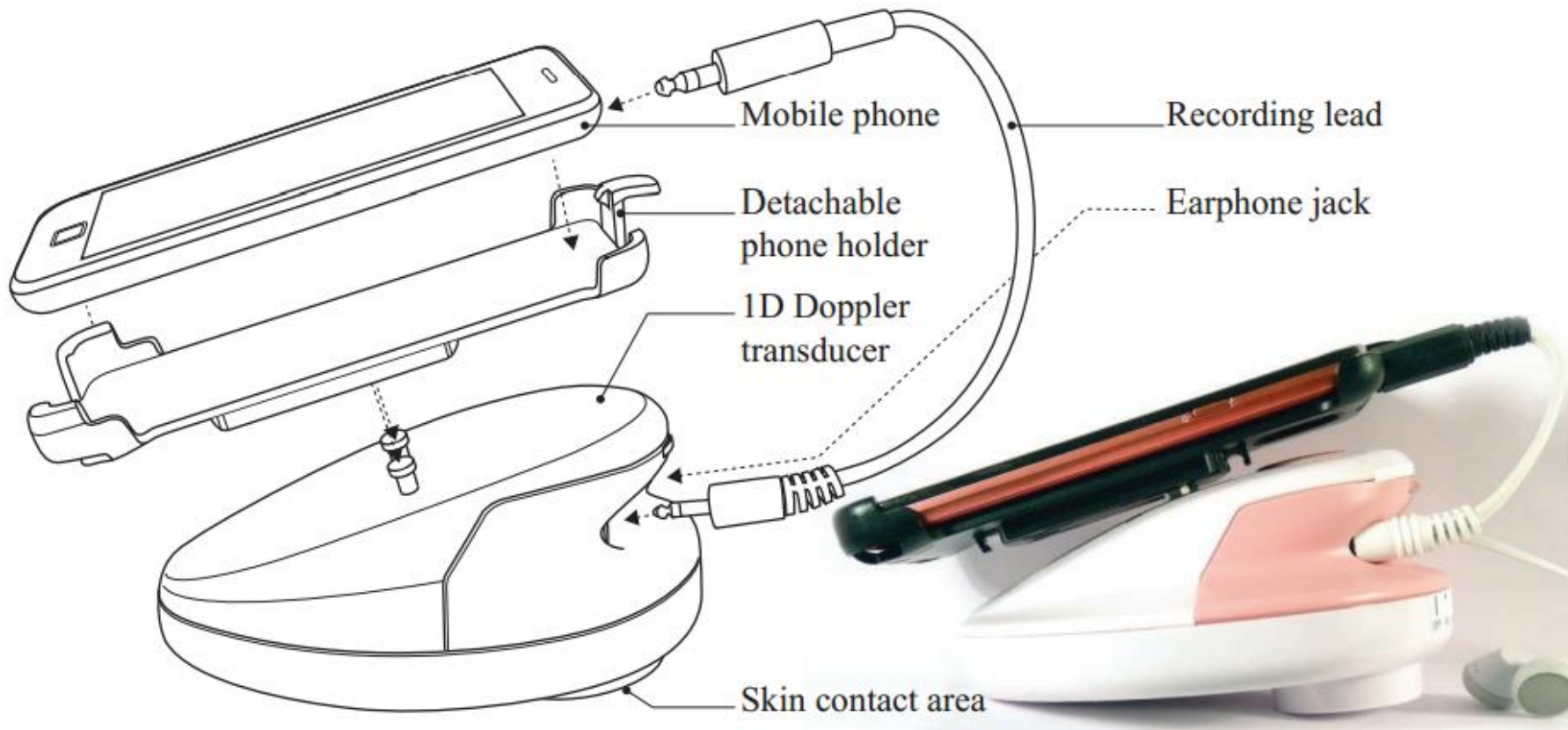
# A Mobile Stethoscope for Remote Cardiac Monitoring

- Handsfree kit + eggcup = digital stethoscope
- Phone app checks quality of recording and analyses rhythm
- Uploads recording and diagnosis to back-end database
- Clinical trial on rheumatic heart disease in South Africa underway



# Perinatal Screening System

- \$20 1D ultrasound probe – output through 2 audio jacks
- Android smartphone processes audio, user listens simultaneously
- Phone assesses fetal wellbeing and explains to you how to use device & check quality of data



