Signal Filtering

ADINSTRUMENTS

This technique note was compiled by ADInstruments Pty Ltd. It includes figures and tables from S.S. Young (2001): "Computerized data acquisition and analysis for the life sciences". For further information on any of the following topics, please refer to this textbook.

SUMMARY

Filters play a vital role in data acquisition systems to remove selected frequencies from an incoming signal and minimize artifacts (i.e. baseline wander, mains interference and noise).

Analog/hardware filters are used to filter the incoming, continuous signal before it is sampled by the analog to digital converter (ADC). These filters are included in ADInstruments front-ends (Bio Amps, Bridge Amps etc) and in some of the PowerLab units themselves.

ADInstruments front-ends initially amplify the signal to a level suitable for filtering. The analog filters are then used to remove unwanted frequencies, following which further amplification is performed before digitization. Filtering the signal prior to full amplification is essential for biopotential measurements to improve the signal to noise ratio.

The analog/hardware filters included in the S, SP and 30 series PowerLabs provide additional filtering to remove high frequency components (anti-aliasing low-pass filters) before the signal is digitized.

Additional Digital/Software filters are included in Chart and filter the data after it has been sampled and recorded by the PowerLab.

Digital filters are used post data acquisition and are advantageous because:

- It is possible to design digital filters that are impractical to make in analog form
- They are stable over time and provide consistent, reproducible signal filtering
- In Chart, they can be applied after data acquisition while the raw data is retained

However, a disadvantage of post-acquisition digital filtering is that unless analog/hardware filters have also been used prior to digitization, any noise or baseline offset present in the signal has also been amplified and will have a negative effect on signal resolution.

Important Terminology

To understand the basics of filtering, it is first necessary to learn some important terms used to define filter characteristics. While these terms apply to all types of filters, for simplicity the following examples will only refer to low-pass filters.

- Cut-Off Frequency (fc): Also referred to as the corner frequency, this is the frequency or frequencies that define(s) the limits of the filter range(s). It is the desirable cut-off point for the filter.
- Stop Band: The range of frequencies that is filtered out.
- Pass Band: The range of frequencies which is let through and recorded.
- Transition Band: The range of frequencies between the passband and the stopband where the gain of the filter varies with frequency.

Low-Pass Filter:

A low-pass filter allows signal frequencies below the low cut-off frequency to pass and stops frequencies above the cut-off frequency. It is commonly used to help reduce environmental noise and provide a smoother signal.

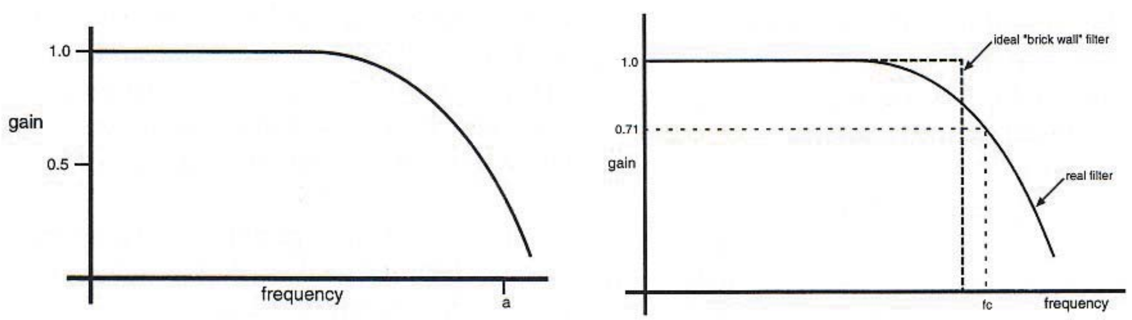


Figure 1. Effect of low-pass filtering on signal gain (S.S. Young, 2001).

A simple way to understand how a filter works is to plot signal frequency against signal gain (Figure 1). When a signal is unfiltered, it is recorded at a gain of 1, that is, the full signal is being recorded. However, when a signal is filtered, the gain (amount of signal recorded) is reduced (< 1). The frequency at which the gain starts to decrease by a reasonable amount is the cut-off (corner) frequency (fc).

