BEGN 186B Winter 2023

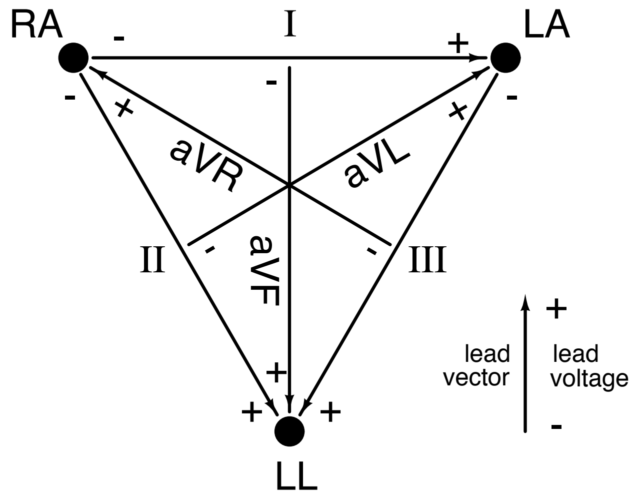
Quiz 3

Friday, March 10, 2023

Last Name, First Name: ______________________________

- This quiz is on-line, open-book, and open-notes. You may use a calculator or an equivalent program, but web search is prohibited. You may follow electronic links from Canvas or the class web pages, but not any further. **No collaboration or communication in any form is allowed**, except for questions to the instructor and TAs.
- The quiz is due March 10, 2023 at 11:59pm, over Canvas (Gradescope). It should approximately take 2 hours to complete, but there is no time limit other than the submission deadline. Do not discuss any quiz-related material among yourselves before or after you have completed your quiz, and until the submission deadline has passed.
- There are 4 problems. Points for each problem are given in **[brackets]**. There are 100 points total, but also a bonus +10 points challenge.

1. **[20 pts]** Consider Einthoven's triangle of the frontal electrocardiogram (ECG) shown below. The triangle is equilateral and the augmented lead vectors (aVR, aVL, and aVF) bisect the bipolar lead vectors (I, II, and III). All three electrodes RA, LA and LL are at distance $r = 40$ cm from the heart.