# Perinatal Screening System

Development into a complete fetal monitoring system



# BabeeMon

a Neonatal Monitoring System

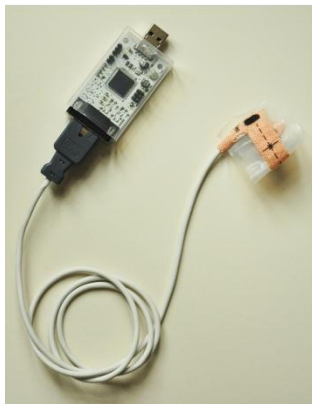


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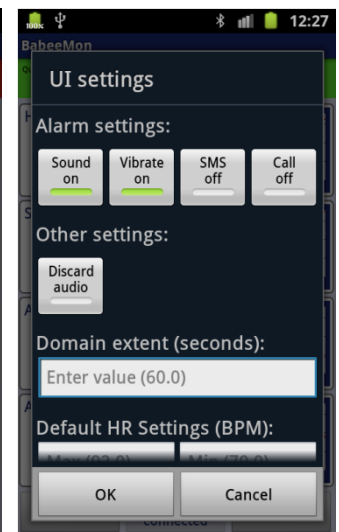
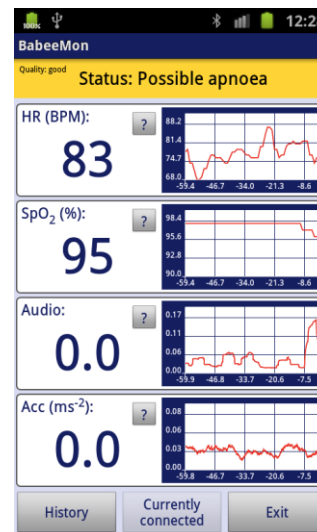
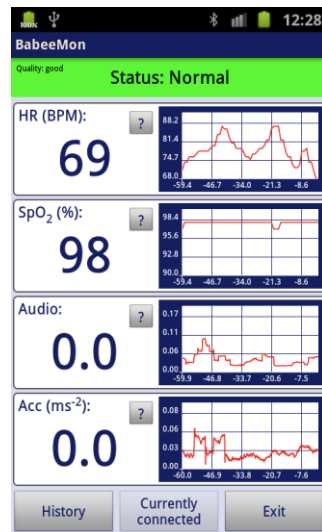


Pulse oximetry +  
Accelerometry +  
video and sound

intelligent signal processing  
to generate smart alarms



Cost <\$22





breathing monitors



audio/video monitors  
and monitoring apps



NICU incubators



available neonatal  
pulse oximeters > \$50



**scientifically validated**  
**reduced false alarms**  
**affordable**  
**home monitoring**  
**hospital monitoring**  
**early discharge from hospital**



# CVD Risk Prediction

- Data inputted inc. blood glucose and acquired BP
- Logistic Regression model predicts  $P(\text{CVD})$
- Probability converted to lifestyle change
- \$1m RCT underway in southern India to lower blood pressure

Risk Calculator

Blood Glucose measure:

4.6

Enter between 0.6 and 33.3 mmol/L

Blood Pressure measure:

Systolic BP: 167

(in mmHg) between 50 and 200

Diastolic BP: 103 HR: 62

(in mmHg) between 20 and 150

Blood Cholesterol Measure:

TC and HDL known

Presence of ECG-LVH:

No

Ethnic Group:

Other

危险度计算器

血糖测量

4.6

输入(介于0.6 - 33.3 mmol/L)

血压测量

收缩压 167

舒张压 103 心率 62

介于 50 - 200 (mmHg)

介于 20 - 150 (mmHg)