Ideally, low-pass filters would provide a gain of 1 below the cut-off frequency and a gain of zero above this cut-off value (i.e. no signal is recorded). However, filters are imperfect and some level of the signal is always recorded. This reduction in signal gain after the cut-off frequency is commonly referred to as signal attenuation and is commonly presented in decibel (dB) units. While signal attenuation is progressive rather than an ideal "all-or-none" process, all low-pass filters have a frequency (fa; Figure 1) above which the gain is very small (the signal is virtually non-existent).

Note: Decibels are not units of measurement in the conventional sense (ie meter or joule) but represent a ratio, thereby describing how much bigger or smaller one thing is compared to another.

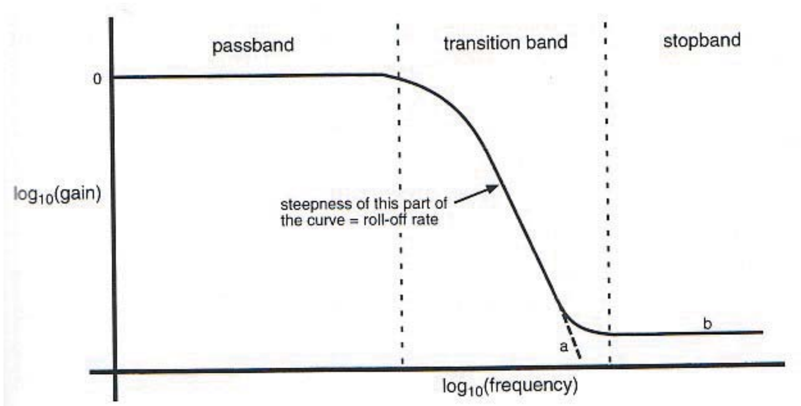


Figure 2. Filter Bands (S.S. Young, 2001).

All signal frequencies below the cut-off frequency are referred to as the passband (Figure 2). Within the passband, the gain should ideally be equal to 1; however, filter response characteristics may result in some form of passband ripple. A measure of how well the filter maintains this pass band gain is called passband flatness.

All signal frequencies above the cut-off frequency are referred to as the stopband. Within the stopband, the gain should ideally be equal to 0; however, there is always some level of signal within this region (although it is dramatically attenuated so as not to affect the recording).

The region between the pass- and stop-bands is referred to as the transition band or transition width. This width (in Hz) depends on how sharply the filter response drops from the pass band to the stop band. Related to this is the roll-off rate, which, for low-pass filters is the rate at which the signal gain decreases when the signal is above the cut-off frequency. The narrower the transition band, the steeper the roll-off. It is also important to note that the narrower the transition width of a filter the more ringing there will be in the step response. The following graph shows a step input signal (red) and the responses of two digital filters both with a cut-off frequency of 20Hz. The blue filter has a transition width of 1Hz while the green filter has a transition width of 40Hz (Figure 3).

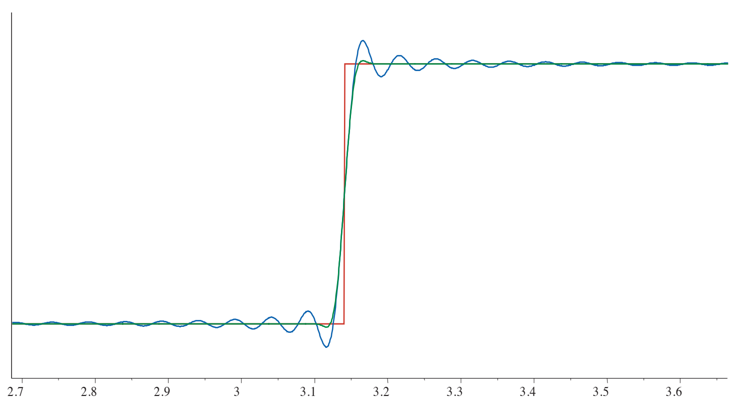


Figure 3. Effect of transition width on low-pass filters.

Other Filter Types:

High-Pass Filters:

A high-pass filter allows frequencies higher than the cut-off frequency to pass and removes any steady direct current (DC) component or slow fluctuations from the signal. Such filters are often used to stabilize the baseline of a signal (i.e. minimize baseline drift in an ECG signal). A useful comparison of the effects of a low-pass filter in comparison to a high-pass filter is presented in Figure 4.

