BE 172 Spring 2018

Week I: Hydraulically Coupled Blood Pressure Recording System

Objective

To understand how extravascular blood pressure is measured using a liquid filled catheter system (Figure 1), and to investigate the limitations of such a system. A test setup will be assembled to generate pressure waveforms, and the frequency response of the second-order catheter/fluid/transducer system will be characterized, using catheters of different sizes and materials to demonstrate how these properties affect the readings. There will also be an initial introduction to the oscilloscope and function generator.

The main objectives are:

1. To become familiar with the electronic measuring devices in the lab.
2. To assemble a power amplifier/electromagnetic shaker system, and measure the frequency response of the calibrated pressure transducer.
3. To characterize the natural frequency, damping ratio and frequency response for 3 catheters.
4. Determine which catheter properties are important in clinical design.

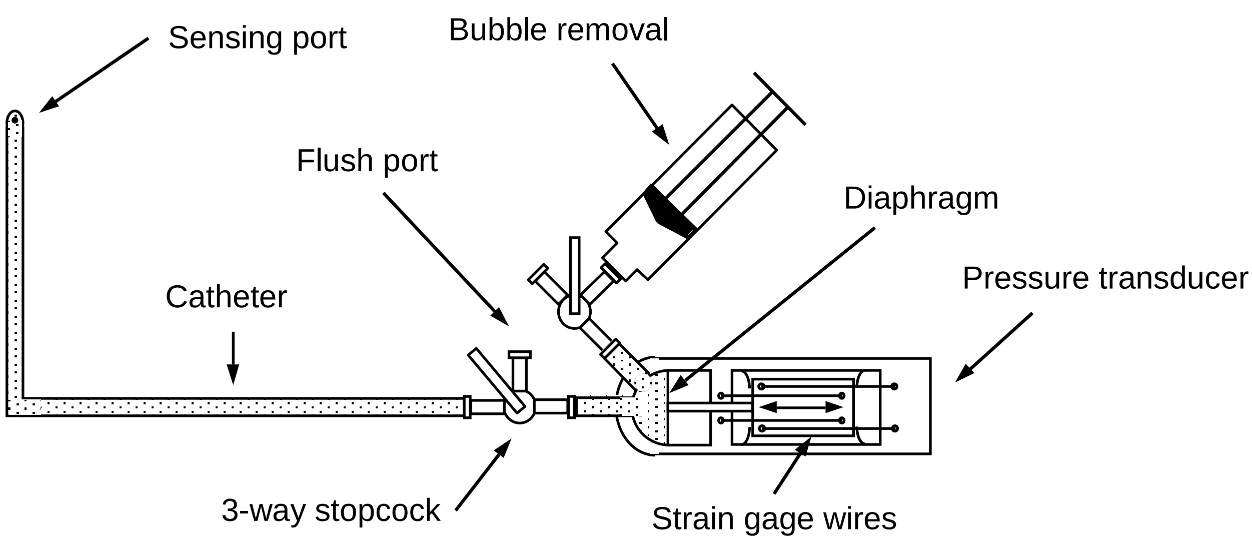

Figure 1: Extravascular blood pressure measuring system

Introduction

In clinical situations, blood pressure is often measured directly by introducing a fluid-filled catheter into a vein or artery and connecting it to a pressure recording apparatus (Figure 1). The pressure in the blood vessel is transmitted via the liquid column in the catheter to the pressure transducer. The pressure-sensing element in the transducer (strain gauge) is a deformable diaphragm. While one side of the diaphragm is hydraulically coupled to the blood stream by the catheter, the other side is bonded to a series of strain gauge wires which provide an electrical signal proportional to pressure. The fidelity with which the recorded response represents the true dynamic blood pressure waveform is affected by the mechanical properties of the catheter-fluid-transducer system. Therefore, in this laboratory, you will build a test system for characterizing the dynamics of the hydraulically coupled pressure recording system. The basis of the measurement system is described in Cobbold (*Transducers for Biomedical Measurements*, Wiley, 1974).