血脂测量

已知总胆固醇和高密度脂蛋白数据

有心电图左心室肥大症状

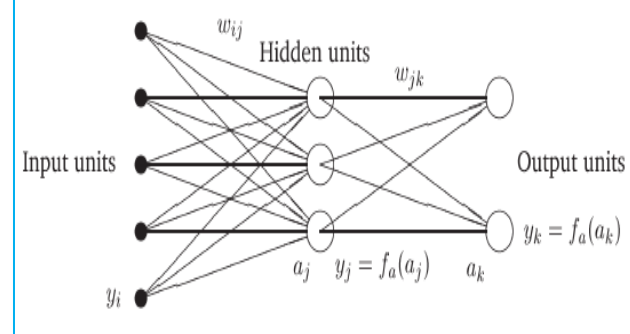
否

民族

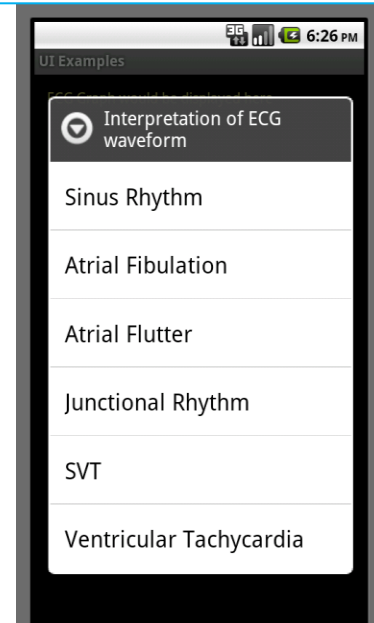
其他



# ECG Screening App

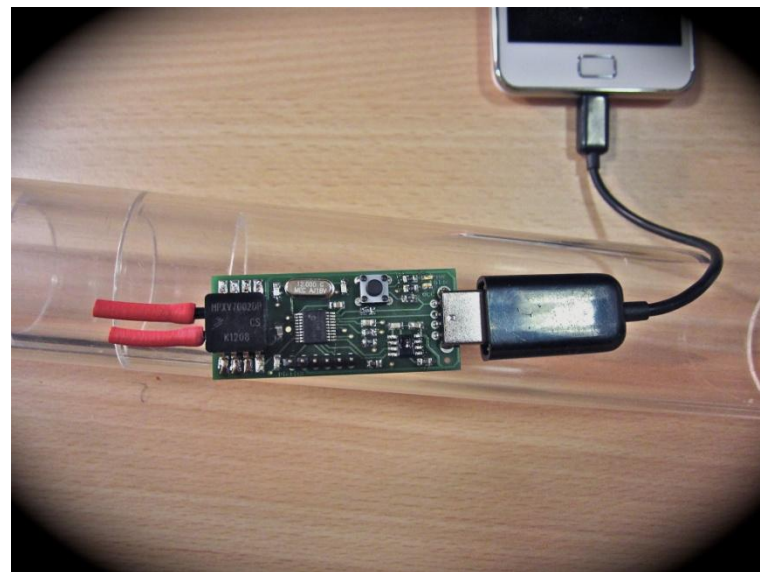


- Automatically classifies ECG rhythm (AF) and signal quality
- Neural net trained & tested on 1500 ECGs
- Accuracy: 99% train/test (highest accuracy in PhysioNet/CinC International Competition 2011)
- User can add diagnoses or opinions
- Data is uploaded to central database and diagnoses aggregated