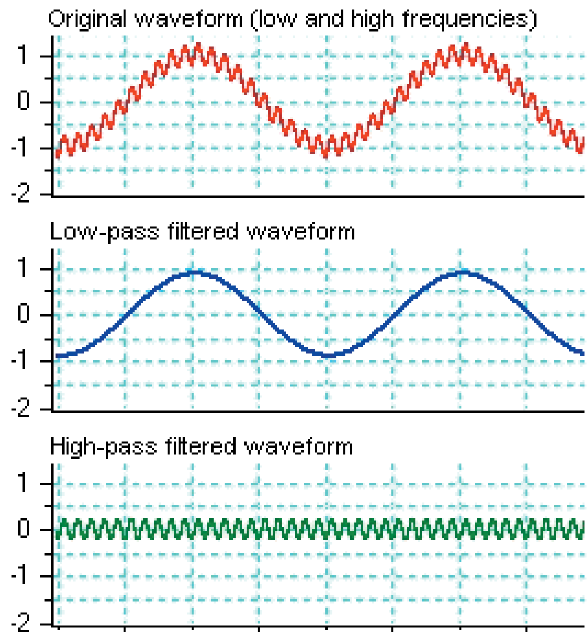


Figure 4. Effects of low and high pass filters on a signal waveform.

Mains Filters:

Mains interference (50/60 Hz) from power lines etc is not static and may vary during the day with the degree of variation greater in some countries than others. Therefore, to remove mains noise from a signal use the adaptive mains filter in the PowerLab. This filter tracks and removes the mains noise (including the harmonics of the fundamental) with minimal distortion to the recorded signal. Mains filters are digital and included in Chart versions for use with PowerLab /10, /20, /25 and /30s.

Do NOT use a notch filter to remove mains frequency noise as they are not ideal and may distort signals of interest in physiology, particularly ECG recordings. Notch filters for mains filtering have been predominantly superceded but there are some specific situations in which they are the best choice.

Notch Filters:

A notch filter removes a particular frequency from a signal and has a frequency response that falls to zero over a narrow range of frequencies (i.e. a 50 Hz notch may block signals from 49.5 – 50.5 Hz). Notch filters are available in all ADInstruments Bio Amps (Animal [ML136], Single [ML132], Dual [ML135] and Dual Bio/Stim [ML408]).

One problem with sharp notch filters is ringing. This ringing occurs at two frequencies either side of, but close to, the notch frequency. This is a problem with ECG signals where the spiky R wave can drive the ringing.

Narrow Band-Pass Filters:

Narrow band-pass filters are used to remove all signal frequencies except for a particular band (i.e. to record 8-12 Hz activity in EEG recordings). Frequencies either side of this band are not passed.

Band-Pass Filters:

A band-pass filter may be used to pass a larger range of frequencies (i.e. 0-100 Hz EEG activity). Frequencies either side of this band are not passed.

Band-Stop Filters:

A band-stop filter blocks a certain range of frequencies and allows frequencies either side of this range to be passed (i.e. You may wish to block Beta [β1: 16 – 32 Hz] activity from an EEG recording but record all other frequencies between 0 – 15 Hz and 33 -100 Hz).

Cut-Off Frequency and Center Frequency

For low-pass filters, the cut-off frequency is the frequency at which higher frequencies are blocked and lower frequencies are passed. For high-pass filters, the cut-off frequency is the frequency at which higher frequencies are passed and lower frequencies are blocked. Band-pass and band-stop filters have two cut-off frequencies (representing lower and upper limits).

For notch filters, the center frequency is the component frequency which is removed when the filter is applied to a waveform. For narrow band-pass filters, the center frequency is the frequency which is allowed through.

Transition Width (Filter Sharpness or Roll-off)

As mentioned earlier, all filters are imperfect. For example, a 200 Hz low-pass filter might leave frequencies up to 150 Hz untouched, reduce a 200 Hz signal to half its original amplitude and reduce the amplitude of higher frequencies more and more. However, it is not an "all-or-none process".

