Estimation of Blood Oxygen Saturation and Heart Rate Using Pulse Oximetry

Merrill Datwyler[1] and Kristin Rominger[1]
1 – Department of Bioengineering, University of Utah

Introduction

Pulse oximeters are widely used in clinical settings to measure and display blood oxygen saturation (SpO_2), as well as pulse rate. Typically, these devices are clipped onto the finger to allow clinicians to measure both SpO_2 and heart rate quickly and non-invasively. This lab featured the development of a circuit-board pulse oximeter, consisting of both a red light-emitting diode (LED) and an infrared (IR) LED, each with corresponding photodiodes connected to two transimpedance amplifiers preceding a differential amplifier. This circuitry served to output voltages associated with the amount of red and IR light transmitted through finger of three subjects, from which each subject's concentrations of hemoglobin and oxyhemoglobin (and thus SpO_2) were determined. LABVIEW was used to acquire both the red and IR traces under both normal-breathing and held-breath conditions, from which post-acquisition analysis could be performed. This analysis included calculation of instantaneous SpO_2 values over time to determine if each subject's measured blood oxygenation fell within standard ranges for the two breathing conditions, to compare the oxygenation for the two breathing conditions, and to help assess the functioning of the pulse oximeter. In addition, estimation of heart rate using both thresholding and Fourier methods was performed to compare the techniques, to determine if the subject's measured heart rate fell within standard ranges for the two breathing conditions, and to compare the heart rates for the two breathing conditions.

Methods

The red channel of the pulse oximeter circuit was constructed first. This channel consisted of a red LED (660 nm) in series with a resistor, with a red photodiode positioned immediately across from the LED, approximately 2 cm away. The LED and photodiode were positioned such that the active area of the photodiode was centered along the central axis of the LED (0° viewing angle) to maximize the light detected. The photodiode was then connected to two identical transimpedance amplifiers that were connected to a differential amplifier. Fig. 1 shows an overall schematic of the circuit. This design served to increase the gain of the signal, eliminate coupled noise, and provide filtering. The transfer function of this circuit, calculated using circuit analysis, is shown in Eq. 1, where i_p represents the current through the photodiode.

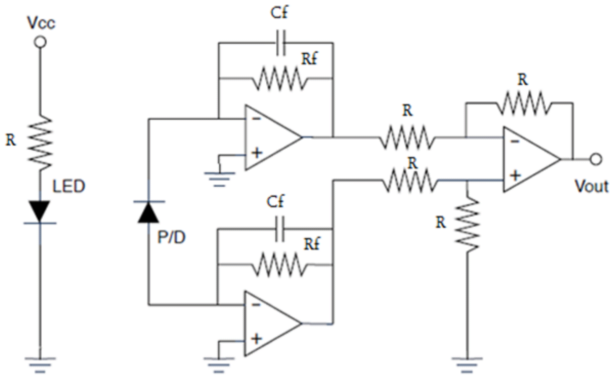


Fig. 1: Circuit Constructed for Each Channel of the Pulse Oximeter

$$H(f) = \frac{V_{out}}{V_{in}} = \frac{-2R_f}{1 + j \cdot 2\pi f \cdot C_f R_f} \quad \text{(Eq. 1)}$$

TL071CP op-amps were used in the construction of the circuit, and resistor and capacitor values were as follows: $R = 200\ \Omega$, $R_f = 1\ \text{M}\Omega$, and $C_f = 10$ nF. Thus, the derived gain of the circuit was approximately 2,000,000, and the cutoff frequency was approximately 16 Hz (well outside of a physiological heart rate frequency). ± 5V was supplied to the op-amps using a Tektronix 250CPS Power Supply. In addition, the output of the circuit was monitored using a Tektronix TBS 1052B-EDU Digital Oscilloscope. This same circuit was duplicated (using the same parameter values) for a separate IR channel. The only difference was that IR LED (940 nm) and photodiodes were used in place of red LED and photodiodes in the sensing part of the circuit. The full setup, including the pulse oximeter circuit, is included in the appendix.

Red and IR voltage traces from each of the three subjects were recorded as follows. Each LED and photodiode was positioned for each of the different fingers, to account for different finger sizes and to allow each LED and photodiode to be as close to the finger as possible without touching. The red LED was positioned closer to the top of the fingertip, while the IR LED was positioned right next to the red LED, closer to the bottom of the fingertip. Each corresponding photodiode was directly across from its LED, on the other side of the inserted finger. A jacket was placed on top of the circuit (and over the subject's hand) to block out any surrounding environmental signals. This step was necessary to acquire usable data. Each subject began by breathing normally for approximately 60 seconds and then held their breath for as long as they could (typically around 20-25 seconds). Subjects were instructed to move as little as possible during this process.

The output voltages from both the red and IR channels of the pulse oximeter were input into LABVIEW using a National Instruments BNC-2110 DAQ converter. In LABVIEW, two separate channels (one each for the red trace and the IR trace) were created, and the data from each of these channels was read inside a timed loop. The timed loop was set with a sampling period of 1 ms to sample the voltages from each channel (however, the actual sampling period deviated from this value and varied throughout the trials). In addition, a Write to Measurement File Icon was place inside the loop to record all traces, as were two waveform charts to display each of the traces as they were being recorded. The LABVIEW block diagram and front panel are included in the appendix.

MATLAB was used in all post-acquisition processing. First, each subject's trace was divided into normal breathing and held-breath sections. Only the part of the held-breath section that was at steady state (*i.e.*, not including the changes as the subject inhaled) was kept. Next, the instantaneous absorption ratio (A) of red light absorbed to IR light absorbed over time was calculated for both breathing conditions for every subject. A moving window was used to evaluate approximately one cycle on either side of the data point being evaluated (since the sampling period varied throughout each trace, the smallest sampling period of each trace was selected when calculating the number of data points, or the window, required when calculating each A value). Each A value was calculated according to Eq. 2, where V_{AC} represents the

amplitude of the (cyclical) trace in the window being evaluated, while V_{DC} represents the mean value of the signal over the window being evaluated.

$$A = \frac{V_{AC}^{red} / V_{DC}^{red}}{V_{AC}^{IR} / V_{DC}^{IR}} \quad \text{(Eq. 2)}$$

Instantaneous blood oxygen saturation (SpO_2) values were calculated directly from the instantaneous A values for both breathing conditions of each subject, according to Eq. 3.

$$SpO_2 = \frac{\alpha_{dHb}^{IR} A - \alpha_{dHb}^{red}}{(\alpha_{dHb}^{IR} - \alpha_{oHb}^{IR})A - (\alpha_{dHb}^{red} - \alpha_{oHb}^{red})} \quad \text{(Eq. 3)}$$

Each a represents the corresponding absorption (or extinction) coefficient of hemoglobin (dHb) or oxyhemoglobin (oHb) in response to red (660 nm) or IR (940 nm) electromagnetic waves. The following a values, referenced from class lecture notes, were used: = 3200 $cm^{-1}M^{-1}$, = 320 $cm^{-1}M^{-1}$, = 690 $cm^{-1}M^{-1}$, and = 1200 $cm^{-1}M^{-1}$.

Each subject's heart rate was estimated for both breathing conditions using two different methods—thresholding and Fourier Transform.

The thresholding technique requires a bit of signal manipulation. Segments of the data, both while normal breathing and while holding breath. We employed the method of baseline correction. For a moving window of 100 data points, the average was taken and then subtracted from the actual data. This provided a nearly homogeneous signal, with a single DC value. Once the signal is in this format, we employed MATLAB's findpeaks command to calculate the number of peaks that were greater than a certain threshold. Findpeaks also allows us to specify the minimum peak width, which also helped us to narrow down those peaks that qualified as peaks. Most of the samples taken from the before and after were less than a minute. In order to extrapolate the heart rates, we needed to calculate the number of beats per second and then multiply by 60. This same analysis was taken for the red and infrared data sets, for each lab partner's and TA's trial runs, for both normal breathing and while holding breath. It was found that the results from the thresholding technique was similar to that of the Fourier transform technique. All that was required to find identical values is to adjust the numerical value of admissible peaks. Those peaks were then identified with arrows to assist us to identify their accuracy.

MATLAB's fft command was used to take the Fourier Transform of a known, simulated trace as well as each experimental trace, converting the time-varying traces into a frequency space spectrum over the range of plus or minus the sampling frequency (f_s). To generate the known trace, the vector $y = 10 \cdot \sin(6\pi t) + 10$ was used (with a t vector of [0:0.001:20]). For each of the twelve experimental traces (for three subjects with two breathing conditions each for both the red and IR traces), an overall Fourier Transform was taken to find which frequencies were most prominent in the trace, and thus calculate heart rate from the most prominent frequency (ignoring the zero frequency peak). When taking the Fourier Transform over an entire trace (corresponding to the average heart rate across the entire trace), the sampling period (and thus the sampling frequency) often varied significantly from the beginning of the trace to the end.

