

S2014, BME 101L: Applied Circuits Lab 10

Electrocardiogram (EKG)

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1 Design Goal

For this lab you will design and solder a one-channel electrocardiogram circuit.

This is not a medical-grade EKG, as it does not include electrical isolation, electrostatic protection for the electronics, or calibration signals. It is also only a single channel, not the 12 channels of a standard EKG.

All electrode leads should be connected through resistors to make sure that any current from the EKG to the body stays under $50\mu\text{A}$ (the limit according to the ANSI/AAMI ES1-1993 standard, as reported by Company-Bosch and Hartmann [3]), even if the wires are accidentally connected to the highest voltages in the EKG circuitry.

2 Background

An EKG measures small differential voltages using electrodes on the patient's skin to view the electrical behavior of the heart muscles. For EKG purposes, the heart is modeled as an electrical dipole that changes its orientation and magnitude as waves of depolarization pass through the muscles of the heart.

The EKG Wikipedia page has a pretty good explanation of the basics of the EKG signal [9]. The explanation by Ashley and Niebauer may be clearer and more informative. [1] If you want a more medically oriented presentation that is in a cartoon-like format, try Ken Grauer's *A 1st Book on ECGs—2014* [5]

We will be looking at lead I (left arm minus right arm, often abbreviated LA–RA) or lead II (left leg minus right arm, LL–RA) which have the classic EKG signal shown in Figure 1. The vertical spike of the large R part of the wave is typically around 0.5mV – 1mV , depending mainly on the quality of the electrode-skin contact. See Ashley and Niebauer's explanation of what physiological events the parts of the the ECG correspond to [1].

The single-channel EKG usually uses 3 electrodes: the pair of electrodes that carry the differential signal and an extra body electrode that provides a reference voltage to keep the differential pair between the power rails of the instrumentation amp. For our purposes, it suffices to generate a V_{ref} voltage with a unity-gain buffer, as we've done for other amplifiers, for the body electrode.

You won't be connecting the electrodes to your wrists and ankles, as that requires keeping your arms and legs relaxed to avoid picking up electromyogram (EMG) signals from your skeletal muscles, which can be difficult to do when you are adjusting the circuit, turning recording on or off, or typing up results. Instead, we'll use the electrode locations commonly used for emergency EKGs: in the hollows just below the collar bones and avoiding the pectoral muscles and sockets for the shoulder joints, and on the abdomen just above and inside the left iliac crest (the bone at the top of the pelvis). You can then choose two of the electrodes as the signal electrodes (for leads I, II, or III = LL–LA) and use the third one as a body electrode, see Figure 3. With this placement of the electrodes, only the pectoral muscles are likely to provide interference with the EKG signal, and they are easier to keep relaxed when you are sitting.

Cardiac monitors are required to have a passband of 0.5Hz to 50Hz [2], and professional EKGs usually go down to lower frequencies (0.05Hz to 100Hz) [3]. We don't want to DC-couple the whole amplifier, as the $\pm 1\text{mV}$ signal we're interested in is often accompanied by a $\pm 300\text{mV}$ DC offset, due to different half-cell