The transition width, or filter sharpness, is the band of frequencies for which the output amplitude is between certain percentages of the input amplitude (between 1% and 99% in the case of Chart's digital filters). In some situations, a narrow transition width or "sharp" filter is desirable. However, if the transition width is too small it can take too long to compute the filtered output. Furthermore, if a signal has sharp steps (such as a square wave), a small transition width can cause ringing in the step response.

The digital filters feature in Chart provides definition of transition width in 1 of 3 modes:

- Auto-Adjust

  Adjusts the transition width to 20% of the cut-off frequency unless this means an excessive calculation time, in which case the transition width will be increased, thereby resulting in a filter that is less sharp.
- Set to 20% of cut-off frequency

  Sets the transition width to 20% of the cut-off frequency.
- User-Defined

  Allows the user to specify a transition width (subject to absolute limits) in the "transition width" dialog.

IMPORTANT:

The smaller the transition width (in Hz), the longer the filter will be for a given sampling rate, where the filter length is the number of input samples that need to be processed to generate an output sample. This is because bandwidth (in Hz in the frequency domain) is inversely proportional to time (in seconds in the time domain).

A sharp filter has a narrow transition bandwidth and needs to look at a long stretch of the input before producing output. This is because a sharp filter has to distinguish between frequencies which are very close together, attenuating some frequencies but leaving others untouched. For example, if two sine waves of slightly different frequency (one in the pass-band and one in the stop-band) were initially in phase with each other, they would gradually go out of phase after a number of cycles; however, you would have to wait a while before you could see that they were different frequencies. The closer they were in frequency the longer you would have wait. In general, a filter has to wait long enough for the two frequencies to go about 180 degrees out of phase with each other, before it can attenuate one but not the other.

Example

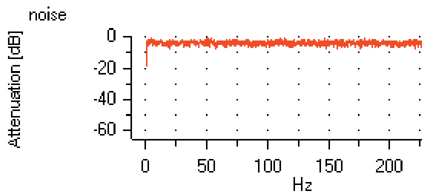
Sampling rate :	1kHz	1kHz
Transition width :	2Hz	4Hz
Length of filter in samples :	1919	959

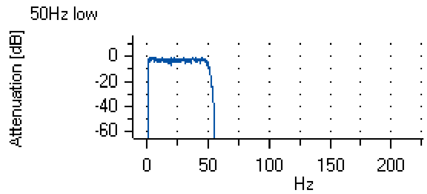
When recording online there will be a delay from when sampling starts until the filter can generate the first output sample. This delay corresponds to the length of the filter in sample periods and is displayed when configuring the digital filter settings. If the user finds this delay unacceptably long then they will need to increase the transition width to obtain a smaller delay value (and a correspondingly less sharp filter).

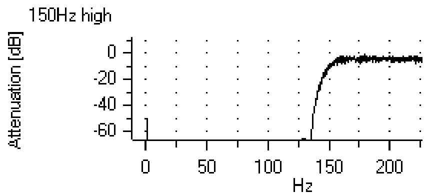
The transition width will be seen as a blank space at the start of the Chart recording; however, all subsequent data is provided in real time (not delayed).

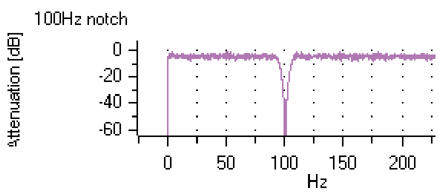
Example Filter Outputs

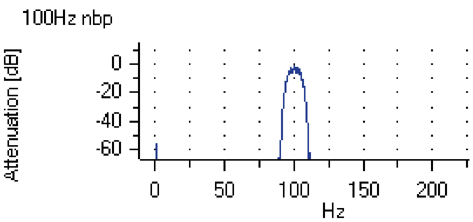
Example outputs of various filter types applied to a single waveform are shown below. The outputs were generated in Chart's Spectrum Window. The top image shows the spectrum of the unfiltered noise; the next six show the output from a filter of each type.

