PLAB 5: Biological Signal Conditioning

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Abstract:

EKG recordings can provide valuable information in diagnosing patient heart function, dysfunction and disease. A clear recording can enhance the ability of a physician to identify abnormalities and take corresponding action. This lab explored the construction of a simple analog EKG amplifier that produced relatively clean Lead I EKG recording with identifiable wave characteristics. Given the 5 bioamplifier design considerations (High Input Impedance, Electrical Isolation, Low Output Impedance, High Signal to Noise Ratio and High CMRR), as well as two other EKG design considerations (Electrode Attachment adds DC component and Contact Resistance, and Noise at 60Hz), component selection and band pass filter construction served to compensate. Results were clear enough to take amplitude and rate measurements of the resultant EKG. Later FFT analysis demonstrated that by combining a low pass filter that attenuated noise at frequencies above its cutoff, and a high pass filter that attenuated noise below its cutoff frequencies, a successful band pass filter was created to reduce noise on either side of the target frequency band, increasing SNR. Theoretical bode plots were created to verify this general behavior.

Results:

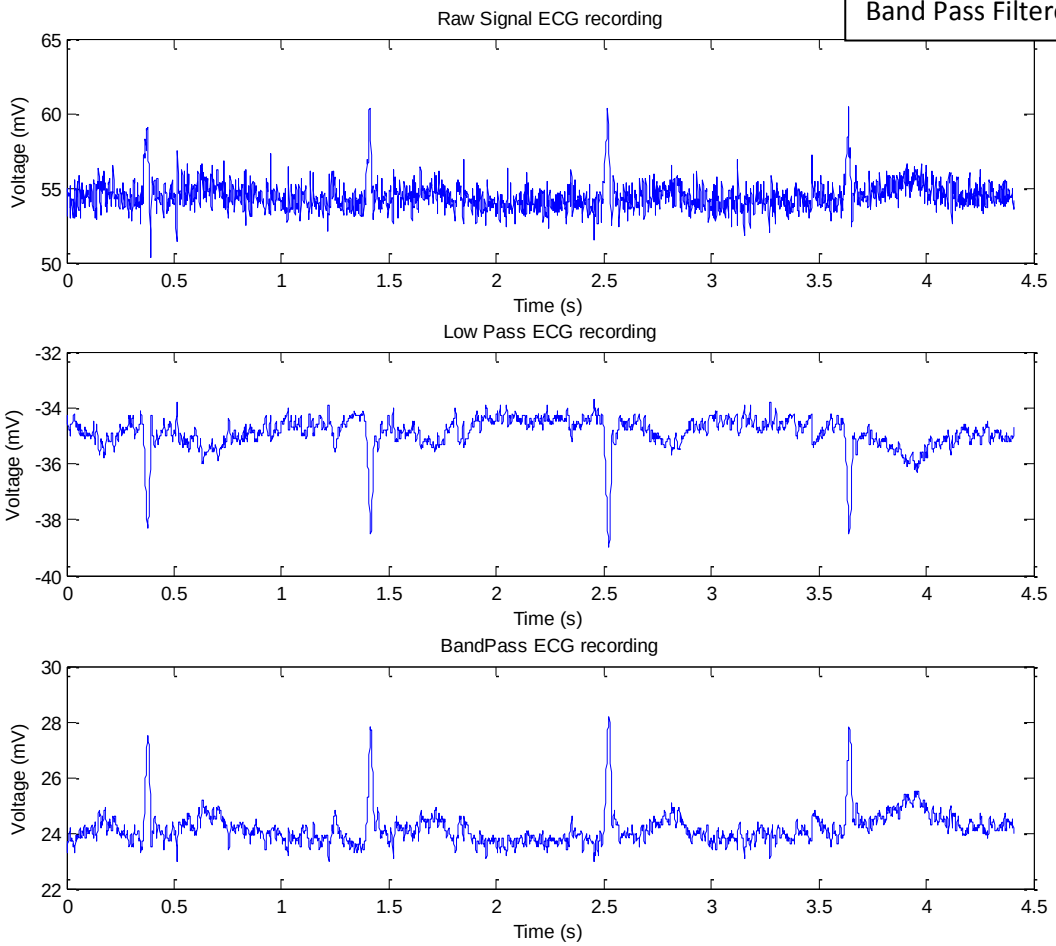
Measurements for P wave, QRS complex and heart rate are shown in table 1. They are averages from 10-12 heart cycles.

