BENG 186B Winter 2025

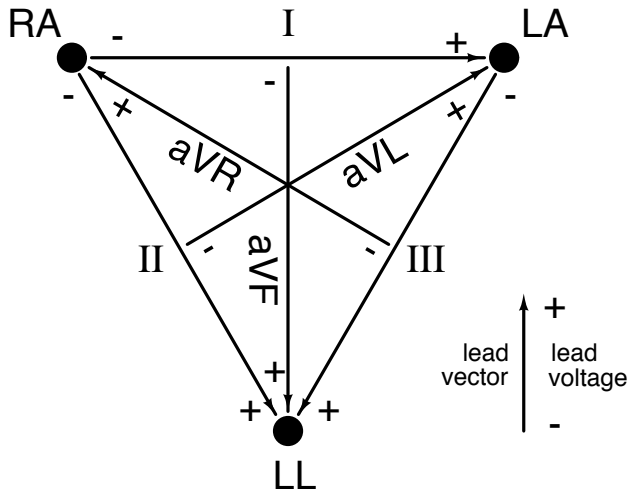
Quiz 3

Friday, March 7, 2025

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 7, 2025 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.

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 $r = 30$ cm from the heart.

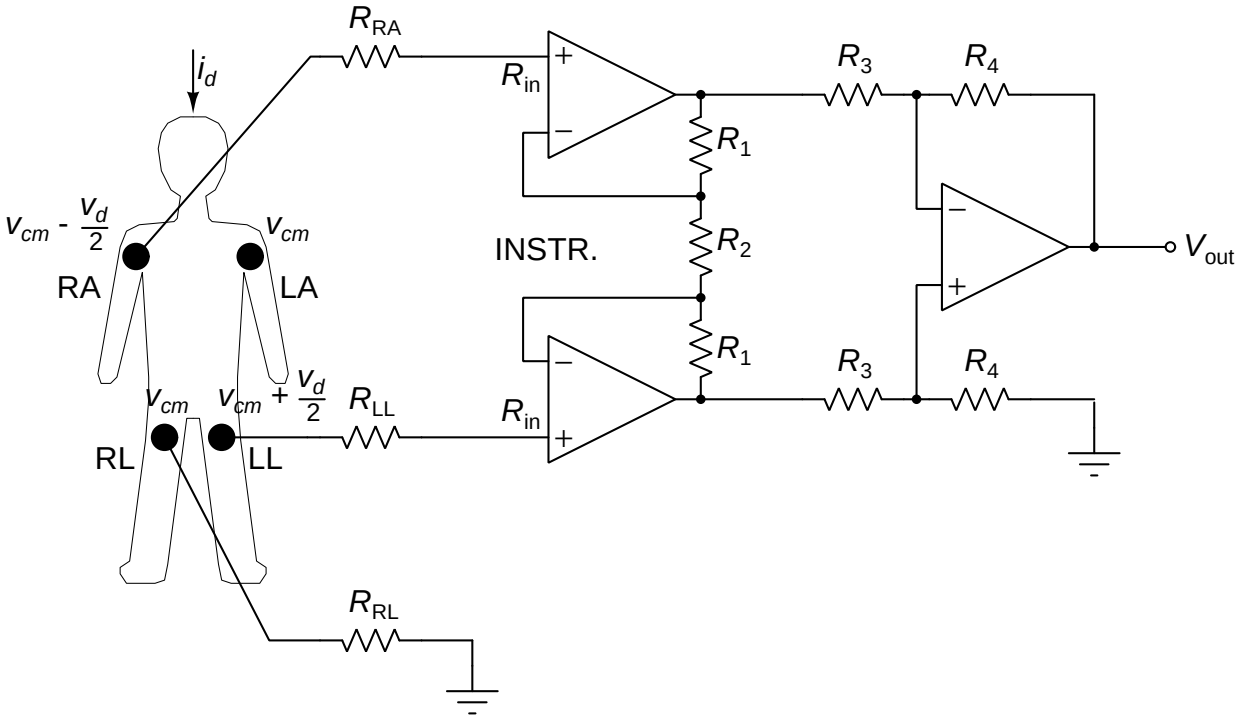


(a) [6 pts] At the R wave, the voltage on lead I measures zero, and the voltage on lead aVF measures 1 mV. Find the length and the direction of the corresponding cardiac vector in the frontal plane.