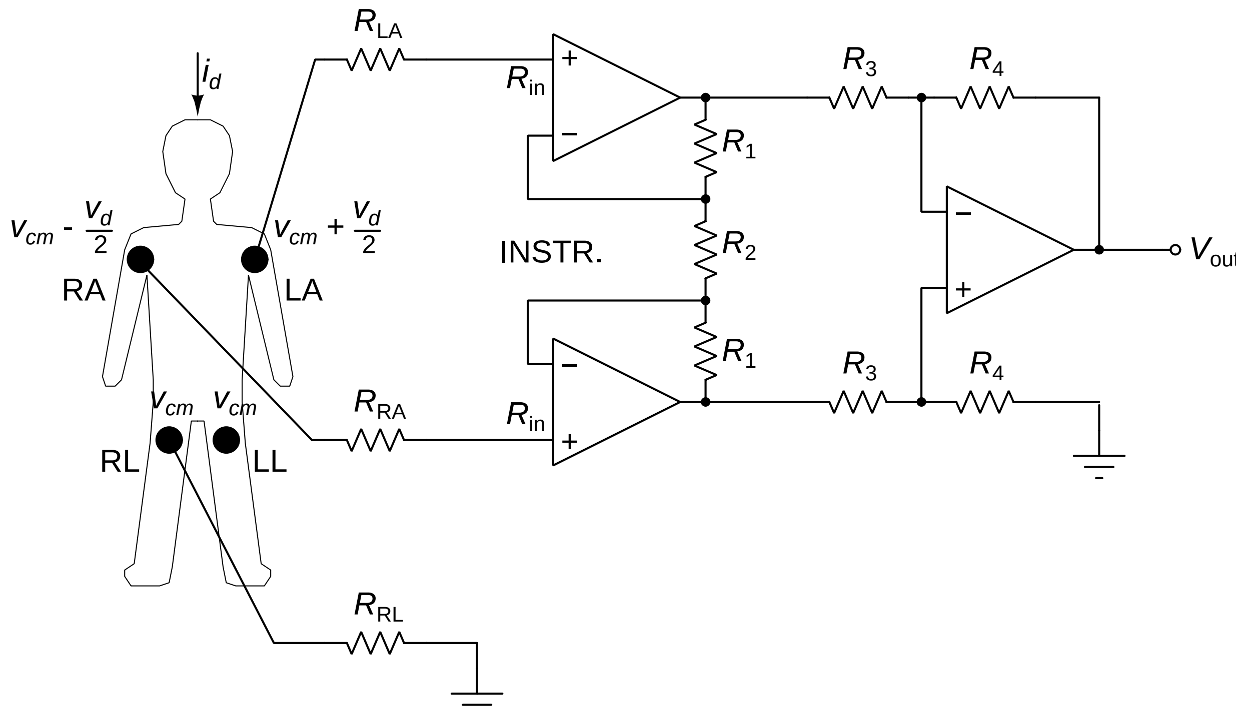


   (a) [6 pts] At the peak of the P wave, the voltage on lead aVL measures zero, and the voltage on lead aVF measures 1 mV. Find the length and the direction of the cardiac vector in the frontal plane.

(b) [6 pts] At the Q wave, the voltage on lead aVL now measures 1 mV, while the voltage on lead aVF measures zero. Find the length and the direction of the cardiac vector in the frontal plane.

(c) [8 pts] Express the bipolar leads I, II, III in terms of the augmented leads aVR, aVL, and aVF. Are these expressions unique? Explain.

2. **[35 pts]** A two-stage instrumentation amplifier (IA) is connected to the body as shown below to record a single-lead electrocardiogram. The electrode-skin resistances are $R_{RA} = 110\ \text{k}\Omega$, $R_{LA} = 120\ \text{k}\Omega$, $R_{LL} = 90\ \text{k}\Omega$, and $R_{RL} = 100\ \text{k}\Omega$. The opamps are ideal with infinite gain and infinite input impedance ($R_{in} = \infty$). The IA resistances are $R_1 = 499.5\ \text{k}\Omega$, $R_2 = 1\ \text{k}\Omega$, $R_3 = 100\ \text{k}\Omega$, and $R_4 = 100\ \text{k}\Omega$, all with 0.1 % tolerance.