This meant that each trace first had to be re-sampled with a uniform sampling frequency to generate a 1D vector of voltage values that were equally spaced with respect to time, which was required for the fft command. A uniform sampling frequency of 200 Hz was chosen, as this was typically the largest sampling frequency observed in the data.

Each trace was sectioned into subsets for different moments of time, and the Fourier Transform of each of these subsets was performed, again using fft. These subsets were not resampled because the data contained in each subset occurred closely in time together. As a result, the sampling frequencies found within each subset were relatively consistent and did not need to be re-calculated. From the heart rates determined from the frequency spectra of the subsets for each combination of subject, breathing condition, and LED type (*i.e.,* red or IR), the standard deviations were calculated to determine the variability and regularity of the heart rates

Results

Raw Voltage-vs-Time Traces Obtained for Each Subject Normal Breathing and Held-Breath Conditions

The raw red and IR voltage-vs-time plots for each subject under both normal breathing and held-breath conditions are shown in Figs. 1-3. Regular cycles (corresponding to heartbeats) can be identified in all traces. However, slow frequency drift is also apparent in these traces. This data was used to determine SpO_2 and heart rates (after further processing) in the following sections.

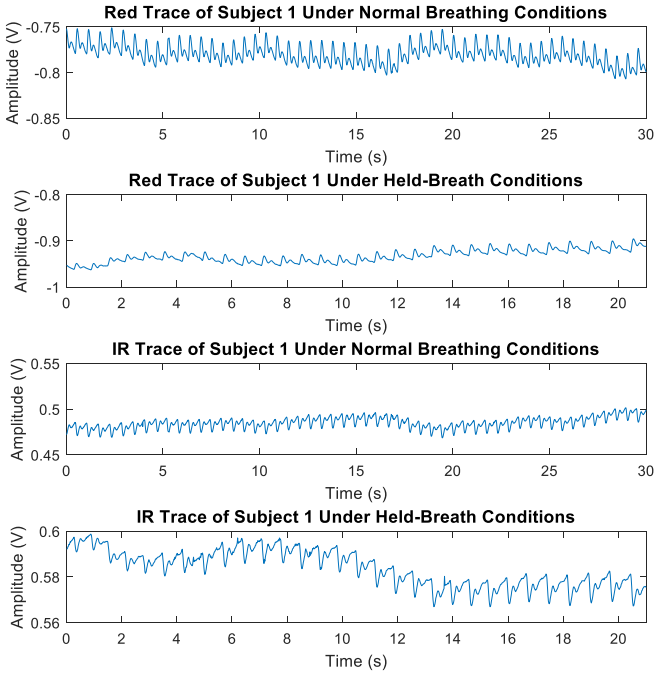


Fig. 2: Raw Data Traces for Subject 1 Under Normal Breathing and Held-Breath Conditions. A circuit gain of $2x10^6$ was used for both the red and IR channels.

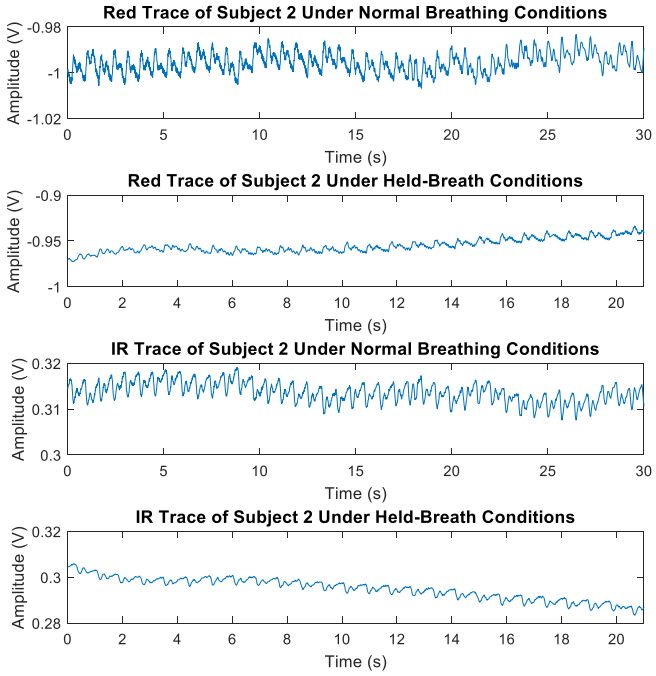


Fig. 3: Raw Data Traces for Subject 2 Under Normal Breathing and Held-Breath Conditions. A circuit gain of $2x10^6$ was used for both the red and IR channels.

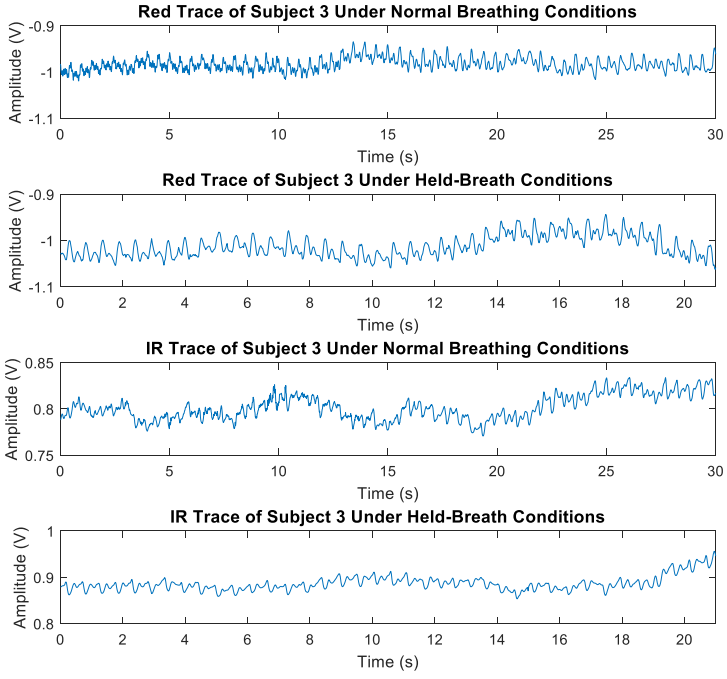


Fig. 4: Raw Data Traces for Subject 3 Under Normal Breathing and Held-Breath Conditions. A circuit gain of $2x10^6$ was used for both the red and IR channels.

Determination of Instantaneous SpO_2 Values for Normal Breathing and Held-Breath Conditions

The plots of instantaneous SpO_2 percentages of the three subjects over time for both normal breathing and held-breath conditions are shown in Figs. 5-7. The mean SpO_2 percentage of each subject for each breathing condition are summarized in Table 1.

Table 1: Mean SpO_2 Levels for Each Subject Under Normal Breathing and Held-Breath Conditions

	Subject 1	Subject 2	Subject 3
SpO2 (normal breathing conditions)	67.65%	81.70%	59.24%
SpO2 (held-breath conditions)	67.51%	83.67%	58.05%

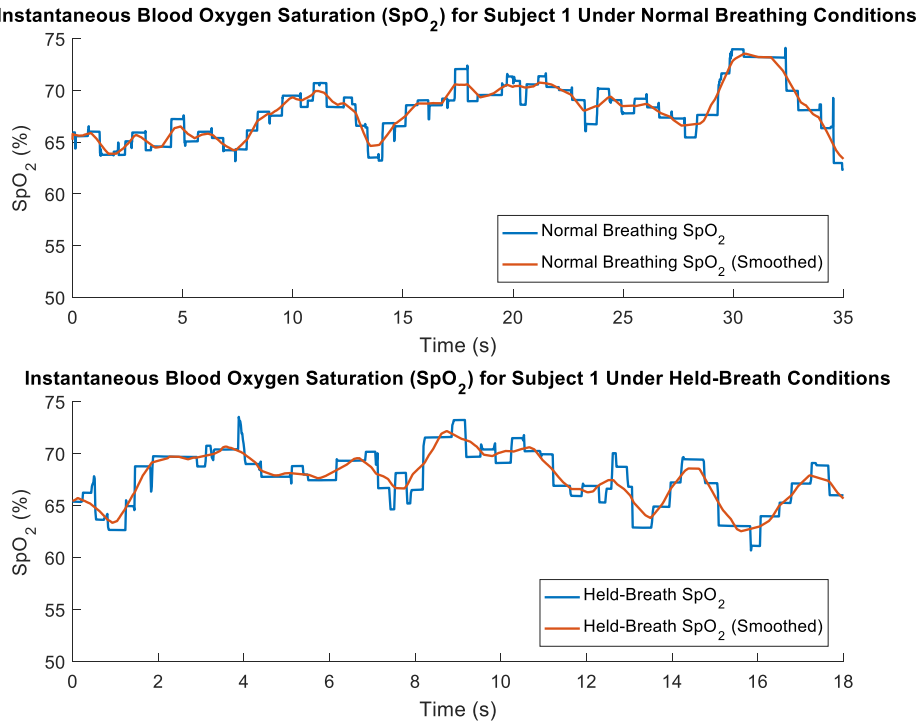


Fig. 5: SpO_2 Levels Over Time for Subject 1 Under Normal Breathing and Held-Breath Conditions. A low-pass-filtered (smoothed) version of instantaneous SpO_2 Levels is included.