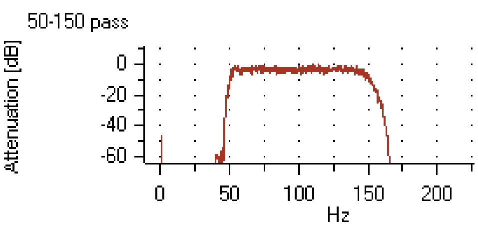


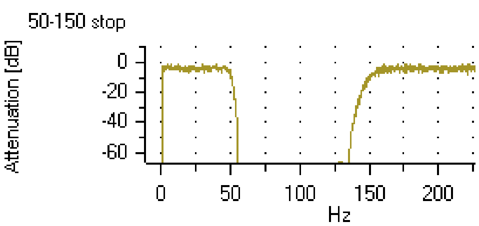












Common Analog/Hardware Filters

Analog Filters

There are 4 classic analog filter types: Butterworth, Chebyshev, Elliptic and Bessel. There is no ideal filter; each filter is good in some areas but poor in others.

- Butterworth: Flattest pass-band but a poor roll-off rate.
- Chebyshev: Some pass-band ripple but a better (steeper) roll-off rate.
- Elliptic: Some pass- and stop-band ripple but with the steepest roll-off rate.
- Bessel: Worst roll-off rate of all four filters but the best phase response. Filters with a poor phase response will react poorly to a change in signal level (i.e. signal ripple; Figure 6). The slow roll-off and the good phase response of the Bessel filter means that it has a step response with no ringing (Figure 6). Even a filter with a perfect phase response will exhibit ringing if it has a sharp cut off.

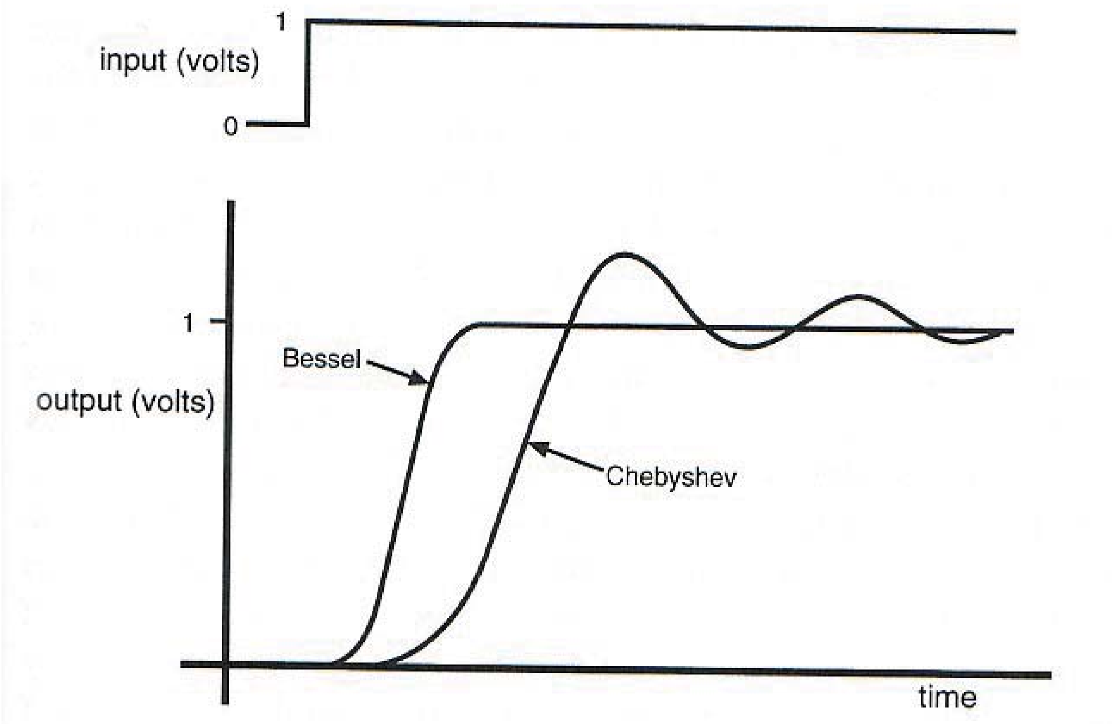


Figure 6. Effects of poor phase response on signal filtering (S.S. Young, 2001).