	Average Value
P-wave Amplitude (mV)	1.300
P-wave Duration (s)	0.111
QRS Complex Amplitude (mV)	4.325
QRS Complex Duration (s)	0.055
R-R Duration (s)	1.047
Heart Rate (bpm)	57.307

Table 1: ECG Statistics from the volunteer's recording averaged over several cardiac cycles

The ECG signals shown in Figure 1 cover 4 heart cycles. The raw signal, low pass filtered signal and bandpass filtered signal are shown.

Figure 1: ECG recordings including Raw Signal, Low Pass Filtered and Band Pass Filtered



The FFTs for the raw, low pass filtered and band pass filtered signals are shown in Figure 2.

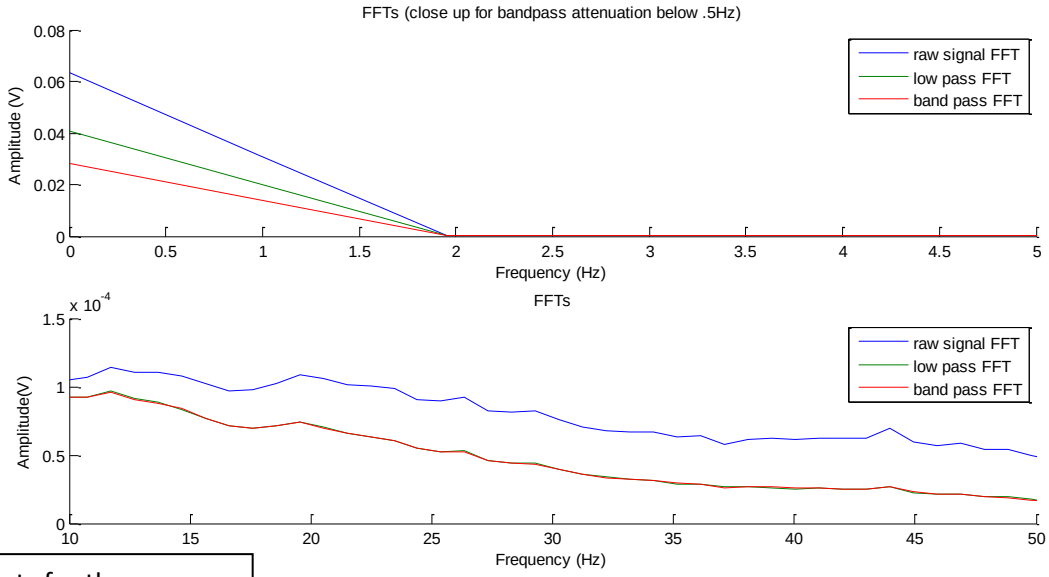


Figure 2: FFT plots for the raw signal, low pass filtered signal and band pass filtered signal

Bode plots for low pass, high pass and BandPass diagrams are shown in figure 3. The transfer functions used were calculated using the parameters in Table 2, and equations 1 and 2 (simplified versions assuming R1 = R2). Cutoff frequencies of 23.4Hz for the low pass, and 0.48 Hz for the high pass were obtained using the formula supplied in both eqn 1.1 and 1.2 from the PLab manual shown below as Eqn 3.

Parameter:	R1	R2	C
Low Pass Filter Value:	68kΩ	68kΩ	0.1µF
High Pass Filter Value:	100kΩ	100kΩ	3.3µF

Table 2: Parameter Values used in circuits and calculations of transfer functions