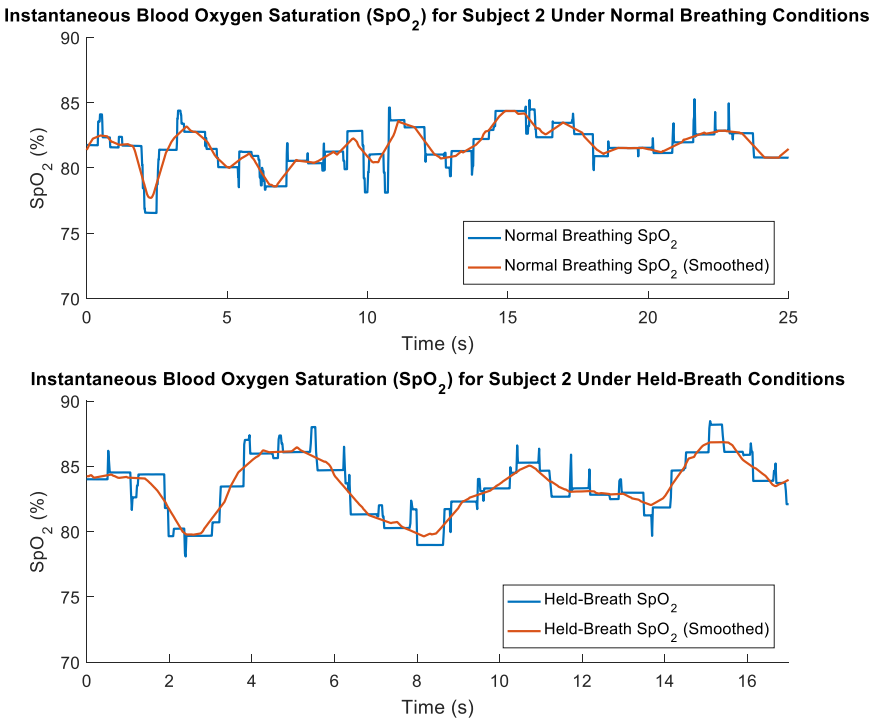


Fig. 6: SpO_2 Levels Over Time for Subject 2 Under Normal Breathing and Held-Breath Conditions. A low-pass-filtered (smoothed) version of instantaneous SpO_2 Levels is included.

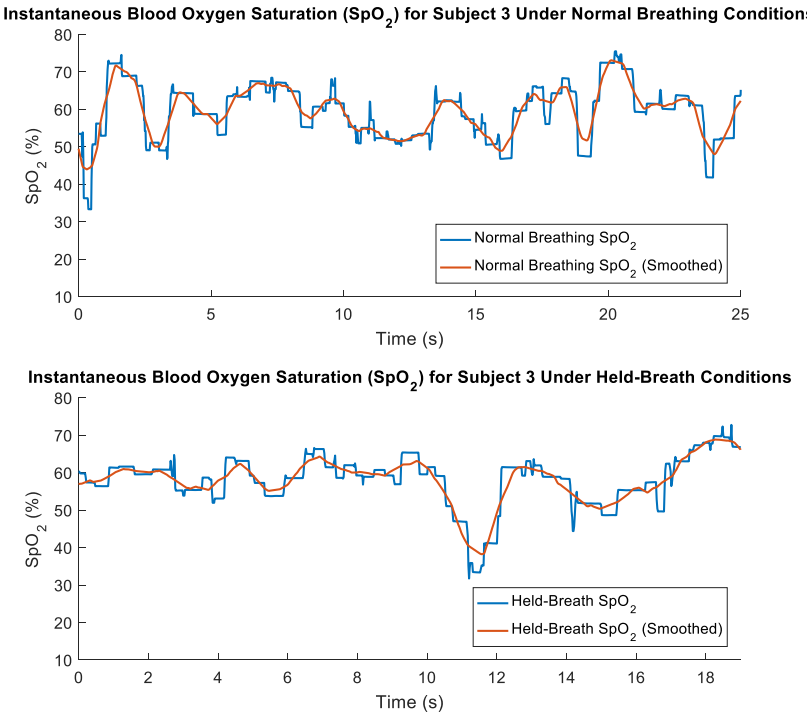


Fig. 7: SpO_2 Levels Over Time for Subject 3 Under Normal Breathing and Held-Breath Conditions. A low-pass-filtered (smoothed) version of instantaneous SpO_2 Levels is included.

Subject 1's SpO_2 varied from approximately 63-74% under normal breathing conditions, and from 62-73% under held-breath conditions. This subject's mean SpO_2 under normal breathing conditions was 67.65%, which was slightly higher than their mean SpO_2 under held-breath conditions (67.51%). A physiological SpO_2 value for a healthy individual is typically in the range of 95-98% under normal breathing conditions, and it would be expected that the SpO_2 would decrease a small amount (1-2%) as the subject holds their breath, as there is less oxygen in the body to saturate the hemoglobin molecules. Subject 1's SpO_2 values were approximately 30% lower than expected based on standard physiological ranges, however, their mean SpO_2 did decrease very slightly under held-breath conditions, which was the expected trend.

Subject 2's SpO_2 varied from approximately 76-85% under normal breathing conditions, and from 78-88% under held-breath conditions. This subject's mean SpO_2 under normal breathing conditions was 81.70%, which was lower than their mean SpO_2 under held-breath conditions (83.67%). Subject 2's SpO_2 values were about 15% lower than standard physiological values (but closer to healthy physiological ranges than Subject 1), however, their mean SpO_2 increased under held-breath conditions, showing the opposite trend of what was expected.

Subject 3's SpO_2 varied from approximately 35-75% under normal breathing conditions, and from 30-70% under held-breath conditions. This subject's mean SpO_2 under normal breathing conditions was 59.24%, which was slightly higher than their mean SpO_2 under held-breath conditions (58.05%). Subject 3's SpO_2 values were about 40% lower than standard physiological values (significantly lower than either Subject 1 or Subject 2), however, their mean SpO_2 decreased under held-breath conditions, showing the expected trend.

Determination of Heart Rate of Known Trace Using Thresholding Method

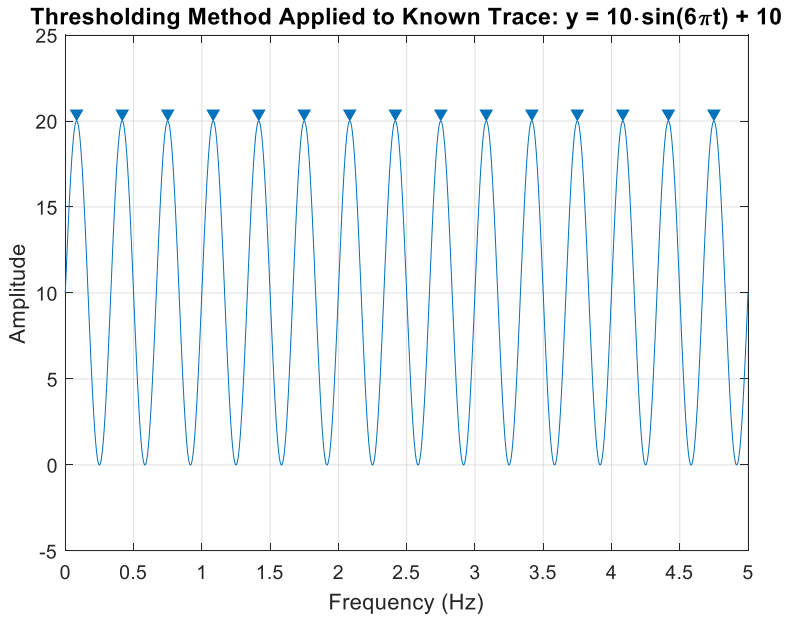


Fig. 8: Peaks of Known Trace $y = 10 \cdot \sin(6\pi t) + 10$ Using the Thresholding Method. Fifteen total peaks were identified over 5 seconds, resulting in a frequency of 3 Hz.

The objective of testing thresholding functioned correctly on this known trace (Fig. 8). The results shown correspond correctly with the expected values of 15 peaks over five seconds, given that the input frequency is three ($6\pi = 3\text{Hz}\cdot 2\pi$). This inspires confidence in the technique and method of thresholding.

Determination of Heart Rate of Experimental Normal Breathing and Held-Breath Traces Using Thresholding Method

This same technique was then applied to each of the sets of data that were obtained. These data can be found in Figs. 9-14. These plots include the data for IR and red spectrums, for both normal breathing and held breath. The summary of the data is found in Table 2, showing that the data was, for the most part, consistent between IR and red traces. The only difference seen was Subject 3, when the values for the threshold while holding their breath resulted in different values for the red and IR traces (additional signal processing may reveal those to be equivalent). A few of the peaks that the naked eye can see were not above the accepted threshold, and therefore resulted in slightly lower heart rates. However, the difference in these numbers is less than 3%, and nearly negligible.