Background

Accurate reproduction of the blood pressure waveform depends upon the characteristics of the catheter-transducer system. The dynamics of this system can be characterized by examining a second-order electrical analog circuit, specifically a series RCL circuit. We can identify the components in the physical transducer system that correspond to the electrical elements in the second-order lumped-parameter system: **inertia** L ($Pa\text{-}s^2/m^3$), **resistance** R ($Pa\text{-}s/m^3$) and total **compliance** C_T (m^3/Pa), that are used in the governing equation for the RCL circuit:

$$L\ddot{V} + R\dot{V} + \frac{1}{C_T} V = P(t) \qquad (1)$$

where V is the fluid volume (m^3) and P(*t*) is the driving pressure (Pa) as a function of time. Dots over the V's represent derivatives as functions of time.

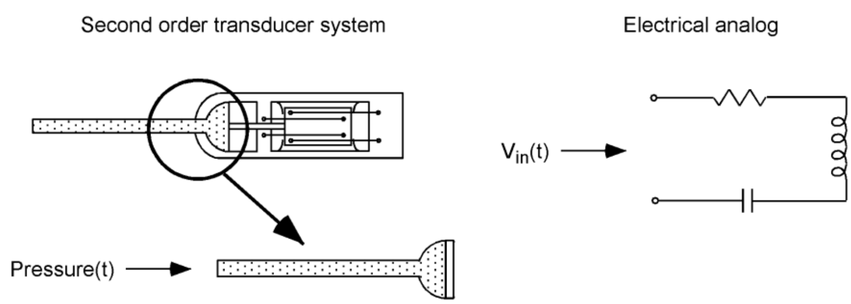

Figure 2: Simplified physical model of a catheter-transducer system

The **inertia** of the system is due primarily to the mass of the fluid in the tube and can be derived from the energy equation:

$$L = \frac{\rho l}{\pi r^2}$$

where ρ = the fluid density (kg/m^3) , *l* = the length of the tube (m), and r (m) is the (inner) radius of the tube. The inertia of fluid in the sensor can typically be ignored.

The **resistance** of the system is due mainly to the fluid viscosity in the catheter (η) and is obtained from Poiseuille's formula for the laminar flow of a Newtonian fluid in a cylindrical tube:

$$R = \frac{8 \eta l}{\pi r^4}$$

The coefficient of viscosity η of water is 0.001 Pa-s at 20°C and 0.0007 Pa-s at 37°C.

There are several sources of **compliance** in the system, including compliance of the catheter wall (C_c), compliance of the fluid in the system, and compliance of the diaphragm in the pressure gauge (C_d). Compliance in the system will allow fluid to enter and expand the volume of the system. Compliance of the fluid is usually small compared to the other two. A simple model will have C_d and C_c in series to form the total compliance of the system (C_T in equation 1 above). The compliance of the transducer diaphragm is often reported by the manufacturer as the volume modulus of elasticity, $E_d = 1/C_d$. For the transducers in this lab, assume the volume modulus of elasticity is $E_d = 1.0 \times 10^{15}$ N/m^5. The compliance of the catheter depends on its dimensions (including the wall thickness h in meters) and the Young's modulus E_c (Pa) of the catheter material:

$$C_c = \frac{2 \pi r^3 l}{E_c h}$$

The total compliance is the parallel combination of these 2 components, making one equivalent capacitance in the RCL circuit. Remember when adding these compliances, make sure the units match!

Therefore, the dynamic response of the hydraulically coupled blood pressure transducer system will depend on the radius, wall thickness, length and Young's modulus of the catheter, the volume modulus of the transducer diaphragm, and the density, volume, compliance and viscosity of the fluid in the tube. One objective of this laboratory is to examine the effects of different dimensions and material properties of catheters on their frequency response, and compare measured parameters to theoretical.

Two experimental tests of the frequency response will be used: The system will exhibit an underdamped response to a **pressure step** as shown in Figure 5. Such a response can be found in the lab by applying a square wave pressure signal with proper frequency so as not to mask the response. The step response can be characterized by the *damping ratio* ζ, which you have probably derived before for a second order system:

$$\zeta = \frac{R}{2} \sqrt{\frac{C}{L}}$$

$\zeta>1$	**Over damped**
$\zeta=1$	**Critically damped**
$\zeta<1$	**Underdamped**

The damping ratio can be determined from the measured step response by computing the *logarithmic decrement*:

$$\Lambda = 2 \ln\left(\frac{\theta_n}{\theta_{n+1}}\right) = \frac{2 \pi \zeta}{\sqrt{1 - \zeta^2}}$$

where θ_n and θ_{n+1} are the heights of successive peaks in the response (See Figure 5). Notice the factor of 2 difference from the equation in the book (1.37) since here we are using the full amplitude for θ. The damped natural frequency can also be found with this test by direct inspection of the oscillating signal.