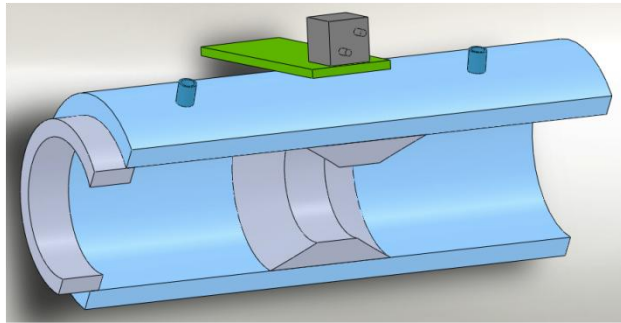
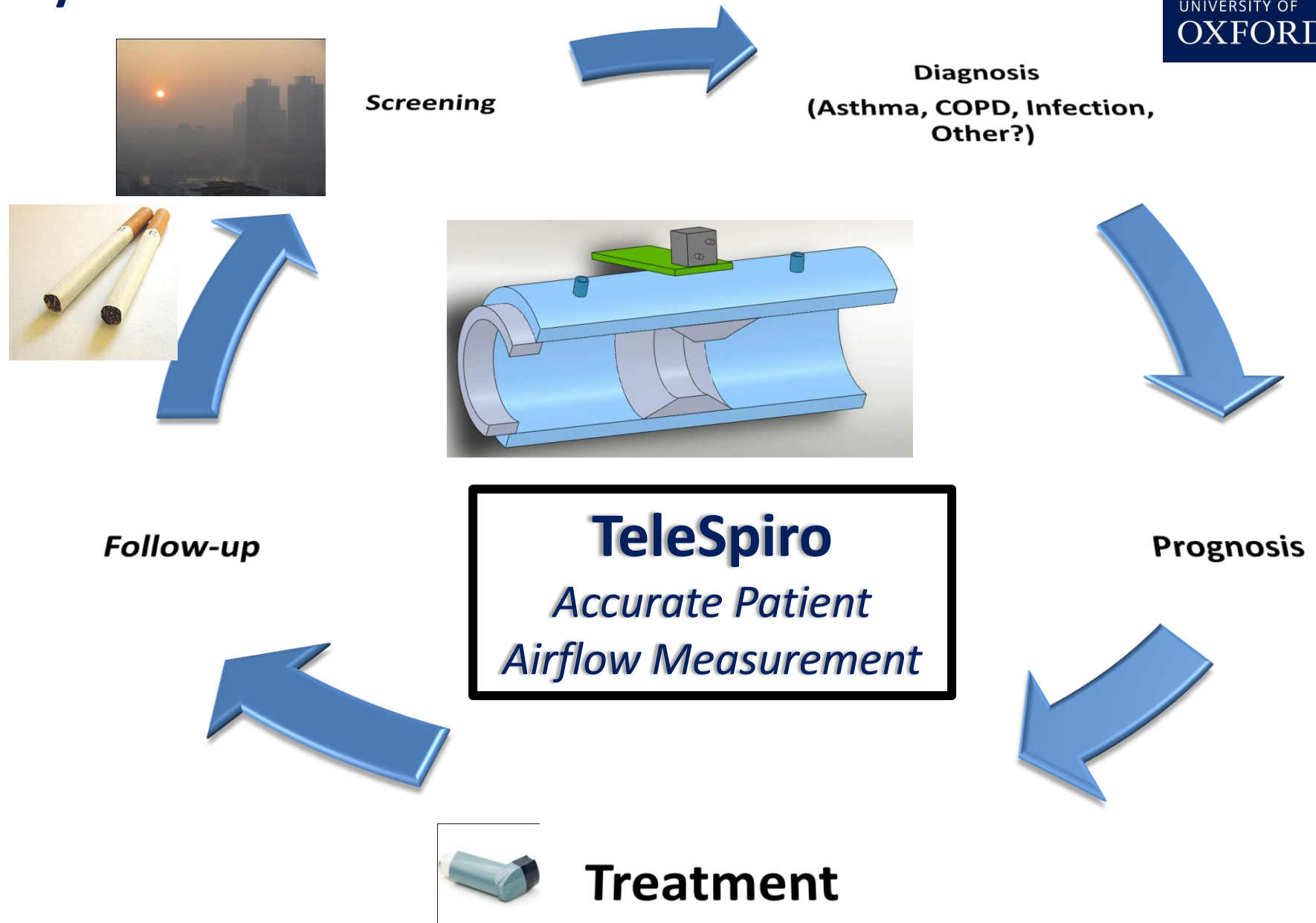


# TeleSpiro

## Helping the world breathe better



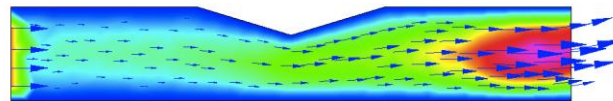
# System overview



# TeleSpiro: Smarter Mobile Health

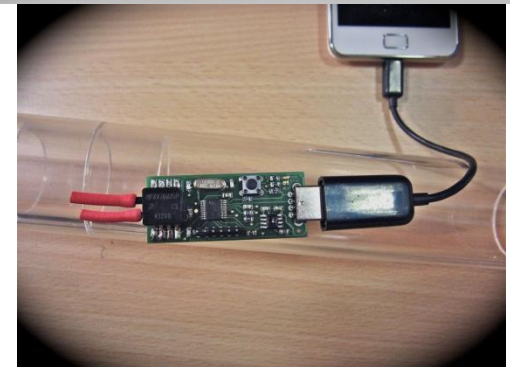
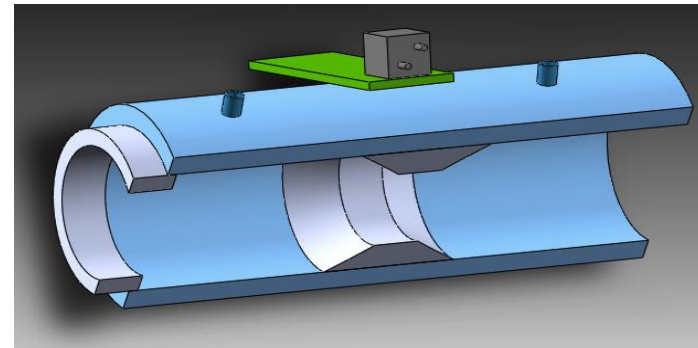
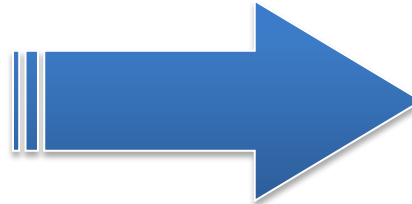
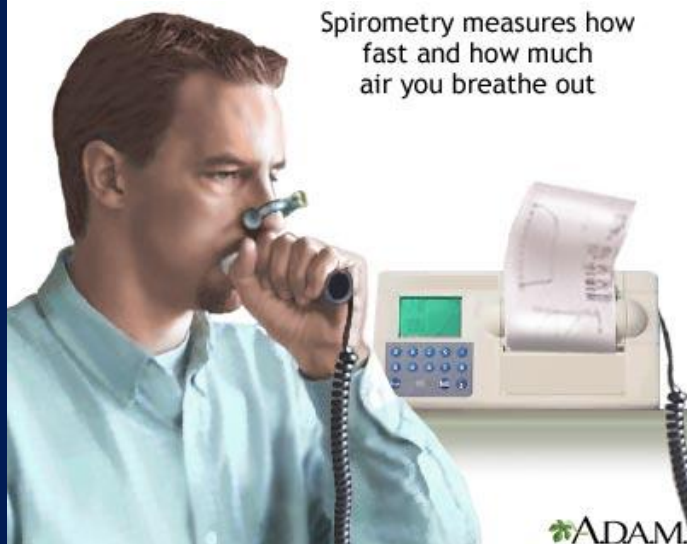