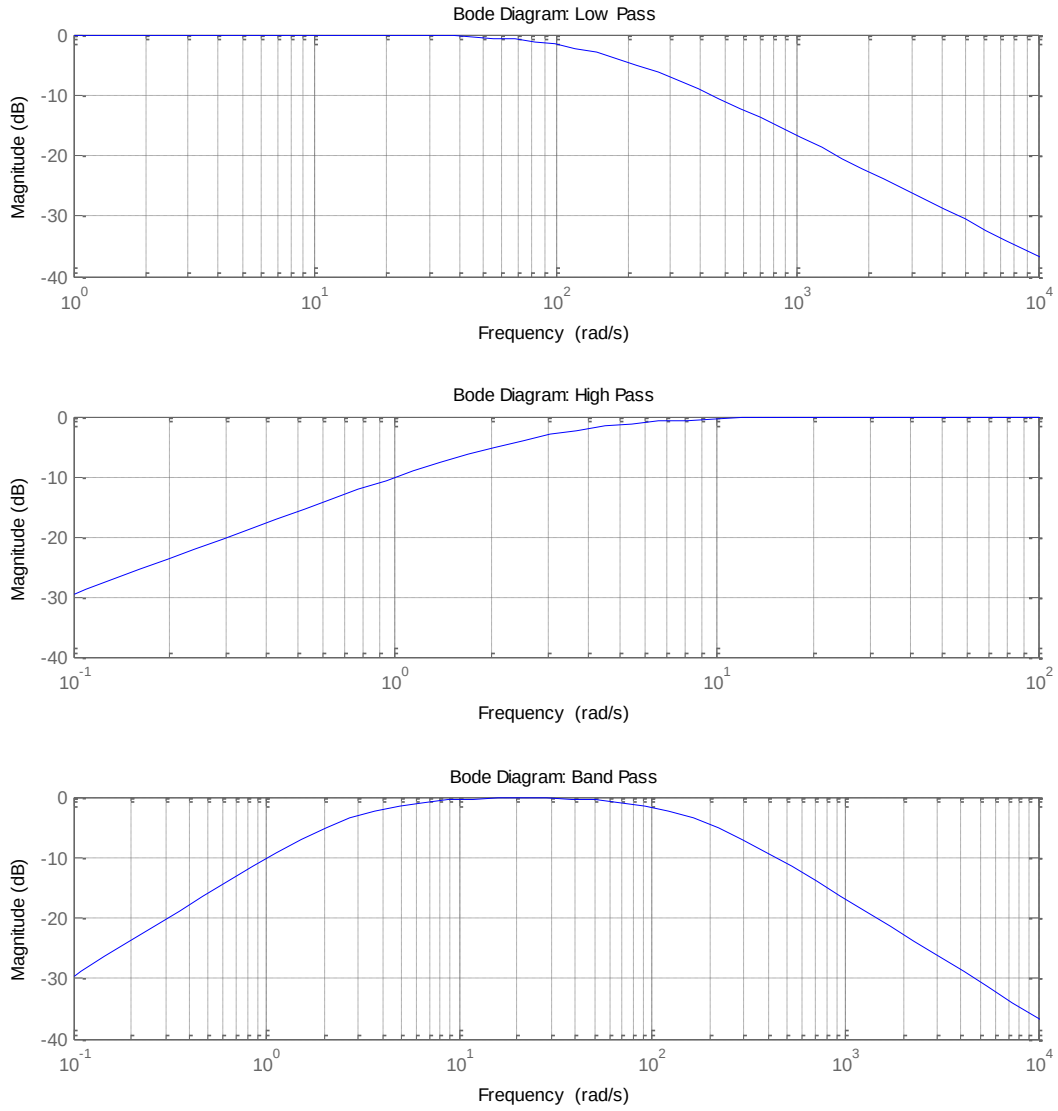
If R1=R2 the following equations apply.

$$LowPass\ H(s) = \frac{-1}{1 + RsC} \qquad (Eqn.\ 1)$$

$$High\ Pass\ H(s) = \frac{-RsC}{RsC + 1} \qquad (Eqn.\ 2)$$

$$f = \frac{1}{2\pi RC} \qquad (Eqn.\ 3)$$

Figure 3: Theoretical Bode Plots for Low pass, High pass, and Band Pass filter designs



Discussion:

The 5 bioamplifier design considerations are High Input Impedance, Electrical Isolation from the Patient, Low Output Impedance, High Signal to Noise Ratio and High CMRR. The 2 special ECG design considerations are Electrode Attachment adds DC component and Contact Resistance, and Noise at 60Hz.