In the second type of test, the system is driven with a **sinusoidal pressure waveform** to determine the frequency response of the system (bandwidth) and the *natural frequency* f_n at which practical resonance is observed. For undamped oscillations, the natural frequency (in Hz) of a second-order system is:

$$f_n = \frac{1}{2 \pi \sqrt{LC}}$$

Power Amplifier

To provide a dynamic pressure signal to the pressure transducer, an electromagnetic shaker will be used. Since the output voltage of the function generator is not sufficient to drive the shaker actuator, a power amplifier is used to increase the power level of the function generator output. The power amplifier for this lab (Figure 3) utilizes a special high-voltage, high-current op-amp, in this case the

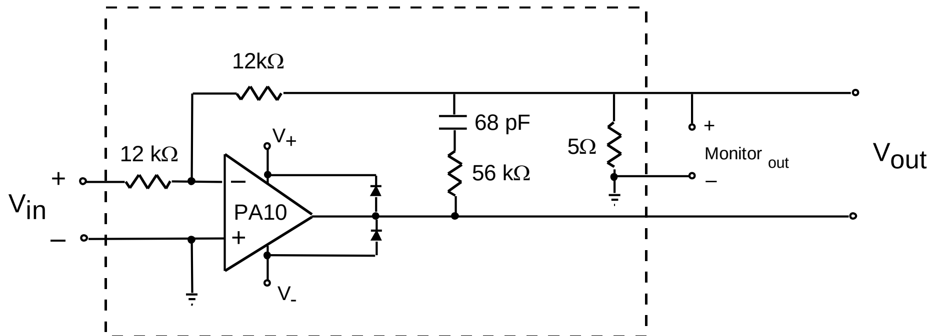

Figure 3: Power Amplifier

PA10. The op-amp is used as an inverting amplifier (thus there is a phase shift of 180° of the output). In addition, the output is connected through clamp diodes to the V+ and V- supplies. These diodes prevent the output voltage, which may be affected by the reactive and EMF-generating shaker motor load, from exceeding the supply voltages. The op-amp requires an internal "heat sink" to prevent overheating because it is capable of providing such a large amount of power. The output of this circuit is "floating", such that neither output wire is connected to ground. Thus you cannot measure the output of the circuit directly with the o-scope (V_{out}) since it is floating.

Since the power amplifier is electronic and not mechanical, its frequency response is much greater than that of the mechanical components of the system. You may assume that the bandwidth of the amplifier itself is at least 10 times greater than that of the pressure transducer by itself.

Prelab Questions: answer these as part of your pre-lab report

- Sketch a typical Bode plot (amplitude and phase) for a second order system.
- What does the -3db point on a Bode plot represent, and how is it computed?
- When performing a frequency response test on the catheter system as done in this lab, why would we not leave a syringe connected the system when performing the tests (like the syringe shown in Figure 1, and the stopcock engaged to let pressure into the syringe)?
- What 2 parameters are we measuring from the square-wave input tests in these experiments?
- Why do bubbles have such a significant effect on the frequency response of a fluid-filled system?

Equipment

- Oscilloscope
- Validyne signal conditioner (strain gauge amp) with output wire (BNC connector)
- Pressure gauge connected to strain gauge pre-amp in back.
- Grey shaker (electromagnetic pressure generator)
- Power Amp/External DC Power supply
- Function generator
- Electrical cables, pole/clamp setup, connectors
- Syringes, tape measure, tubing for pressure calibration, connectors, etc.

Review of Basic Signal Generator/Oscilloscope Functions

The oscilloscope and signal generator are used in most of the labs in this course, and in many test setups for research and development. Thus it is essential that you are familiar with the basic functions of each. Take about 15-20 minutes and follow these instructions for review of how these devices work. Connect the "low" output of the signal generator to one input of the o-scope. If 20 minutes elapses and you are still attempting to locate the power buttons, get help from a TA!

(1) Scaling. The o-scope has a button called "auto-scale" or “auto-set”. Use this as a last resort to "reset" the screen, or when you first turn on the scope. You should use the regular time/amplitude/trigger functions for your measurements here and in all the labs. Set the signal generator to around 100 Hz and around 1V amplitude (none of these values need be exact for this part of the lab) and display the signal (2-3 cycles on the o-scope). Use the time/division and volts/division knobs to set the time/amplitude ranges on the o-scope.