We also saw a consistent drop in heart rate for normal breath and held-breath conditions, which is consistent with known physiological responses of the body. When the breath is held, muscles in the body relax and require less oxygen to function. As a result, heart rate decreases and less oxygen is delivered to muscles throughout the body. The values of these drops did range widely from 15 to only 3-6 beats per minute.

Subject 1's average heart rate under normal breathing and held-breath conditions was approximately 102 and 87 BPM, respectively. Although 102 BPM is slightly high for a resting heart rate under normal-breathing conditions, it is consistent with the subject's history of tachycardia (which is fairly well-controlled with beta blockers). Subject 2's average heart rate under normal breathing and held-breath conditions was approximately 82 and 71 BPM, respectively. This subject's resting heart rate is consistent with a healthy physiological range, and the decrease observed under held-breath conditions is also consistent with known physiological responses of the body. Subject 3's average heart rate under normal breathing and held-breath conditions was approximately 112 and 106 BPM, respectively. This subject was noted drinking an energy drink before their traces were recorded, which may help account for their higher resting heart rate value.

Table 2: Quantified Heart Rates for Each Subject Under Normal Breathing and Held-Breath Conditions Using the Threshold Method

	Subject 1	Subject 2	Subject 3
Red Trace: Normal Breathing Conditions Heart Rate (BPM)	102	82	112
Red Trace: Held-Breath Conditions Heart Rate (BPM)	87	71	106
IR Trace: Normal Breathing Conditions Heart Rate (BPM)	102	82	112
IR Trace: Held-Breath Conditions Heart Rate (BPM)	87	71	109

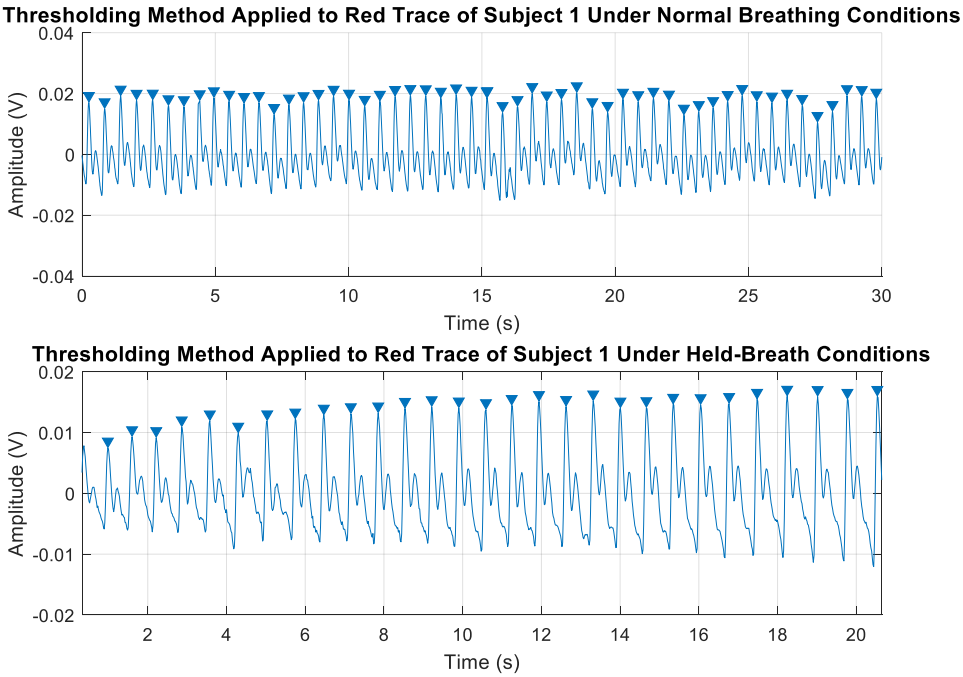


Fig. 9: Identified Peaks of the Red Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 1 Using the Thresholding Method.

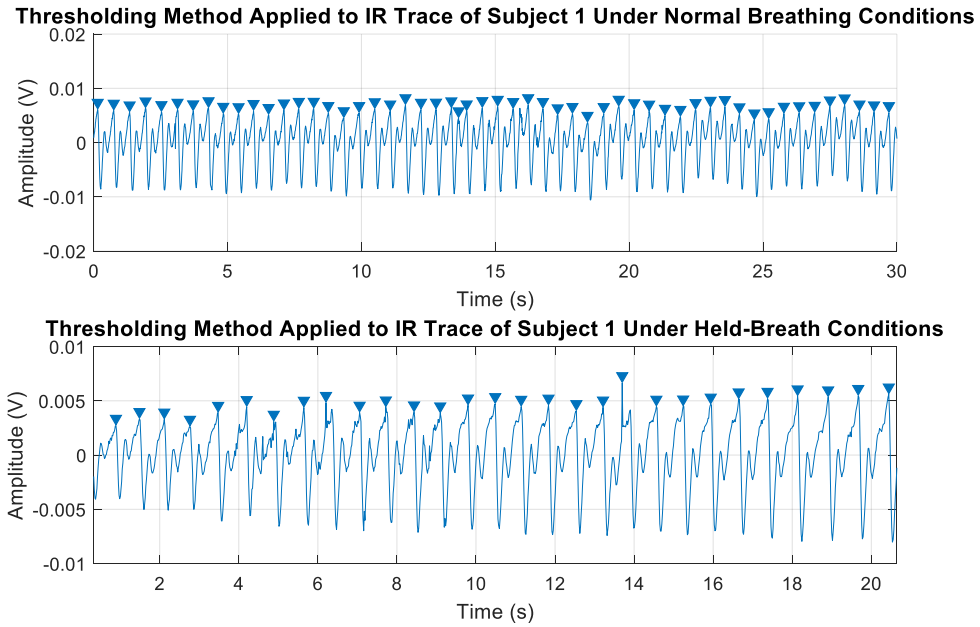


Fig. 10: Identified Peaks of the IR Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 1 Using the Thresholding Method.

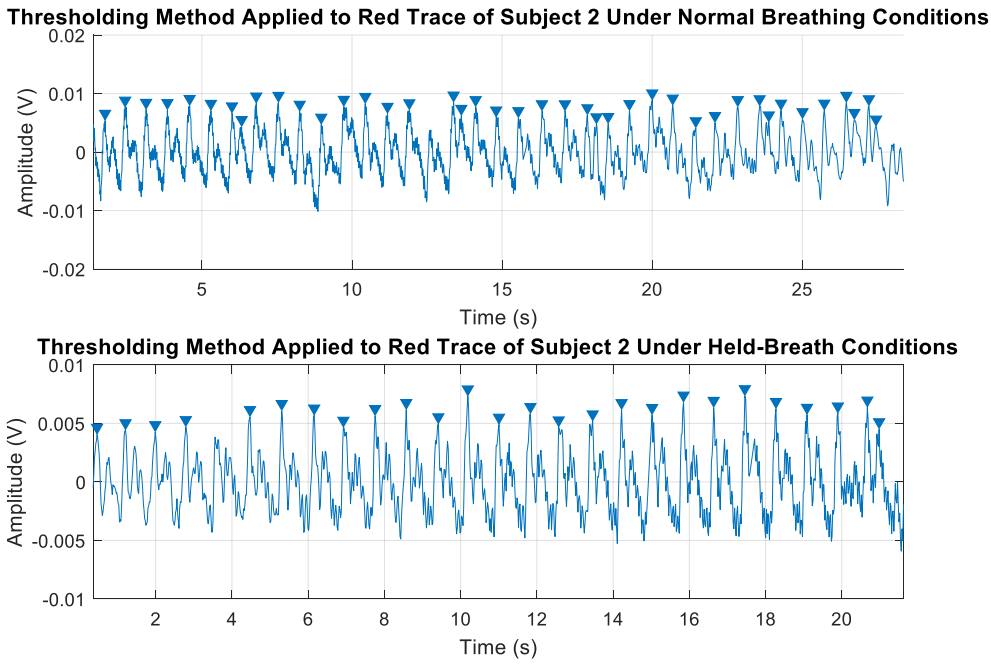


Fig. 11: Identified Peaks of the Red Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 2 Using the Thresholding Method.