The "high input impedance" consideration was covered by using the INA118 instrumentation amplifier which has very high input impedance (~10Mohms according to datasheet). This ensures the measured signal is not degraded by voltage division reducing the potency of the input voltage to the circuit.

The "electrical isolation from the patient" consideration was covered by the presence of surge protection on any power-source in the lab and the absence of other possible sources of unwanted currents. There wasn't much around in lab to send unwanted or dangerous currents.

The "Low output impedance" consideration was achieved by not adding any power draining resistance between the INA118 and the recording hardware (powerLab) for LAB Chart. This ensured enough power was left to see the signal.

The "high signal to noise ratio" consideration was achieved by band-passing the signal in a region from 0.48Hz to 23.4Hz. This is a frequency range close to the signal itself (according to fig 1.6 in the Plab Manual, ECGs are on the order of 0.01-100Hz). This provides the best possible SNR. This was achieved using a low pass and a high pass filter in combination to form a band pass filter that attenuated signals that were unwanted (such as 60Hz noise and DC offset). Using a differential amplifier allowed a high signal to noise ratio by eliminating the difference between the two signals in the differential amplifier to better increase visibility of the desired signal.

The "High CMRR" consideration was accomplishing by picking a differential amplifier (LM741) with a high CMRR (90dB) to be used throughout the circuit. Instrumentation amplifier INA118 had a high CMRR as well (110dB). The high CMRR of these components help minimize common-mode voltage derived interference.

The "Electrode Attachment adds DC component and Contact Resistance" design consideration for ECGs was circumvented by using an amplifier with a very high input impedance and by cutting out extremely low frequencies associated with DC offset (using the band pass filter that attenuates the

lower voltages). Removing the low frequencies associated with DC offset means one doesn't have to worry about the relatively enormous dc offset voltages that come from electrochemical processes between the electrode and the patient's skin

The "Noise at 60Hz" consideration was avoided with the use of differential amplifiers that drastically cut down on noise from common mode interference. The band pass filter design attenuates signals at frequencies outside its cutoffs including 60Hz noise. The general practice of clean circuit formation (ie: not bumping wires, or sloppy bread board layouts) helped as well.

Electrical isolation was handled poorly, although the effects weren't very evident where it mattered. We could have isolated the circuit and the electrodes in a Faraday cage, maybe used conducting electrode gel. But either way, the added circuitry components in the band pass compared to the low pass may have allowed a lot more noise into the band pass recordings. The high CMRR criteria was achieved by using components with a high CMRR and seemed to work well given the negligible effects of noise in most regions despite poor electrical isolation. Some more sophisticated filters, higher quality circuit components, and better shielding could have increased the SNR, but it was adequate for the needs of this lab.

The ECG signals obtained were relatively clean given the manner of the recording. Each wave was discernable and there wasn't much drift of the overall signal. The DC offset was removed and the attenuation of noise at higher frequencies was adequate. The largest contributor to the clean signal was probably the band pass behavior of the device.

The INA 118 was a good choice, because it has a very high input impedance (~10MΩ), a high gain (R_G =2.7kΩ), and a high CMRR (110dB). The high input impedance fulfills the "high input impedance" design consideration for a bioamplifier, by ensuring the measured signal is not degraded by voltage division reducing the potency of the input voltage to the circuit. The high CMRR fulfills the "high CMRR" design consideration for a bioamplifier, helping to minimize common mode voltage derived interference. The high gain helps increase the amplitude of the signal viewable by labchart.

The low pass filter allowed all frequencies below its cutoff frequency of 23.4 Hz through, and the high pass allowed everything above its cutoff frequency of 0.48Hz. Once combined, the band pass behavior allowed frequencies in the window 0.48-23.4Hz through. These behaviors are shown clearest