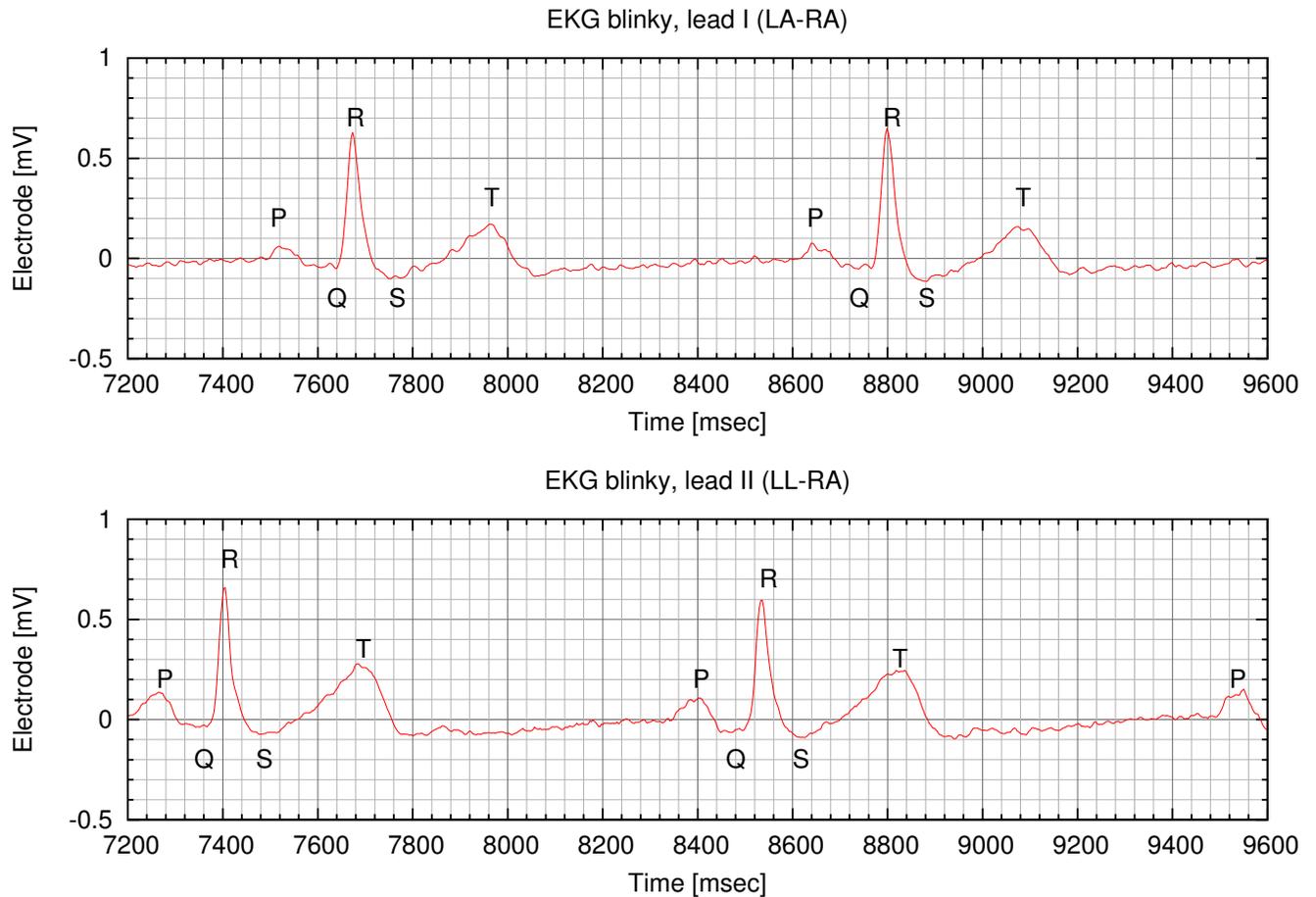


Figure 1: An EKG trace of Kevin Karplus’s heartbeat. Despite the same time scales, these traces were recorded at different times, and correspond to different heartbeats.

The 200ms by 0.5mV grid is standard for EKG traces and is usually printed as a 5mm by 5mm square. In fact, many of the guides for interpreting EKGs refer to the voltage and time both in “cm”, assuming that doctors and nurses can’t deal with mV and msec. The standard scaling is 1mV/cm and 400ms/cm, which is probably not the scaling here. Note that the period in the both traces is about 1125msec for a pulse rate of 0.89Hz or 53.3 beats/minute. The gnuplot commands to create a grid like that seen here are given in Figure 2.

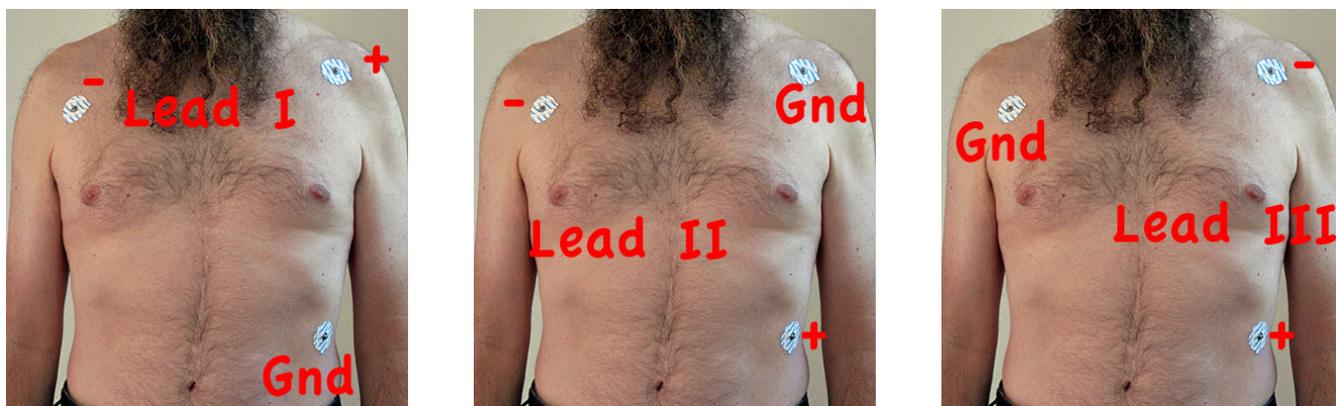
```

set xtics 200
set mxtics 5
set ytics 0.5
set mytics 5
set style line 1 linetype 1 linecolor rgb 'grey40' lw 1
set style line 2 linetype 1 linecolor rgb 'grey70' lw 0.5
set grid xtics ytics mxtics mytics ls 1, ls 2

set size 1,0.5

```

Figure 2: These are the gnuplot commands used to set up the grid and change the shape of the plots for Figure 1. Note that the size command does not guarantee that the grid will come out square—you’ll have to tweak the size or the xrange and yrange to make the grid square.