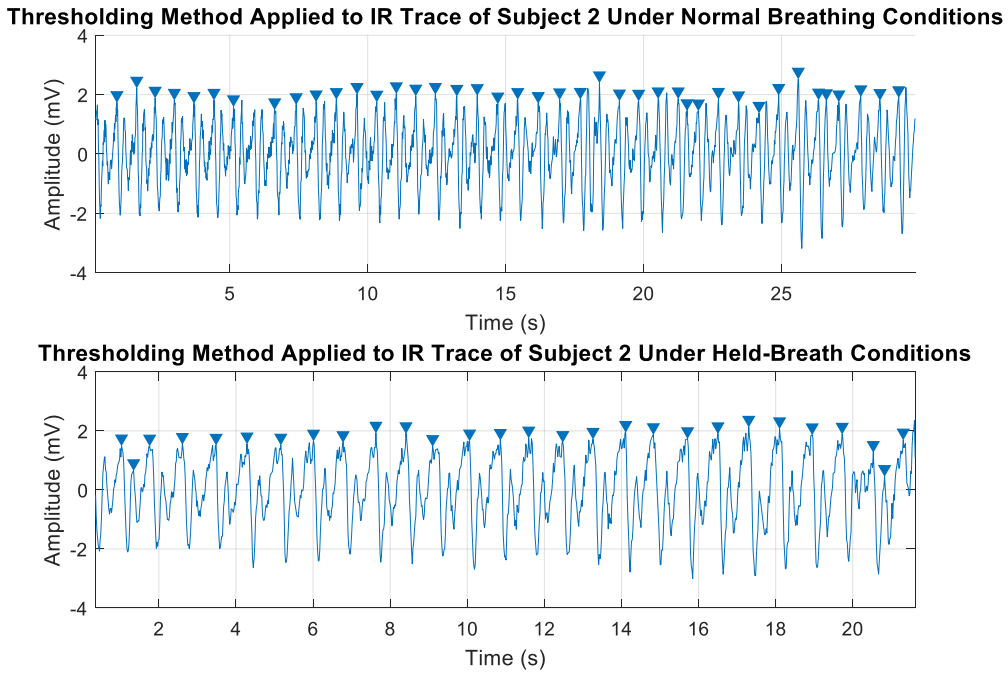


Fig. 12: Identified Peaks of the IR Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 2 Using the Thresholding Method.

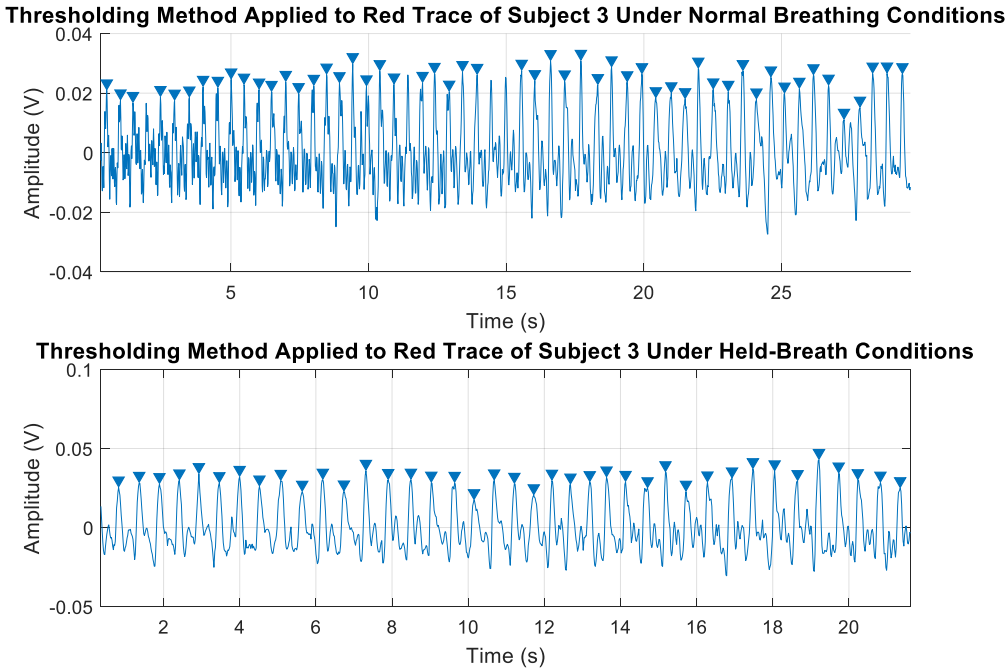


Fig. 13: Identified Peaks of the Red Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 3 Using the Thresholding Method.

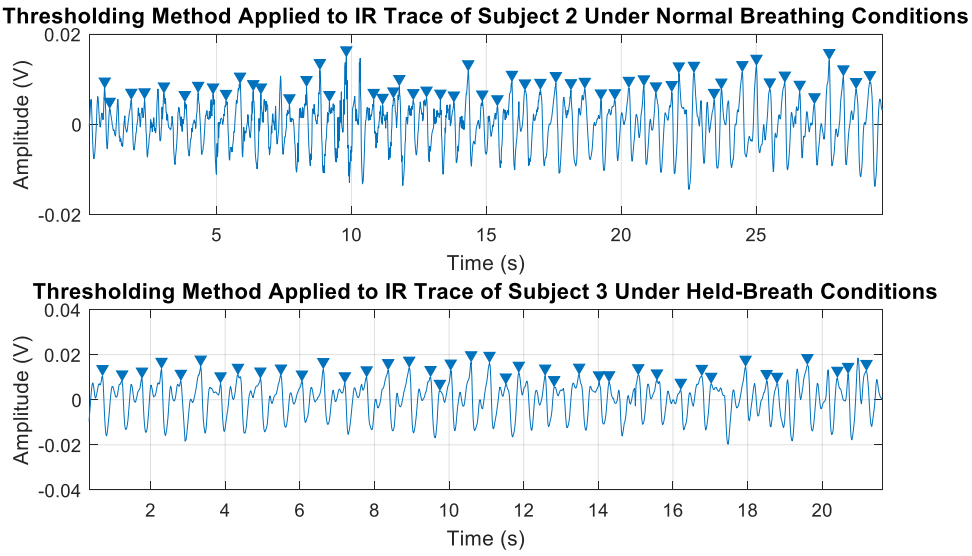


Fig. 14: Identified Peaks of the IR Experimental Traces (Under Normal Breathing and Held-Breath Conditions) from Subject 3 Using the Thresholding Method.

Determination of Heart Rate of Known Trace Using Fourier Method

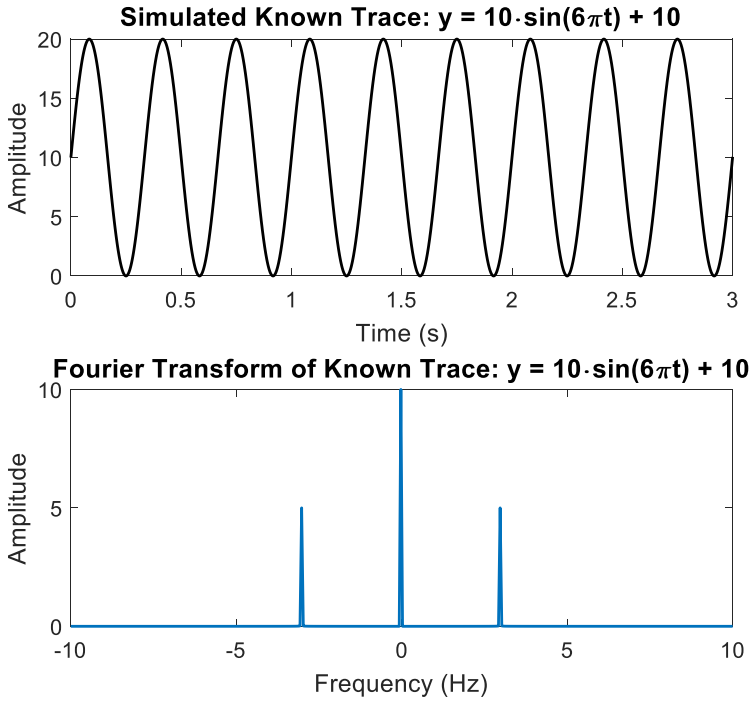


Fig. 15: Simulated Known Trace y = 10·sin(6πt) + 10 with its Fourier Transform. The spectrum shows frequencies at -3, 0, and 3 Hz.

Fig. 15 shows the waveform of the known trace $y = 10 \cdot \sin(6\pi t) + 10$, along with its Fourier Transform frequency spectrum. The frequency spectrum shows the expected result: a zero-frequency peak of amplitude ten, with two peaks of amplitude five at 3 Hz and -3 Hz. By inverse Euler's formula, a sine wave can be written as a sum of two complex exponentials, one with the positive frequency of the original sine wave and the other with the negative frequency of the original sine wave. Further, each of these complex exponential terms will have an amplitude that is half of the amplitude of the original sine wave. Since the original sine wave had an angular frequency of 6π, this corresponds to a frequency of 3Hz, and thus peaks at ± 3 Hz were observed in the frequency spectrum, each with amplitude of five (ten divided by two). The zero-frequency peak had an amplitude of ten, reflecting the constant '10' term in the known trace.