(2) Time base. Change the frequency of the since wave to ~1 kHz and then ~100 kHz, and change the time/div setting on the o-scope so a few cycles are visible on the scope at each frequency. When viewing a sinusoidal signal, it’s usually preferable to see individual waves of the signal.

(3) Amplitude. At about 1 kHz, change the amplitude of the sine wave from the signal generator to its lowest and highest values. Use the 'attenuation' button on the signal generator to change the output voltage range. Adjust the o-scope accordingly to keep the display visible on the screen. You don’t want a signal to be cut off or disappear from the screen.

(4) Triggering. Change the triggering mode to "normal" and adjust the trigger level so that the signal is triggered, then not triggered (move the trigger level above or below the actual signal). Change back to auto triggering. If you don’t understand what triggering an o-scope means, ask a TA or Google.

(5) Measuring. Use the measure functions to measure the peak-to-peak voltage, max and min voltages, frequency and period for a sinusoidal signal of your choice. Also use the “Phase” measurement on a sine wave (although you won’t be able to change it here). Use these functions in our labs to measure values from the o-scope screen. The Phase measurement will come in handy for phase-shift values.

(6) Coupling. With the scope on DC coupling, change the DC offset on the signal generator (to adjust the DC offset on most signal generators you need to press or pull a button, then turn the offset knob). Using the 1 or 2 buttons below volts/div on the o-scope, change the coupling to "AC", which removes the DC component from a signal. Now move the DC offset on the frequency generator and verify AC coupling. Sometimes it is desirable to remove the DC component to better view the AC signal.

(7) Averaging/Storage. Make sure you can average and store (temporarily stop) a signal. Averaging: make a sine wave with the smallest amplitude possible so that there is some "noise" on the signal. Adjust the triggering for a stable display as best possible. Use the "average" function (in display or acquire) on the o-scope to average the signal and “clean it up”. Store: go back to normal display, and use the "storage" or “save/stop” functions to store a low-frequency (about 10 Hz) sine wave. On some scopes there is no “store” button, the save button will work for this purpose. Redisplay the 10 Hz signal with ~3 cycles in run mode and auto-level trigger mode. Now press auto-scale (also known as the “screw up my signal button”). Note why we call it this.

Frequency Response of the Pressure System

1. **Set up the system as shown in Figure 4**. Leave the power off for each instrument until you are ready to use it. At this point the pressure transducer is connected directly to the shaker (via a

stopcock as shown). Fill the transducer and shaker dome with water and attach a syringe via a stopcock to help remove large air bubbles from the system. It is important that big air bubbles be removed from the system in order not to distort the measurements. Take care to avoid exposing the transducer to high pressures (greater than 200 mm Hg), as this could cause irreversible damage! Attach the water column as shown for calibration.

2. **Calibrate the pressure transducer**. Notice that the pressure gauge is connected to the Validyne "strain gauge" pre-amplifier. Set the gain on the preamp to 2.5mV/V, and turn the gain “knob” so the number in the small box at the top of the knob is between 5-8. Balance the gauge first, with zero input pressure: adjust the balance on the pre-amp so that 0 volts corresponds to 0 pressure in the gauge. Now calibrate the pressure gauge with a pressure from your static water-filled tube. A 2-point calibration is sufficient (zero and your pressure). You should obtain a calibration factor to convert your output voltage to mmHg. Write your calibration factor on the white board in the lab, and of course in your notes. Always include units for a calibration value.

