1. ECG Measurement

We would like to monitor the heart rate of a subject while she is exercising. Exercise causes three main difficulties for measurement of the ECG: a) movement artefacts, b) sweat on the electrodes, and c) artefacts from the EMG in the ECG.

We consider two different electrodes systems to measure the ECG. #1) we place two Ag/AgCl electrodes each shoulder of the subject, and #2) we ask the subject to hold onto stainless steel handles which act as electrodes.

(a) (5 points) Briefly describe the origin of movement artefacts. Use an equation or diagram if necessary. Do movement artefacts differ for electrodes #1 and #2? Explain (≤ 50 words).

(b) (5 points) Briefly describe the effect of sweat on the electrodes. Show equivalent electrical models of the electrodes. Does sweat affect electrodes #1 and #2 differently? Explain (≤ 50 words).

(c) (5 points) Briefly describe how artefacts from the EMG affect the ECG. Can a filter be used to clean the signal? Use a diagram if necessary. How is the effect different on electrodes #1 and #2 different? Explain (≤ 50 words).

(d) (5 points) Draw a diagram of the ECG waveform. Label the $P$, $Q$, $R$, $S$, and $T$ events. In a segment of the ECG, $R$ waves occur at the following times (after the start of measurement) 9.95s, 10.49s, 11.23s, 11.61s, and 12.45s. Estimate the heart rate (in beats/min).

(e) (10 points) Consider the circuit diagram shown. The amplifier is configured so that the differential gain is 100. From the specifications of the amplifier, it has a common mode rejection ratio of 80 dB and an input impedance, $Z_{in}$, of 1 MΩ. Two stainless steel electrodes are attached with electrode model parameters $C_d = 0.3 \, \mu F$ and $R_s = 1 \, k\Omega$. The common mode voltage due to power-line interference is 3.0 V and the differential voltage is 3.0 mV (which can consider to be at 10 Hz). What is the ratio of the differential to common mode signal at the amplifier output, $V_0$?
(f) (10 points) Consider a standard Ag/AgCl electrode where the electrode gel is modified by sweat from the subject. When fresh out of the package, the electrode gel has a concentration $[\text{Cl}^-] = 0.1 \text{ mol L}^{-1}$. Sweat has approximately $[\text{Cl}^-] \approx 0.01 \text{ mol L}^{-1}$, and thus will reduce the concentration in the gel. **Calculate the change in electrode voltage when $[\text{Cl}^-]$ changes from $0.1 \text{ mol L}^{-1}$ to $0.05 \text{ mol L}^{-1}$.** Assume skin temperature is 30°C. In practice, will sweat show up as a fast or slow contribution to the signal, and as a differential or common mode effect?

2. Breathing Measurement

We wish to measure breathing parameters patient from a patient using a Fleisch-type pneumotach as shown at right and a fast gas analyzer. (Image reproduced from spirxpert.com/technical2.htm)

(a) (5 points) **How does such a pneumotach work?** Sketch a diagram showing how it is connected to a patient, and what measurements are made on it. Briefly ($\leq 30$ words) describe how the pneumotach can measure air flow.

(b) (5 points) A Fleisch-type pneumotach with 100 channels is used, each has a diameter of 1 mm and a length or 3 cm. **Estimate the flow resistance of the pneumotach in units of $\text{kPa L/s}$.**

(c) (5 points) **Explain one of the following problems with a pneumotach, and discuss a way to address the problem:** (1) Pneumotachs give a different signal level for the same quantity of air flowing into and out of the lungs, due to heating and humidification of the air; (2) Pneumotachs tend to get full of condensation because of humid expired air.

(d) (10 points) We ask a patient to perform a vital capacity manouevre. Starting at FRC, he (a) slowly breathes out (at 200 ml/s for 6.0 s), then (b) rapidly breathes in (at 1000 ml/s for 4.5 s), then (c) holds his breath for 2.0 s, then (d) slowly breathes out (at 150 ml/s for 30.0 s). **Calculate expiratory reserve volume (ERV), Inspiratory Capacity (IC), and Vital Capacity (VC) for this patient.** If the patient has a lung resistance, $R_L = 2.0 \text{ kPa L/s}$, and lung compliance, $C_L = 1.2 \text{ L kPa}^{-1}$, sketch time curves of flow $\dot{V}_L$, volume $V_L$, and muscular pressure $P_{mus}$ required to perform this manouevre. Remember to account for the resistance of the pneumotach.

(e) (10 points) In the previous question, during inspiration (b), the patient inspired heliox gas (80% He, 20% $O_2$). The fraction of He in expired gas $f_{EHe}$ as a function of time during expiration (d) is shown at right. **Calculate residual capacity (RC).** Assume gas remaining in the lungs has He concentration of
f_{\text{He}} = 0.61, and that the patient was breathing atmospheric air (use 80% N$_2$, 20% O$_2$) before the experiment. Ignore water vapour for your calculations.

(f) (5 points) One widely used way to measure the concentration of O$_2$ in arterial blood is with a pulse oxymeter. **How does a pulse oxymeter work?** Sketch a diagram if necessary. Explain why it measures arterial, and not venous blood oxygenation, or tissue oxygenation. Note that there is much more venous blood and tissue than arterial blood.

3. **Blood Pressure and Flow**

(a) (5 points) A time-of-flight Doppler ultrasound system measures blood flow by placing two ultrasound transducers at an angle $\theta$ on either side of a blood vessel. First, one transducer transmits a pulse while the other receives, and then the roles are switched. **Describe how flow can be measured from such an ultrasound system.**

(b) (10 points) A Doppler ultrasound system is shown at right, where blood flows through a 0.5 cm diameter artery in the arm at 2 ml/s. Assume the flow profile is uniform (blood flows at the same speed at any position in the artery). An ultrasound transducer transmits a 3.0 MHz pulse which travels at 1500 m/s through the tissue. The distance between transducers is 15 cm.

**Calculate the transmit-receive delay from transducer #1 to #2.** How different is this from the delay when the flow is zero? **Comment briefly on any difficulties measuring changes in a delay of this size.**

(c) (5 points) A photoplethysmography (PPG) system can be used to monitor peripheral blood flow. **Sketch a PPG system, and discuss briefly how it works.** PPG measures relative changes in flow, but not the absolute flow level. **Discuss why?**

(d) (5 points) If a PPG system breaks, it could potentially become a shock hazard. **Sketch the current pathways for a possible failure mode, and briefly discuss what damage it could cause to the subject.**

(e) (5 points) The compliance of the aorta is a key factor in determining the level of systolic blood pressure. Stiffening of the aorta with age can result in increases in blood pressure. **Calculate the compliance of the aorta,** assuming the aorta length is 30 cm with 3 cm diameter, and the aorta diameter increases 1mm per kPa of blood pressure.

(f) (10 points) A simple model of the circulatory system is shown at right. The heart is a current source which pushes blood into a resistance, $R$, representing the systemic circulatory system. The aortic compliance is $C$.

Assume a heart rate of 60 beats per minute; systole lasts 200 ms and the heart ejects 70 ml. The diastolic pressure is 80 mmHg, and $R = 25 \text{kPa L/s}$. **Calculate the RC time constant and sketch the blood pressure waveform for this model.** **Discuss briefly (≤ 50 words) how this pressure waveform compares to that of a normal subject.**