in the frequency domain bode plots where the bode plot for low pass is monotonically increasing and the bode plot for high pass is monotonically decreasing. Putting them together, the bode plot for the band pass is parabolic with a small plateau band of throughput (no attenuation) in the middle, dropping off to either side of the frequency range where attenuation picks up rapidly. In the FFTs, we can see the low pass filter does not attenuate the signal nearly as much as the band pass at low frequencies. It was expected that the raw signal and the low pass would be close for the initial (pre 23.4Hz) frequency range, but data showed a bit of attenuation for low frequencies using the low pass compared to raw signal. Band pass was definitely more attenuation at low frequencies however. Beyond the cutoff for the band pass, both the low pass and the band pass had nearly identical behavior, attenuating signals beyond the cutoff frequency where the raw signal came through. There was an odd feature worth noting. At around 60Hz where electrical noise was present, the band pass had a significantly larger spike than did the low pass. This was not expected, however it may be the result of extra circuitry that became significantly cluttered when making the band pass filter compared to the low pass. In the time domain, the signal had far less noise after the low pass filter was applied. After the low pass, the ECG was clearly identifiable with lead I wave formations but the signal was inverted (flipped upside down). The further addition of the bandpass inverted the signal again (flipped it right side up) but didn't greatly improve the signal to the naked eye. This was not completely expected. Expected results were the elimination of drift of the baseline, however the recording didn't contain much drift to begin with.

References:

1. Plab Manual
2. ECG data borrowed from Paras Vora, Mathew Everett and Karthik Krishnan
3. https://engineering.purdue.edu/ME365/Textbook/chapter7.pdf
4. http://keisan.casio.com/has10/SpecExec.cgi?id=system/2006/1258032649
5. http://keisan.casio.com/exec/system/1258032632
6. http://www.ti.com/lit/ds/symlink/ina118.pdf
7. http://www.ti.com/lit/ds/symlink/lm741.pdf
8. Patricia Widder

Discussants:

Lauren Bedell, Paras Vora, Maeve Woeltje, Matt Everett

Code:

```
clear all; close all; clc;

data = load('analysis_3_data.txt');
time = data(:,1)-data(1,1);
raw_signal = data(:,2);
low_pass = data(:,3);
band_pass = data(:,4);

figure;
subplot(3,1,1)
plot(time,raw_signal);
title('Raw Signal ECG recording'); xlabel('Time (s)'); ylabel('Voltage (mV)');
subplot(3,1,2)
plot(time,low_pass);
title('Low Pass ECG recording'); xlabel('Time (s)'); ylabel('Voltage (mV)');
subplot(3,1,3)
plot(time,band_pass);
title('BandPass ECG recording'); xlabel('Time (s)'); ylabel('Voltage (mV)');


load('frequencyfft.mat');
load('lowpassfft.mat');
load('rawfft.mat');
load('bandpassfft.mat');

figure; subplot(2,1,1); hold all;
plot(Frequency0x28Hz0x29,RawSignal0x280x29); plot(Frequency0x28Hz0x29,LowPassSignal0x280x29);
plot(Frequency0x28Hz0x29, BandPassSignal0x280x29);
title('FFTs (close up for bandpass attenuation below .5Hz)'); xlabel('Frequency (Hz)');
ylabel('Amplitude (V)');
legend('raw signal FFT','low pass FFT','band pass FFT');
xlim([0,5]);

subplot(2,1,2); hold all;
plot(Frequency0x28Hz0x29,RawSignal0x280x29); plot(Frequency0x28Hz0x29,LowPassSignal0x280x29);
plot(Frequency0x28Hz0x29, BandPassSignal0x280x29);
title('FFTs'); xlabel('Frequency (Hz)'); ylabel('Amplitude(V)');
legend('raw signal FFT','low pass FFT','band pass FFT');
xlim([10,50]);

figure;
subplot(3,1,1);
R_low =68000;
C_low = 0.1*10^-6;
s=tf('s');
H_low = -1/(1+R_low*s*C_low);
bodemag(H_low)
title('Bode Diagram: Low Pass');
grid on

% figure;
subplot(3,1,2);
R_high = 100000;
C_high = 3.3*10^-6;
s = tf('s');
H_high = -R_high*s*C_high/(R_high*s*C_high+1);
bodemag(H_high);
title('Bode Diagram: High Pass');
grid on;

% figure;
subplot(3,1,3);
H_band = H_low*H_high;
bodemag(H_band);
title('Bode Diagram: Band Pass');
grid on;
```