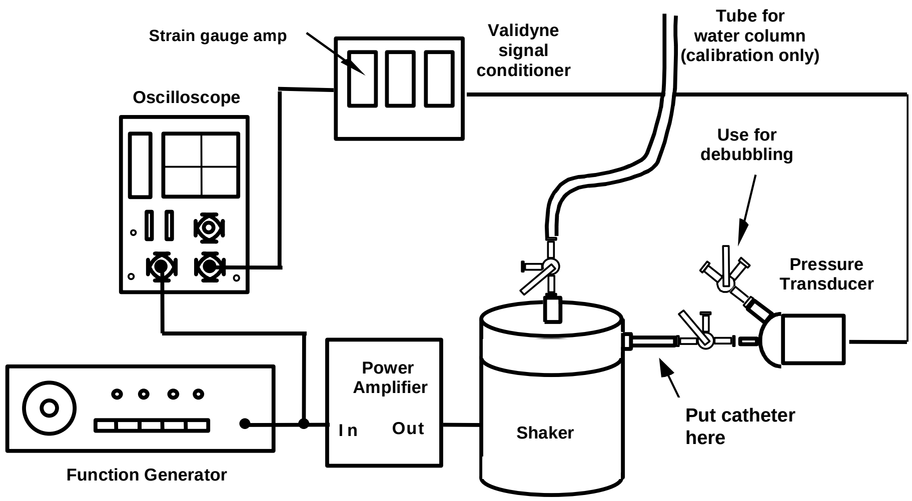

Figure 4: Schematic of Experimental Set-up. Water column tube is used for calibration only, then removed for the duration of the lab. Stopcocks are shown in an intermediate position that is not normally used during tests.

3. **Measure the frequency response of the pressure transducer/shaker system.** Before the frequency response of a catheter system can be found, we should characterize the system without a catheter. Remove the calibration water column. Set the amplitude of the function generator to a value of 1V Pk-Pk. Turn on the power amp, and display the two sine waves as shown in Figure 5: one from the signal generator, and the other from the pressure amplifier. You can increase the input sine-wave amplitude if needed, but not too high: if the shaker is making very loud noises (like a speaker), the amplitude is too high! You will be able to hear the speaker “sing” at higher frequencies which is fine, as long as it’s not too loud. The Pk-Pk amplitude of the pressure transducer output should be at least 100 mV at low frequencies (may be noisy). Initially dial through a range of frequencies to find the resonant frequency of the system, and determine the range you will measure. Think about the Bode plot, and the -3db point which will determine your maximum frequency. There may be resonant peaks above the first main resonance, you do not need to measure past the first -3db point. The range needed for this system without a catheter is typically

between 5-200 Hz. For phase shifts, used the phase measuring system on the o-scope, and you only need to measure up to a phase shift of 180° (technically -180°). Measure the response (amplitude and phase) of the pressure signal compared to the input signal over a range of frequencies which includes the low and high attenuation frequencies (i.e. to make a good-looking plot!) This will allow you to create a Bode plot (magnitude and phase) of the pressure gauge/amp system. Use the measure functions as shown in Figure 5 at each frequency. The frequencies of the amplitude plots can be different than those of the phase plots. Use dB as the units for amplitude in your Bode plot, and normalize your amplitude values so each curve starts at amplitude = 0 dB. About 8 points for such a plot is sufficient. If you change the input amplitude in the middle of your measurements, make sure to take this into account.

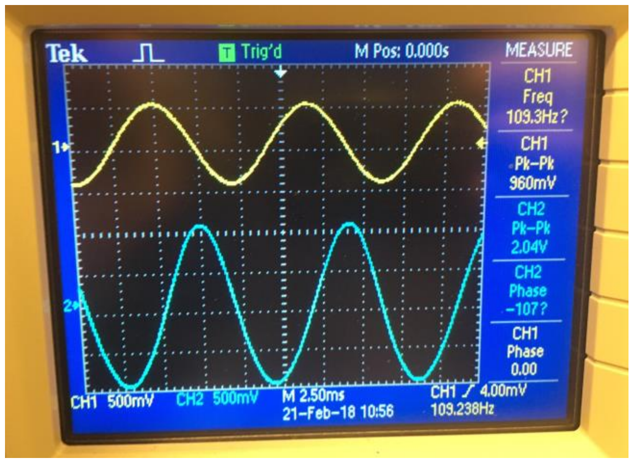

Figure 5: Sample oscilloscope display for sinusoidal input and output. The measure functions in the right column show values of frequency, Pk-Pk amplitude and Phase, values needed to create a Bode plot.

Catheter Characterization

You will characterize 3 catheters of various dimensions and materials. Choose a catheter to be tested and connect the catheter between the pressure gauge and the shaker. Make sure to remove the large air bubbles from the system; small bubbles are OK for these tests.