(b) [6 pts] At the S wave, the voltage on lead I now measures -0.5 mV, while the voltage on lead aVF measures zero. Find the length and the direction of the corresponding cardiac vector in the frontal plane.

(c) [8 pts] Express the augmented leads aVR, aVL, and aVF in terms of the bipolar leads I, II, III. Can you also obtain the transversal leads from the bipolar leads? 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 $R_{RA} = 105$ kΩ, $R_{LA} = 115$ kΩ, $R_{LL} = 95$ kΩ, and $R_{RL} = 100$ kΩ. The opamps are ideal with infinite gain and infinite input impedance ($R_{in} = \infty$). The IA resistances are $R_1 = 49.5$ kΩ, $R_2 = 1$ kΩ, $R_3 = 10$ kΩ, and $R_4 = 100$ kΩ, all with 1 % tolerance.

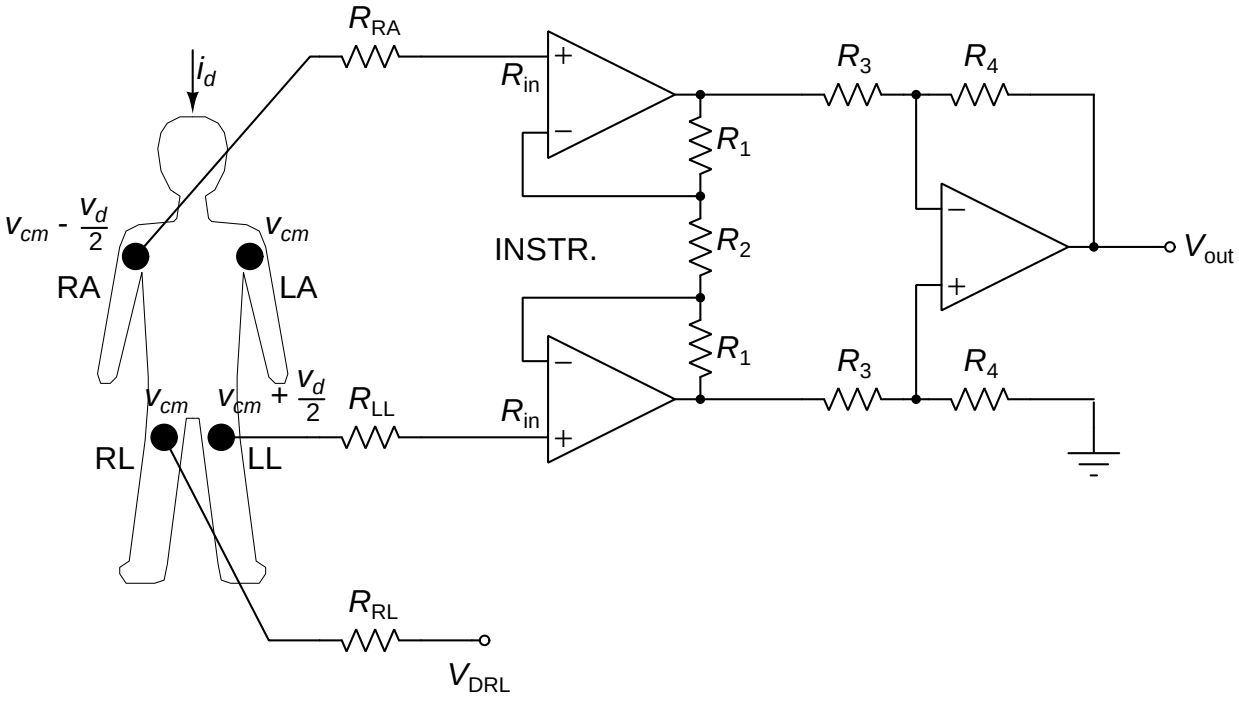


(a) [5 pts] What ECG lead does the IA output V_{out} represent, and with what voltage gain?

(b) [10 pts] 60 Hz line noise causes a displacement current of peak amplitude $i_d = 10$ μA to enter the body. The peak ECG signal between the LL and RA electrodes measures 1 mV. 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 LL electrodes.