Determination of Heart Rate of Experimental Normal Breathing and Held-Breath Traces Using Fourier Method

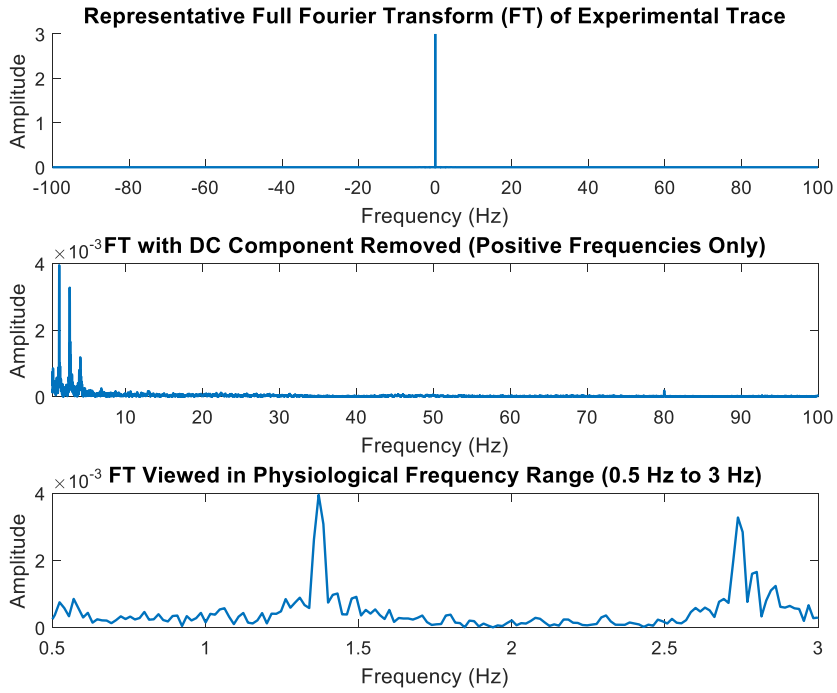


Fig. 16: Fourier Transform of a Single, Representative Experimental Trace Shown in Three Different Frequency Ranges (Full Spectrum, Positive Frequencies Outside DC Range, and Physiological Range).

Fig. 16 shows the Fourier Transform of a representative experimental trace (from Subject 1 under normal breathing condition), plotted over three different frequency ranges: from -100 to 100 Hz, from 0.5 to 100 Hz, and from 0.5 to 3 Hz. The purpose of the -100 to 100 Hz spectrum was to show an overview of the full transform, and illustrate how the zero-frequency peak

dominates the spectrum. The 0.5 to 100 Hz spectrum shows what the transform looks like with the zero-frequency peak removed (allowing other peaks to become visible). Since the spectrum is symmetric about 0 Hz, only the positive frequencies were included. This view shows the presence of harmonic peaks. The highest-amplitude peak in this view occurs at a frequency of approximately 1.75 Hz, with a smaller peak at 3.5 Hz, and an even smaller peak at 5.25 Hz. Thus, these smaller peaks are occurring at integer multiples of the first (fundamental) peak, and are harmonics. Although the pulse oximeter waveforms are cyclic, they are not perfectly sinusoidal. As a result, they will exhibit harmonics at integer multiples of the fundamental frequency[1]. The 0.5 to 3 Hz spectrum shows the transform in a physiological frequency range, corresponding to heart rates between 30 and 180 beats per min. (BPM). The fundamental frequency and its first harmonic (*i.e.*, the first two peaks in the 0.5 to 100 Hz spectrum) are apparent in this view. As this is the range of interest when identifying heart rate, all further Fourier Transforms will be shown in this frequency range. Since all traces follow the same pattern of this representative spectrum (a dominant zero-frequency peak, with a fundamental frequency in the physiological range of 0.5-3 Hz and harmonics at integer multiples of the fundamental frequency), these plots will not be included.

Figs. 17-19 show the Fourier Transforms of the full trace for each of the three subjects, under both normal breathing and held-breath conditions, for both the red trace and the IR trace. Table 3 shows the average heart rate (in BPM) for each trace, corresponding to the frequency at which the highest-amplitude peak occurs in the corresponding spectrum. Both the red and IR traces gave nearly identical results for the estimated heart rate (out of six comparisons between the red and IR traces for the same subject and breathing condition, four gave the same heart rate, while the other two comparisons differed by less than 1 BPM). This is expected, as the red and IR traces were recorded at the same time and qualitatively appeared to contain similar levels of noise.

Table 3: Quantified Heart Rates for Each Subject Under Normal Breathing and Held-Breath Conditions Using the Fourier Method

	Subject 1	Subject 2	Subject 3
Red Trace: Normal Breathing Conditions Heart Rate (BPM)	105.6	82.14	112.92
Red Trace: Held-Breath Conditions Heart Rate (BPM)	87.3	73.74	107.04
IR Trace: Normal Breathing Conditions Heart Rate (BPM)	105.6	82.14	112.92
IR Trace: Held-Breath Conditions Heart Rate (BPM)	86.64	73.74	107.64

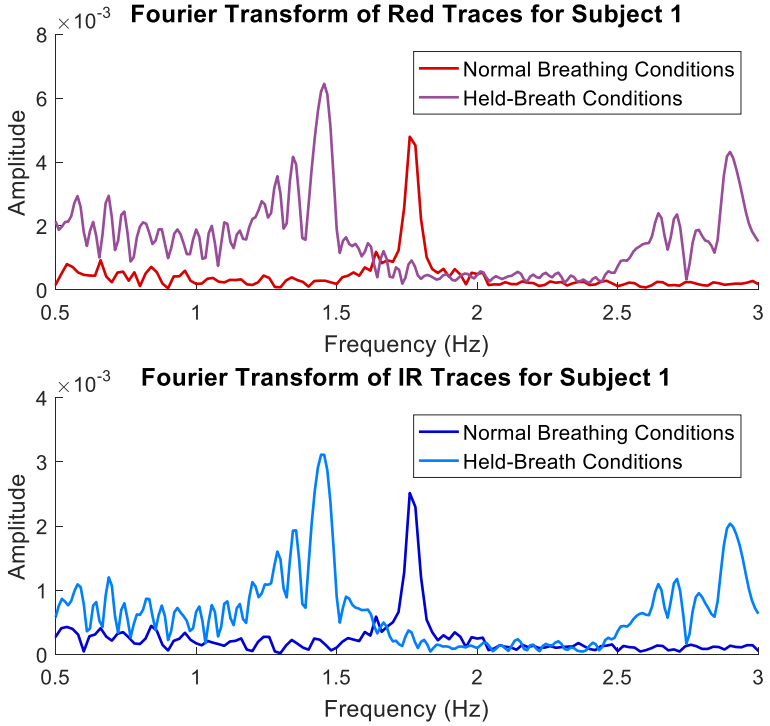


Fig. 17: Fourier Transforms of Subject 1's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used.

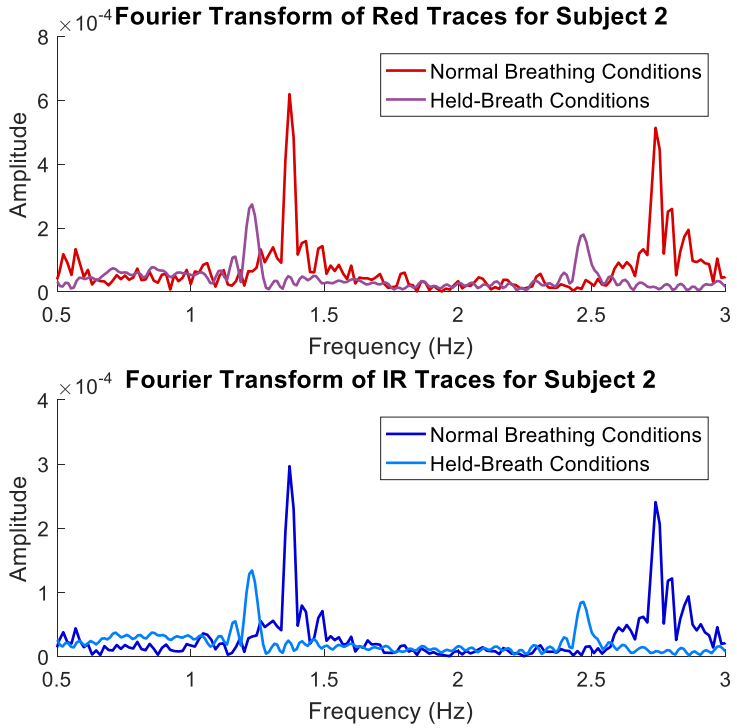


Fig. 18: Fourier Transforms of Subject 2's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used.