Comparison of FIR and IIR Digital Filters

Digital, software filters within Chart implement finite impulse response filters (FIRs) rather than infinite response filters (IIR) technology because of their linear phase response and the performance benefits that result from being able to start the calculation part way through the data rather than always having to start at the beginning. When using FIR filters, it is common to specify the transition width rather than the roll-off rate since the roll-off rate is not a constant number (unlike classic IIR or analogue filters). For example, if you set the low pass filter to a 45 Hz cut-off and a 10 Hz transition band width, its response will be 0.99 at 40 Hz, 0.5 at 45 Hz and 0.01 at 50 Hz.

A Guide to Amplifier Settings for Common Biological Recordings

It is important to determine appropriate filter and sampling rate settings for all signals prior to recording. The Spectrum Window in Chart may be used to determine maximum signal frequency of pre-recorded data, if required.

A simple guide for low-pass filter & sampling settings (S.S. Young, 2001):

Step 1: Determine the maximum frequency (fmax) of the signal to be recorded.

Step 2: Select a low-pass filter with a cut-off frequency 1.3 to 2 times higher than fmax. The cut-off frequency should NOT be identical to fmax because some of the signal component may be lost due to filter imperfections.

Step 3: Decide on the Nyquist frequency. A typical value is 3 to 6 times the filter cut-off frequency.

Step 4: Sample at twice the Nyquist frequency

For example if the fmax of a signal is 30 Hz, then the low-pass filter cut-off should be 40 - 60 Hz. The Nyquist frequency will be 120 - 360 Hz and the sampling rate should be 200 - 400 Hz.

Sampling Rates for Various Signals

Signal	Sampling Rate
• Temperature • Ionic Composition • Other variables that do not change much over a period of a few seconds	5 – 20 Hz (or less)
• Blood pressure (fluid-filled transducers) • Respiratory gas temperature • Joint angle (goniometry) • ECG* • EEG	400 Hz – 4 kHz *Varies according to species
• EMG (variable according to muscle types)	600 Hz – 4 kHz
• Blood Pressure (Millar transducers) • All studies involving impact such as force plate studies	2 – 3 kHz
• Extracellular Recordings	10 kHz - 20 kHz
• Intracellular Recordings	40 kHz – 200 kHz

Modified table from S.S. Young, 2001.

The sampling frequency must be at least twice the highest frequency component present in the signal to be sampled. Signal frequencies vary dramatically between species.

Suggested Amplifier Settings

1) ECG:

Range:	10 - 20mV
Sampling rate:	
Mouse	4kHz
Rat	2 - 4 kHz
Rabbit	1 - 2 kHz
Guinea Pig	1 - 2 kHz
Dog	400 Hz – 1kHz
Pig	400 Hz – 1kHz
Human	400 Hz – 1 kHz

*Should be 15-30 sample points in the QRS Complex

ECG signals contain limited information above 100 Hz

- High Pass: 0.3Hz to minimize iso-electric (baseline) drift
- Low Pass: ≤ 25 - 50 % sampling rate (typically 200 - 1kHz low-pass cut-off)
- Notch: Do NOT use as may distort ECG signal.
- Mains: Will suppress electrical interference without distorting signal.

2) EEG/ECoG:

Range: 200 - 500µV

Sampling Rate: 400 - 1000Hz

EEG signals contain limited information above 50 - 100 Hz (Humans, Rat, Mice, Lambs)

- High-Pass: 0.1 or 0.3
- Low-Pass: 100 – 200 Hz cut-off
- Notch: No (unless the user is aware of affect on signal)
- Mains: Yes

Frequencies of Particular Interest:

- Delta: 0.5 - < 4 Hz
- Theta: 4 - < 8 Hz
- Alpha: 8 - < 12 Hz
- Spindles: 12 – 14 Hz
- Sigma: 12 - < 16 Hz
- Beta: (ß1) 16 – 32 Hz
- Beta: (ß2) 30 – 60 Hz

3) EOG

Range: 200-500 µV

Sampling Rate: 400Hz – 1kHz

EOG signals contain limited information above 50 Hz (Humans, Rat, Mice, Lambs)

- High-Pass: 0.1 or 0.3
- Low-Pass: 100 Hz cut-off
- Notch: No (unless the user is aware of affect on signal)
- Mains: Yes

4) EMG

Range:	Variable between species and muscle types.
Sampling Rate:	2 to 4 kHz

EMG signals contain variable frequencies; however, most common frequency bands recorded are 0.3 Hz to 1 or 2kHz.