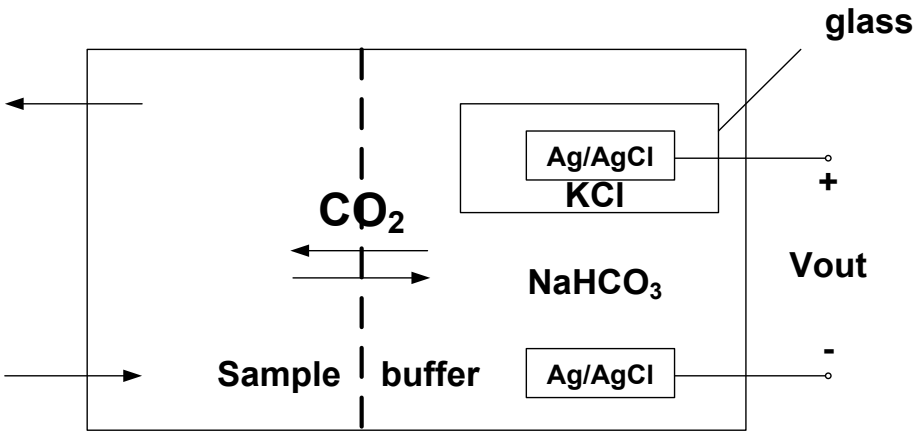
(c) [10 pts] Find the common-mode rejection ratio (CMRR) of the IA, accounting for 10 pF parasitic capacitance at each input. Find the resulting signal-to-noise ratio at the IA output.

(d) [10 pts] Now consider active grounding. Design a driven right leg (DRL) circuit that interfaces with the IA circuit (replicated below) to boost its output signal-to-noise-ratio by at least 40 dB. You may use any combination of operational amplifiers and resistors, connecting to any nodes in the IA circuit. Show all your work, indicating values for all components used. You may assume that all operational amplifiers are ideal, with infinite gain and infinite input impedance, and with ± 3V dual rail voltage supplies. Write the effective driven right leg electrode resistance $R_{RL\ \mathrm{eff}}$, and the resulting signal-to-noise ratio at the IA output.



3. **[20 pts]** Consider the Severinghaus electrode shown below for measurement of PCO_2. The solution internal to the glass membrane is 100 mmol/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 1 mmHg produces an output voltage $V_{out\ \text{cal}}$ of 10 mV. In turn, an unknown blood sample produces an output voltage $V_{out\ \text{blood}}$ of 130 mV. Find the PCO_2 of the blood sample.

(b) [5 pts] Why is it necessary to use a buffered solution separate from the sample to obtain PCO_2 from the pH measurement, rather than directly measure pH of the sample? Explain.

(c) [5 pts] How would the reading be affected if the membrane separating the sample from the buffered solution were permeable to H^+ as well? Explain.

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

(a) [3 pts] Measurement of the 12-lead electrocardiogram requires:

i. 12 electrodes
ii. 10 electrodes
iii. 8 electrodes
iv. 4 electrodes
v. None of the above

(b) [3 pts] A Clark oxygen sensor measures PO_2 as:

i. voltage between electrodes
ii. current passing through electrodes
iii. resistance between electrodes
iv. absorbance of incident infrared light
v. None of the above

(c) [3 pts] Lowering inertance of a fluid-filled catheter:

i. increases its bandwidth
ii. dampens its resonance
iii. lowers its settling time
iv. lowers its rise time
v. All of the above

(d) [3 pts] The sphygmomanometer is able to measure:

i. the blood pressure waveform over time
ii. central blood pressure
iii. cardiac output
iv. heart rate
v. All of the above

(e) [3 pts] SCO2 measures:

i. partial pressure of oxygen in the bloodstream
ii. relative fraction of carboxygenated hemoglobin
iii. saturation of oxygen in the bloodstream
iv. lung volume
v. None of the above

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

i. **TRUE / FALSE**: An IA with infinite CMRR offers infinite signal-to-noise ratio.

ii. **TRUE / FALSE**: The magnitude of the cardiac vector depends on the distance of the electrodes from the heart.

iii. **TRUE / FALSE**: The 6-lead frontal electrocardiogram uses four electrodes.

iv. **TRUE / FALSE**: The tonometer measures dynamic pressure in a vessel near the skin surface.

v. **TRUE / FALSE**: An electromagnetic flowmeter requires a constant magnetic field.

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

vii. **TRUE / FALSE**: An IMFET is capable of measuring either antigens or antibodies.

viii. **TRUE / FALSE**: Beer's law quantifies alcohol content in the blood stream.

ix. **TRUE / FALSE**: Optical fibrosensors are capable of measuring partial pressure of blood gases.

x. **TRUE / FALSE**: Pulse oximetry is a ratiometric technique to optically measure oxygen saturation and heart rate.