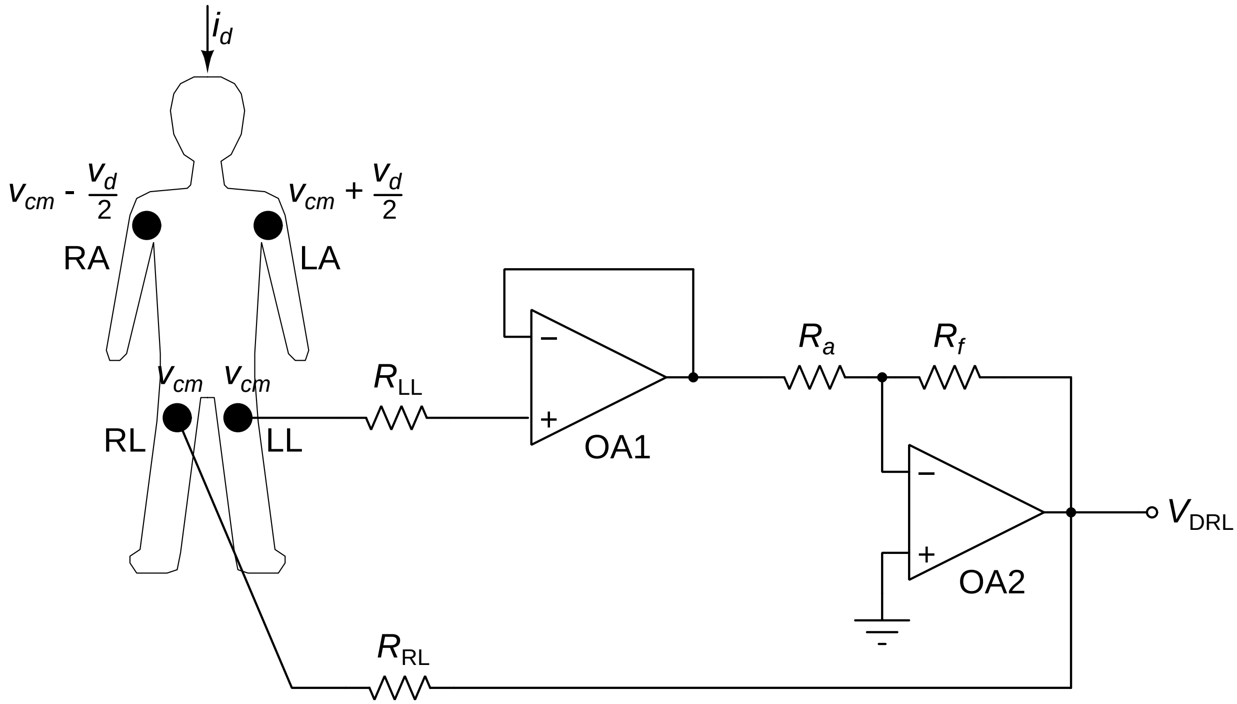


(a) [5 pts] What ECG lead does the IA output V_{out} represent, and with what voltage gain?

(b) [10 pts] 60 Hz line noise causes a displacement current of peak amplitude $i_d = 20$ μA to enter the body. The peak ECG signal between the RA and LA electrodes measures 500 μV. Find the peak amplitude of the common-mode voltage v_{cm} in the body, and the resulting signal-to-noise ratio at the RA and LA electrodes.

(c) [10 pts] Find the common-mode rejection ratio (CMRR) of the IA, accounting for 15 pF parasitic capacitance at each input. Find the resulting signal-to-noise ratio at the IA output.

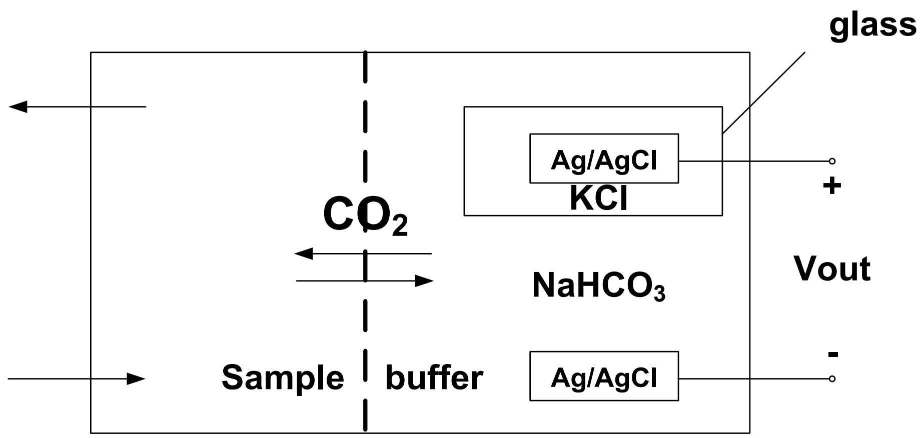
(d) [10 pts] Now consider active grounding by the driven right leg (DRL) circuit shown below. You may assume that the operational amplifiers OA1 and OA2 are ideal, with infinite input impedance. The DRL amplifier resistances are $R_a = 10\ \text{k}\Omega$ and $R_f = 1\ \text{M}\Omega$. Find the effective driven right leg electrode resistance $R_{RL\ \text{eff}}$, and the resulting signal-to-noise ratio at the IA output.