For *each* catheter:

1. **<u>BODE PLOT</u>**: Measure and plot the frequency response (as a Bode plot, both amplitude and phase) to a sine wave input, similar to that done for the pressure gauge itself. Again 8 strategically placed points will make a nice plot. Remember a Bode plot uses dB as the units of amplitude, and both amplitude and phase angle are plotted vs. log frequency (frequency on a $\log_{10}$ scale, using frequency in Hz). From the amplitude plot you should find the natural resonant frequency (f_n). You should again normalize the gain values so that the plot starts at 0 dB (at the lowest frequency). There may be multiple resonant peaks with a catheter (why?), but do your best to create the Bode plot in a range that includes the first -3db point, and phase shifts up to -180°.

2. **DAMPING**: Set the function generator to a square wave pulse (reduce the frequency to 5Hz or lower) and the oscilloscope to trigger from that square wave in order to measure the damping of the system. You are trying to simulate a single step function as input. The output should resemble Figure 6 (you will have to adjust the time scale of the o-scope to see the step response). Measure the amplitude of successive peaks and calculate the logarithmic decrement, Λ, given by the following formula:

$$\Lambda = 2\,(\ln \theta_1 - \ln \theta_2) = f(\zeta)$$

From this decrement find the damping ratio (ζ). Also measure the damped natural frequency (f_d), i.e. the frequency of the damped sinusoid wave.

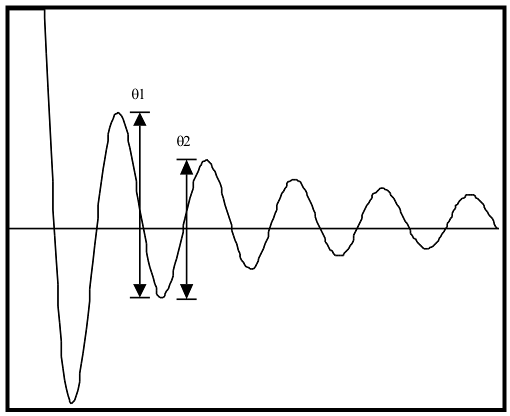

Figure 6: Damped System Response

3. Record the inner diameter, thickness, length and Young's modulus for each catheter. You will need these values to calculate theoretical values for the catheters.

4. Tabulate your results as follows: from the experiments, find the damping ratio, natural frequency and damped natural frequency of the system for the 3 catheters. From the theoretical second order system equations, find and tabulate the same 3 values (these can all be in one big table). Compare theory to experiment, and comment on the discrepancies. Discuss on the effects of changes in length, diameter, wall thickness and material stiffness. You may use the following values for Young's modulus for the various materials: Stainless steel=300GPa, Polyethylene=300MPa, Silicone=1MPa, Teflon= 500 Mpa, Polyurethane= 25 MPa.

5. Determine the bandwidth of the catheter/shaker systems. Use the "half-power" definition of bandwidth, i.e. the ratio $|V_{out}/V_{in}|$ is -3dB at the cut-off frequency. Comment on the bandwidth as a function of catheter properties, particularly for the materials that you used in the tests.

Write-up notes

Your 2-page write up should include the following:

Introduction:

Problem statement and objective of the lab. Background for frequency response and catheters, how is this info valuable with clinical relevance?

Materials and methods:

Describe your system for the experiment and how you will use it to determine the desired quantities. Note any calibrations and limitations (mistakes!) This section should be fairly brief, and simple overview.

Data/Analysis/Results:

Information on catheter properties (geometry and material properties)

Table of experimental and theoretical results as described above in (5) in "For *each* catheter"

Plot of amplitude vs. freq. and another plot of phase vs. freq. for all catheters and pressure gauge itself. Should be Bode plots (log scale for frequency, use dB on a linear scale for amplitude, and degrees on a linear scale for phase shift). Each of the 2 plots will have 4 curves (3 catheters and no catheter). Color really helps here!

Bandwidth values for each catheter

Give all frequencies and bandwidths in Hz (as opposed to rad/sec)

Discussion topics to include (others are OK, but make sure to comment on these):

Significance of the bandwidth of these systems, and how this bandwidth relates to physiological situations.

Comments and explanations for differences between theory and experimental values of resonance and damping (there are typically inaccuracies in both experimental and theoretical values).

What would be the effects of air bubbles in the system (make sure the mention compliance changes)? What might happen with a blood clot in a catheter?

Relationship of geometry and material properties to catheter bandwidth.

Comments on the positives and negatives of your specific catheters, and in general, how the catheter properties should be optimized for clinical use.

Limitations of the experiment.

** Remember to attach your signed Raw Data to the back of the 2-page report! **