- Notch: No (unless the user is aware of affect on signal)
- Mains: Yes

Removing ECG artifacts, particularly in intrathoracic recordings (ie esophageal EMG) often requires difficult template matching (not available in Chart). If the customer needs to remove low frequency artifacts > 2 Hz (i.e. respiratory or ECG artifacts) prior to recording/digitizing the signal, then the high-pass filters available in the Animal Bio Amp (ML136), Bio Amp (ML132), Dual Bio Amp (ML135) or Dual Bio Amp/Stim (ML408) are required. The 8 (GT205) and 16 (GT201) Channel Bio Amps may not be suitable for this application as they have limited high-pass filter settings (see below) and the required filtering can only be applied after recording the data in Chart.

5) Blood Pressure

Typical Heart Rates:

- Humans: 80-200 bpm (max 4Hz)
- Guinea Pigs/Rats: 200-400 bpm (max 7Hz)
- Mice: 500-700 bpm (max 12 Hz)

For accurate reproduction of dicrotic notches and BP harmonics, sampling speeds of 50 to 100 times the heart rate (in Hz) are desirable. As a minimum, the low-pass filter frequency should be 10 times the heart rate (in Hz) and half the sampling rate.

Sampling Rates

- Humans: 400 Hz
- Guinea Pigs/Rats: 2 kHz
- Mice: 2 kHz

Recommended Low Pass Cut-Off Frequency

- Humans: 100 - 200Hz
- Guinea Pigs/Rats: 100 Hz – 1 kHz
- Mice: 100 Hz – 1 kHz

Current Analog/Hardware Filter Settings available with ADI Bio Amplifiers.

High-Pass Filters		Low-Pass Filters	
ADI Bio Amps	**GT201 & GT205**	**ADI Bio Amps**	**GT201 & GT205**
0.02 Hz††*	-	-	1 Hz
0.1 Hz††	[0.1 Hz]	-	2 Hz
0.3 Hz	-	-	5 Hz
-	0.5 Hz	-	10 Hz
1 Hz	-	20 Hz **	20 Hz
-	2 Hz	50 Hz	50 Hz
3 Hz*	-	100 Hz	100 Hz
10 Hz	-	200 Hz	[200 Hz]
30 Hz†	-	500 Hz	[500 Hz]
		1 kHz	1 kHz
		2 kHz***	[2 kHz]
		5 kHz	
			[25 kHz]
EEG Mode*	**-**	**EEG Mode***	**-**
0.03 s	-	3 Hz	-
0.1 s	-	10 Hz	-
0.3 s	-	30 Hz	-
1 s	-	60 Hz	-
		120 Hz	-

ADI Bio Amps include the Animal Bio Amp (ML136), Bio Amp (ML132), Dual Bio Amp (ML135) & Dual Bio Amp/Stimulator (ML408).

The GT201 and GT205 are the third-party 16 and 8 Channel Bioamplifiers, respectively.

††Visible but not actively available with Chart for Macintosh.

†Available only on Dual Bio (ML135) with Chart for Windows.

*Not available with Dual Bio Amp/Stimulator (ML408) and 4/25T (ML865)

**Only available on Dual Bio Amp/Stimulator (ML408) and 4/25T (ML865)

***Only available on Dual Bio (ML135), Dual Bio/Stim (ML408) and 4/25T (ML865)

Italicized and underlined numbers indicate hardware settings available on the 8 and 16 channel bio amps (GT201 & GT205). However, additional filter settings (normal font) are available via the PowerLab Input Amplifier when using the GT201 and GT205. Settings within square parentheses are irrelevant depending on the filter setting of the multi-channel bio amps.

It is always important to ask the customer whether they need any form of specialized filtering for their signals and whether analog/hardware or digital filtering is required.

In some cases (particularly in neurophysiology), high-frequency, high pass filters may be required and special headstages with additional amplification and filter settings are required.