(a) Lead I is LA-RA.

(b) Lead II is LL-RA.

(c) Lead III is LL-LA.

Figure 3: This figure shows the approximate electrode placement for the three electrodes. The left-arm and right-arm electrodes should really be at the same height—the right-arm electrode looks a little low in these pictures. The left-leg electrode is also too high, though that is not important if you are just recording Lead I.

potentials at the skin-electrode contact. The DC blocking is usually done after the first stage of amplification by the instrumentation amp, and the initial gain is limited to avoid saturating the instrumentation amplifier with the DC offset.

3 Pre-lab assignment

- Choose the size for your current-limiting resistors on the EKG electrode wires.
- Figure out what gain you need to achieve to record your EKG signal on the KL25Z with PteroDAQ. Split the gain into different stages so that the instrumentation amp is directly driven (through the current-limiting resistors) by the electrodes, and any high-pass filtering is done after the instrumentation amp. Don't use so much gain in the first stage that the expected $\pm 300\text{mV}$ DC offset could cause saturation of the amplifier.
- Draw a block diagram for your EKG, complete with signal levels.
- Have a complete, clear circuit (preferably drawn with a tool like SchemeIt [4]) before coming to lab.
- Have a layout for the circuit on the instrumentation-amp protoboard worksheet [7] before coming to lab.

4 Parts, tools, and equipment needed

Parts for this lab from kit:

- instrumentation amp protoboard
- INA126P instrumentation amp
- MCP6004 quad op amp
- various resistors and capacitors
- EKG electrodes

- alligator clips
- KL25Z board
- USB cable

Equipment in lab:

- soldering irons
- oscilloscopes and multimeters for debugging only

5 Procedures

Populate and solder your board.

Make a wiring harness by twisting three color-coded wires together and attaching an alligator clip to each. You need twisted wires to reduce AC pickup by the leads. Wires should be about 2–3' long (60–100cm) with the last 8" (20cm) before the alligator clips not twisted together, so that the leads can spread out to the electrodes.

Prep your skin by cleaning the spots where you want the electrodes. Using some Scotch tape to peel off a layer of dead skin (part of the *stratum corneum*) is effective in reducing the resistance of the skin. Other methods include gentle abrasion with fine sandpaper [8] or shaving, non-alcohol wipes, and gentle abrasion [6]. Dry the skin thoroughly before attempting to attach the electrode—not only does this remove any loose dead skin cells, but the electrodes don't stick well to wet skin.

6 Demo and writeup

Record several seconds of heartbeat at 120Hz sampling rate.

Plot the data with properly labeled x and y axes (showing the voltage at the electrodes, not after amplification). Remember to put in the title what lead was used for the recording. Compute the pulse rate from the recording.

The report should, of course, include the block diagram and schematics for the one-channel EKG, along with any design notes about why the design ended up the way that it did.

References

- [1] Euan A. Ashley and Josef Niebauer. *Cardiology Explained*, chapter 3, Conquering the ECG. Remedica, London, 2004. <http://www.ncbi.nlm.nih.gov/books/NBK2214/>
- [2] Ajay Bharadwaj and Umanath Kamath. Techniques for accurate ECG signal processing. *EE Times*, February 14 2011. <http://www.eetimes.com/design/medical-design/4213140/Techniques-for-accurate-ECG-signal-processing>
- [3] Enrique Company-Bosch and Eckart Hartmann. ECG front-end design is simplified with MicroConverter. *Analog Dialogue*, 37, November 2003. <http://www.analog.com/library/analogDialogue/archives/37-11/ecg.html>
- [4] Digi-Key. Scheme-It: Free online schematic drawing tool, 2014. <http://www.digikey.com/schemeit>
- [5] Ken Grauer. *A 1st Book on ECGs—2014*. KG/EKG Press, P.O. Box 141258, Gainesville, FL, 32614-1258, 2014.

- [6] Philips Healthcare. Improving ECG quality, September 2008. <http://incenter.medical.philips.com/doclib/getDoc.aspx?func=11&objId=8616008&objAction=Open>
- [7] Kevin Karplus. Instrumentation amp protoboard rev 3.0 worksheet, November 23 2012. <http://users.soe.ucsc.edu/~karplus/bme194/w13/pc-boards/EKG-proto-rev3.0/EKG-proto-rev3.0-worksheet.pdf>
- [8] Craig D. Oster. Proper skin prep helps ensure ECG trace quality. 3M Health Care, 2005. http://multimedia.3m.com/mws/mediawebsserver?mwsId=SSSSSu7zK1fslxtUm8_em8mvev7qe17zHvTSevTSeSSSSSS--
- [9] Wikipedia. Electrocardiography, March 7 2013. <http://en.wikipedia.org/wiki/EKG>