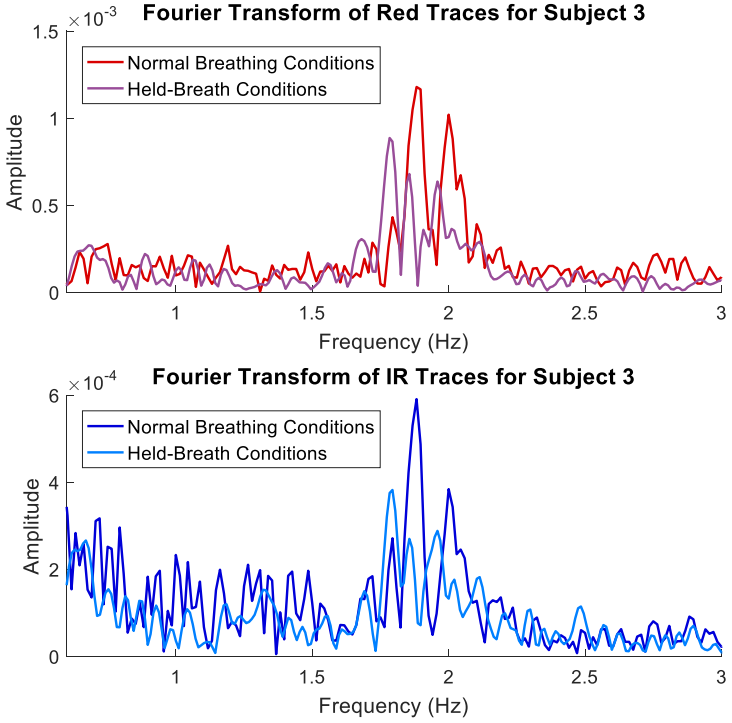


Fig. 19: Fourier Transforms of Subject 3's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used

Subject 1's average heart rate under normal breathing and held-breath conditions was approximately 106 and 87 BPM, respectively. This consistent with the subject's history of tachycardia (fairly well-controlled with beta blockers), and the decrease in heart rate while holding their breath is also consistent with known physiological responses of the body.

Subject 2's average heart rate under normal breathing and held-breath conditions was approximately 82 and 74 BPM, respectively. This subject's resting heart rate is consistent with a healthy physiological range, and the decrease observed under held-breath conditions is also consistent with known physiological responses of the body.

Subject 3's average heart rate under normal breathing and held-breath conditions was approximately 113 and 107 BPM, respectively. This subject was noted drinking an energy drink before their traces were recorded, which may help account for their higher resting heart rate value. A small decrease in heart rate was observed under held-breath conditions, which is consistent with known physiological responses of the body.

Determination of Heart Rate of Subsets of Experimental Normal Breathing and Held-Breath Traces Using Fourier Method

Each of the traces analyzed in the preceding section (for each subject, breathing condition, and whether the trace represented red or IR light) was then divided into subsets to evaluate the most prominent frequency for different moments of time. The number of sections of each trace varied depending on the length and noise level of the trace. Longer, less noisy traces could be divided into a greater number of subsections. The largest number of sections was selected for each trace, such that each section contained a nonzero frequency peak that was clearly identifiable to serve as the fundamental frequency (heart rate). The plots of each of the subsets for the three subjects are shown in Figs 20-22. The quantified heart rates from these subsets are included in Table 4. From these values, the standard deviation for each combination of subject, breathing condition, and LED type (red or IR) was calculated, and the standard deviations are shown in Table 5.

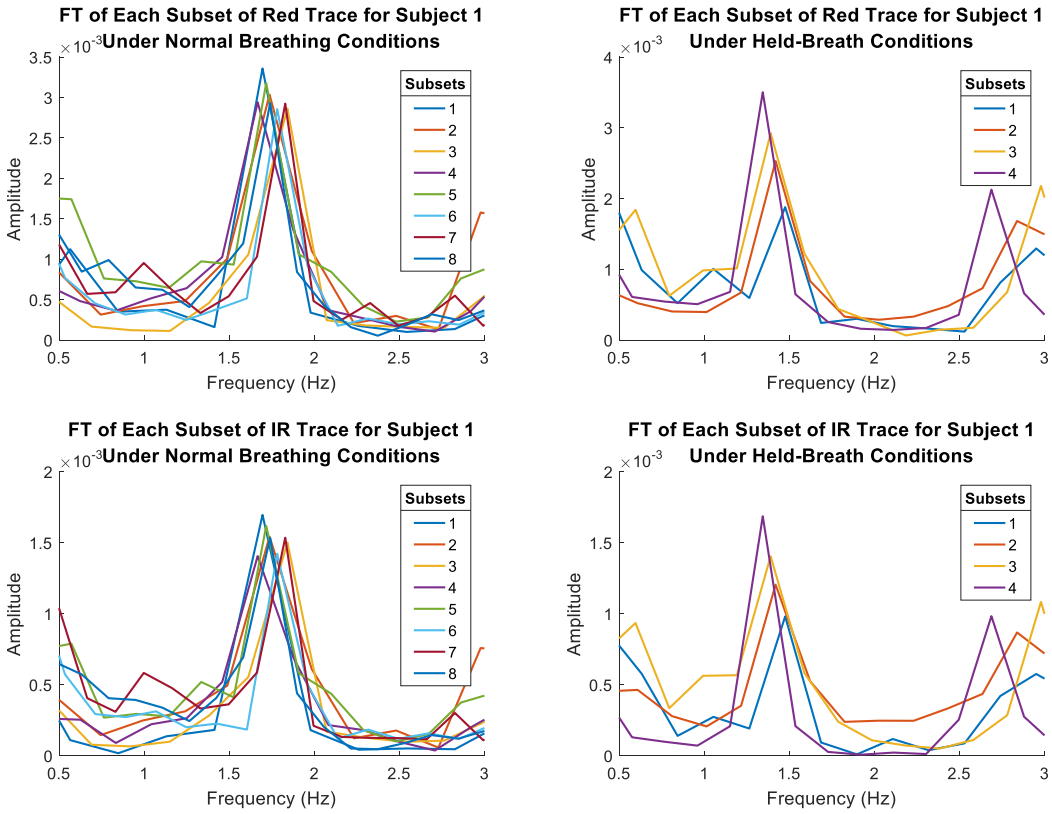


Fig. 20: Fourier Transform of Each Subset of Subject 1's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used

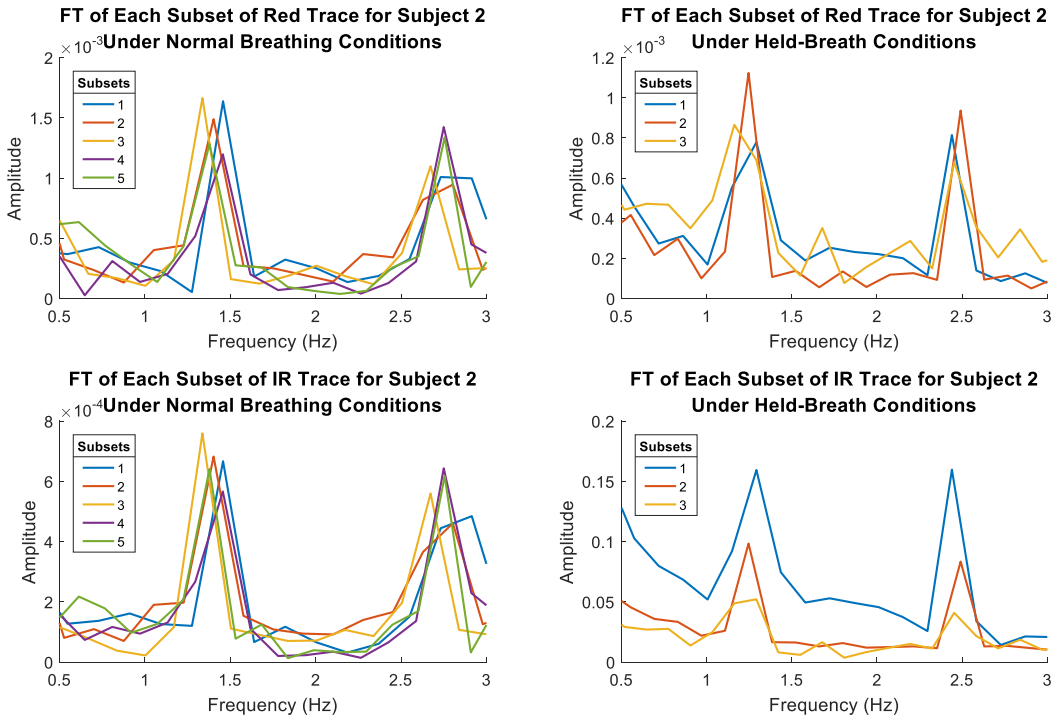


Fig. 21: Fourier Transform of Each Subset of Subject 2's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used