(e) **Bonus** [extra +10 pts]: Modify the design of this DRL circuit to only use a single operational amplifier, and to limit the current entering the body to no larger than 10 μA in magnitude from a ± 1.5 V dual voltage supply, while providing at least the same level of common-mode suppression as the circuit shown in (d).

3. **[20 pts]** Consider the Severinghaus electrode shown below for measurement of PCO_2. The solution internal to the glass membrane is 1 mol/L KCl in pure water, and the glass membrane is permeable to H^+ only. The buffer contains a saturated solution of $NaHCO_3$, and is separated from the sample by a CO_2-permeable membrane. Assume $RT/F\ln(10) = 60$ mV at room temperature. The following equation may be useful:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$



(a) [10 pts] A calibration sample with a PCO_2 of 10 mmHg produces an output voltage $V_{out\ \mathrm{cal}}$ of 90 mV. In turn, an unknown blood sample produces an output voltage $V_{out\ \mathrm{blood}}$ of 30 mV. Find the PCO_2 of the blood sample.

(b) [5 pts] Why is it necessary to have a saturated solution of $NaHCO_3$ in the buffer, and a saturated solution of KCl in the glass bulb? Explain how the accuracy of the PCO_2 measurement is compromised at lower buffer $NaHCO_3$ and bulb KCl concentrations.

(c) [5 pts] What is the purpose of the CO_2-permeable membrane separating the sample from the buffer? Does it have a Nernst potential? Explain.

4. **[25 pts]** Circle the **best answer (only one answer per question)**:

(a) [3 pts] The Wilson Central Terminal is obtained by:

i. the voltage on an electrode placed at close proximity to the heart
ii. averaging the voltages on the electrodes at the corners of the Einthoven triangle
iii. shorting all electrodes
iv. driving the right leg towards zero potential
v. None of the above

(b) [3 pts] A platinum electrode is used in a Clark oxygen sensor because it:

i. is non-polarizable
ii. is capable of injecting electrons into solution
iii. oxidizes in solution
iv. has zero half-cell potential
v. All of the above

(c) [3 pts] Increasing compliance of a fluid-filled catheter:

i. lowers its bandwidth
ii. dampens its resonance
iii. increases its response time
iv. increases sensitivity of displacement based pressure measurement
v. All of the above

(d) [3 pts] The accuracy of tonometry based pressure measurement is affected by:

i. The angle at which the transducer is placed over the blood vessel
ii. The depth below the skin where blood vessels are located
iii. The position of the transducer
iv. The size of the blood vessel in relation to the transducer
v. All of the above

(e) [3 pts] SCO2 measures:

i. partial pressure of oxygen in the bloodstream
ii. relative fraction of oxygenated hemoglobin
iii. saturation of carbon dioxide in the bloodstream
iv. short-circuit current in Clark electrode amperometry
v. None of the above

(f) [10 pts] Indicate for each statement below whether it is true or false:

i. **TRUE / FALSE**: Higher CMRR directly contributes to increasing output signal-to-noise ratio.

ii. **TRUE / FALSE**: The magnitude of the cardiac vector is inversely proportional to the square of the distance between the heart and the electrode.

iii. **TRUE / FALSE**: The twelve-lead electrocardiogram uses ten electrodes.

iv. **TRUE / FALSE**: The sphygmomanometer measures systolic and diastolic pressure along with heart rate non-invasively.

v. **TRUE / FALSE**: Fick's technique measures cardiac output by rapid injection of a bolus in the blood stream.

vi. **TRUE / FALSE**: Doppler frequency shift is maximum perpendicular to blood flow.

vii. **TRUE / FALSE**: Gate voltage in an ISFET is set by ionic charge.

viii. **TRUE / FALSE**: Beer's law quantifies optical transmission through absorptive media.

ix. **TRUE / FALSE**: Optical fibrosensors are sensitive to electrical interference.

x. **TRUE / FALSE**: Pulse oximetry is a type of photoplethysmography.