- Novel Design
- Low Cost
- Portable
- No batteries, no charging
- Real time patient feedback
- Portable
- Calibrated
- Interoperable



# TeleSpiro

- **Chronic Lung Disease: 4<sup>th</sup> in Mortality Globally**
  - **ASTHMA, COPD & OBSTRUCTIVE LUNG DISEASES**
- **No objective data to manage patients**



# Electronic Medical Records

- Lack of longitudinal and accurate data one of the biggest issues
- Medical errors account for \$billions every year



## Sanamobile.org:

- End to end EMR and telemedicine system
- Winner of mHealth Alliance Award 2009 & Vodafone Wireless Innovation Prize (\$150k)
- Currently adding drug-drug module
- Also adding a crowd sourcing annotation component

***Won Vodafone Americas foundation mhealth Alliance award and Vodafone wireless innovation prize 2010***



# Drug-Drug Interactions



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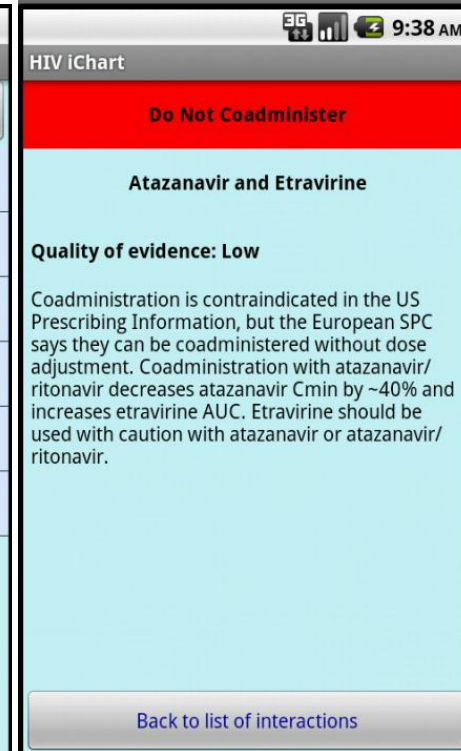
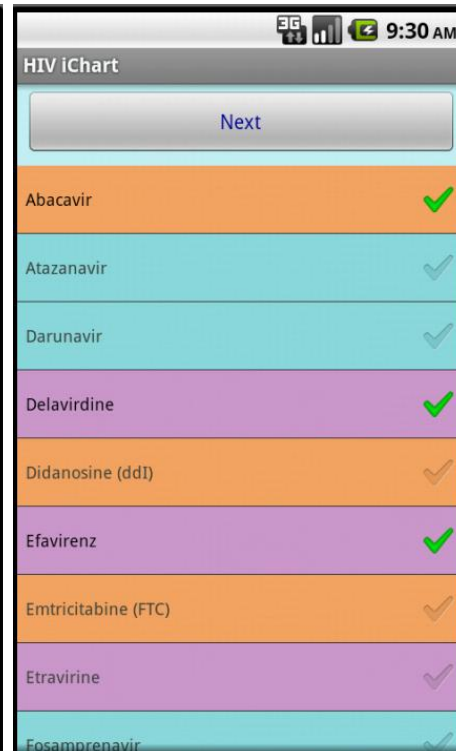
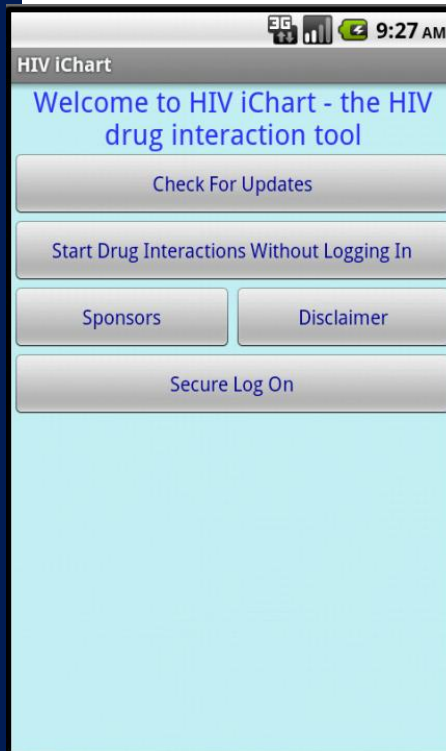


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sanamobile.org



- Collaboration with University of Liverpool Institute of Translational Medicine
- Android App to look up HIV Drug-Drug Interactions
- Integrated with EMRs like OpenMRS



# Sw4d – Smart Water for Development

❖ One-in-three handpumps in Africa are non-functioning at any given moment:

- When breakdowns occur fault can take weeks to be reported
- Systems of maintenance are variable and generally inefficient
- Lack of safe drinking water has huge health and socio-economic impacts
- Effect can be long-term and irreversible in the case of children



❖ Automated monitoring of handpumps by SMS:

- Repairs to be undertaken faster as faults are reported immediately
- Improved information can increase maintenance regime efficiently
- Objective data allows for monitoring and regulatory oversight by governments and donors
- Increased usage data allows for better targeted future investment



# Prizes / press

Noninvasive Fetal Monitoring,- 1<sup>st</sup> Place,  
**PhysioNet/Computing in Cardiology Prize**,  
Sept 2013

Blood Pressure Monitoring Device –Technology  
Leveraging Award, **Dell Social Innovation  
Competition**, June 2012

COPD/Asthma Screening Device – 2<sup>nd</sup> Place, **IBM-  
Novartis NCD University Challenge**, Jan 2012

Mobile ECG Screening System – 2<sup>nd</sup> Place,  
**PhysioNet/Computing in Cardiology Prize**, Sept  
2011

Blood Pressure Monitoring Device – 1<sup>st</sup> Prize,  
**International Engineering World Health  
Competition**, Aug 2011

Mobile Health Challenge winner; ‘best R&D  
project’ (mStethoscope), **Mobile Health  
Industry Summit**, London, 2010

AF Detection system: Premio di laurea  
"Gruppo Nazionale di Bioingegneria  
(Top 5 MSc )in Italy 2013)

Telespiro: 1<sup>st</sup> prize paper at IEEE Point  
of Care Healthcare Technology  
Conference , Jan 2013

Mortality prediction, 1<sup>st</sup> Place,  
**PhysioNet/Computing in Cardiology  
Prize**, Sept 2012

Neonatal Apnea Monitor – 2<sup>nd</sup> Place,  
**GSMA Mobile Health University  
Challenge**, May 2012

Smart Water Project – **BBC Highlight**,  
June 2012

Diabetic Wristband Device – 2<sup>nd</sup> Place, **IBM-  
Novartis NCD University Challenge**, Jan  
2012

Mobile Heart Monitor – **MSc in Biomedical  
Engineering Thesis Prize**, 2011



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# Thanks to our partners & funders:



- Univ. of Oxford, JFF, EPSRC, Wellcome Trust, NIH,
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- George Institute for Global Health
  - (Oxford, India, China & Australia)
- Australian National Health & Medical Research Council
  - Global Alliance for Chronic Disease
- Depts of:
  - Cardiology, Public Health, Primary Care, Ophthalmology, Psychiatry, Clinical Trials Unit
  - Cardiology, Univ. of Cape Town



Australian Government  
National Health and Medical Research Council



[www.ibme.ox.ac.uk/ipm](http://www.ibme.ox.ac.uk/ipm), [www.oxcaht.org](http://www.oxcaht.org)