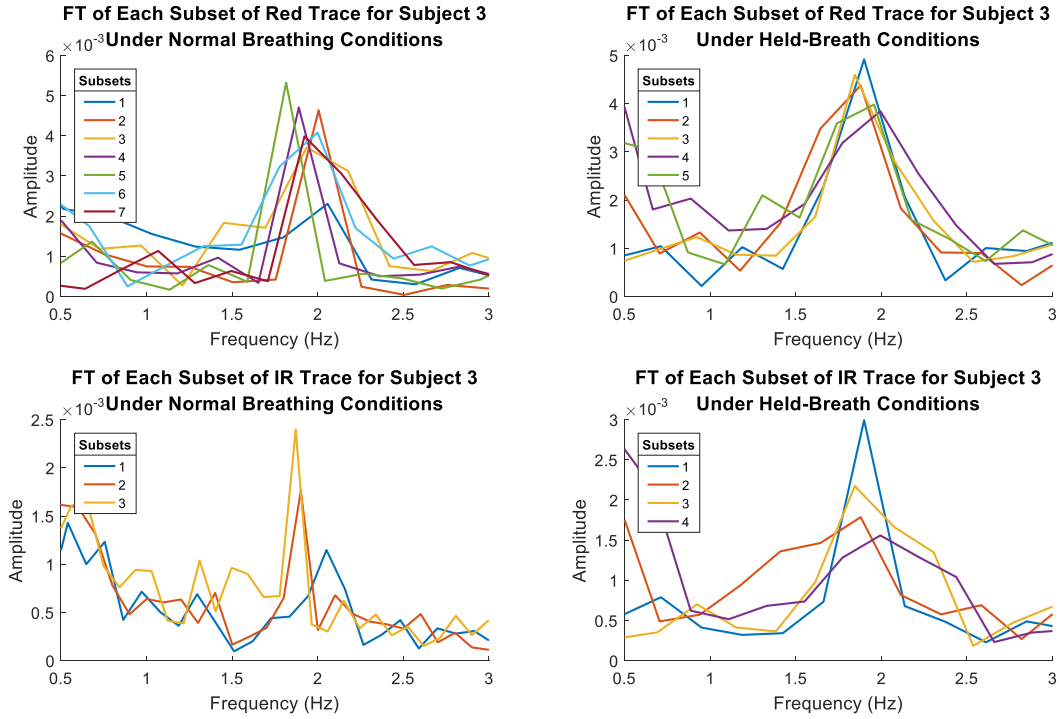


Fig. 22: Fourier Transform of Each Subset of Subject 3's Red and IR Traces Under Normal Breathing and Held-Breath Conditions. A sampling frequency of 200 Hz was used

Table 4: Quantified Heart Rates of Each Subset for Each Subject Under Normal Breathing and Held-Breath Conditions Using the Fourier Method

	Subject 1	Subject 2	Subject 3
Red Trace: Normal Breathing Conditions Subset Heart Rates (BPM)	101.76 110.52 104.22 100.02 103.02 104.40 109.74 106.92	80.22 87.42 84.12 87.36 82.68	108.90 113.34 120.30 119.94 115.32 116.10 123.42
Red Trace: Held-Breath Conditions Subset Heart Rates (BPM)	80.64 83.4 85.1 88.56	74.76 69.72 77.52	113.94 109.64 107.42 110.70 112.74
IR Trace: Normal Breathing Conditions Subset Heart Rates (BPM)	101.76 110.52 104.22 100.02 103.02 104.40 109.74 106.92	80.22 84.12 87.42 82.68 87.36	112.26 123.06 114.06
IR Trace: Held-Breath Conditions Subset Heart Rates (BPM)	85.14 83.40 88.56 80.64	77.52 74.76 77.46	113.94 110.70 112.74 109.64

Table 5: Calculated Heart Rate Standard Deviations for Each Subject Under Normal Breathing and Held-Breath Conditions Using the Fourier Method Subsets

	Subject 1	Subject 2	Subject 3
Red Trace: Normal Breathing Conditions Standard Deviation (BPM)	3.7180	3.0977	4.8817
Red Trace: Held-Breath Conditions Standard Deviation (BPM)	3.3159	3.9551	3.6017
IR Trace: Normal Breathing Conditions Standard Deviation (BPM)	3.718	3.0977	5.7862
IR Trace: Held-Breath Conditions Standard Deviation (BPM)	3.3159	1.5765	3.8310

Most of the calculated standard deviations were between 3 and 4 BPM, corresponding to heart beat intervals that were fairly regular. Subject 3's normal breathing traces contained the greatest variation in heart rate, with standard deviations of 5.79 BPM for the IR trace and 4.88 BPM for the red trace. Although these values are higher than those observed for the other subjects, they are not large enough to be classified as irregular, as normal heart rates fluctuate over time, and 5-10 BPM changes in a period of several seconds to a minute are not abnormal. Subject 2's held-breath IR trace (standard deviation of 1.58 BPM) contained the most regular heart rate intervals, with very little variation in heart rate.

Discussion

The calculated SpO_2 values for the three subjects were consistently lower than the standard physiological range of 95-98% blood oxygen saturation. Subject 3 in particular had low mean SpO_2 values (< 60%), and their instantaneous SpO_2 varied considerably over the course of the trial. It is unlikely that this subject would be conscious (or even alive) with SpO_2 values this low. This indicates that the pulse oximeter and sampling circuitry were likely reporting a value that was lower than the subject's true SpO_2. Possible reasons for this lower value include the photodiodes and LEDs being positioned slightly too far apart or out of alignment with the viewing angle, the subject touching either of these components during the course of the trial, the subject moving during the recording, the LED outputs not producing a consistent signal, a lack of sensitivity of the photodiodes, or the influence of external sources (even with use of the jacket to try and minimize these signals). The large variations in SpO_2 over time that were observed for the subjects were likely the result of movement throughout the trials. If the finger were to move more in and out of alignment with the LEDs and photodiodes, this would alter the amount of red and IR light transmitted to the photodiodes (perhaps disproportionately affecting the transmittance of one type of light as compared to the other depending on the direction that the finger moved). As a result, this would change the calculated absorbance ratio and therefore the SpO_2 values. Subject 3 had the largest variations in SpO_2 values, which may have been due to the energy drink increasing his sympathetic response, making it harder for him to remain still.

If this pulse oximeter were to be adapted for clinical use, it would be more beneficial for it to be in the form of a finger clip. The finger clip would latch onto the finger and would move with the finger if the subject were to move. In addition, the finger clip would surround the finger and help to block out external light.

Although two of the subjects showed decreases in mean SpO_2 when they held their breath, these decreases were very small and, given the wide variation of SpO_2 values recorded throughout the trials, it is difficult to say that these were the result of changing oxygenation levels rather than movement of the subject during the trial. Subject 2's increase in mean SpO_2 was more significant (nearly 2%), and may have been due to either movement or his taking a large, deep breath before the trial was recorded. This deep breath would allow more oxygen to saturate the hemoglobin molecules in his blood, leading to a higher SpO_2 value.

The thresholding method and Fourier method were equally successful at identifying the frequency (heart rate) of the known, theoretical trace: $y = 10 \cdot \sin(6\pi t) + 10$. This is not surprising, as this trace contained no noise or slow frequency drift that would make identification of its frequency difficult to determine. However, the effectiveness and efficiency of these two methods needed to be measured for clinical use, using experimental traces. The thresholding method and Fourier method yielded similar average heart rates for all subjects under all experimental conditions, as no heart rates compared by the two methods differed by more than 4 BPM. In general, the Fourier method resulted in heart rates that were 1-2 BPM higher than those calculated using thresholding. This may be due to a small number of relatively low-amplitude peaks (or peaks that are slightly closer together than for the typical cycle) not meeting the required thresholds to be identified as a peak in the thresholding method. The thresholding method relies on identifying peaks that meet some minimum amplitude and width criteria. As the trials went on for a longer period of time, the typical amplitude of the peaks often began to vary, which made accurate identification of all peaks more challenging. In contrast, the Fourier method resulted in more clearly-defined peaks when data was analyzed over a longer period of time. The Fourier method relies on determining the frequency content of the trace, showing amplitudes associated with each frequency in proportion to their content in the trace. These frequencies tended to average out to a consistent value as more cycles were taken.

The calculated heart rates (and response to holding the breath) were generally consistent with the known physiological responses of the body. Although the resting heart rates were slightly elevated above accepted ranges, these heart rates are consistent with the tachycardic condition of one subject and the consumption of an energy drink (positive chronotropic effector) by the other subject. In addition, all subjects showed a decrease in heart rate under held-breath conditions. This is a known physiologic response, as muscles in the body relax in response to the breath being held and require less oxygen to function. As a result, heart rate decreases and less oxygen is delivered to muscles throughout the body. Subject 1 showed a substantially greater decrease in heart rate (15 BPM) than the other two subjects, who showed more modest decreases. This may again be related to the subject's medical history, as the subject is very practiced in breathing slowly in an attempt to control their heart rate.

Although the data traces obtained for this experiment contained relatively small levels of noise, other real-world signals may be noisier and require additional filtering. An additional low-pass filter could be implemented before the thresholding was performed to try and minimize high-frequency noise and make the detection of the heart rate peaks more feasible. Theoretically, this filtering would not be necessary for the Fourier method since the device is set to look for the heart rate only in a physiological range, well below the expected frequency values of the noise.

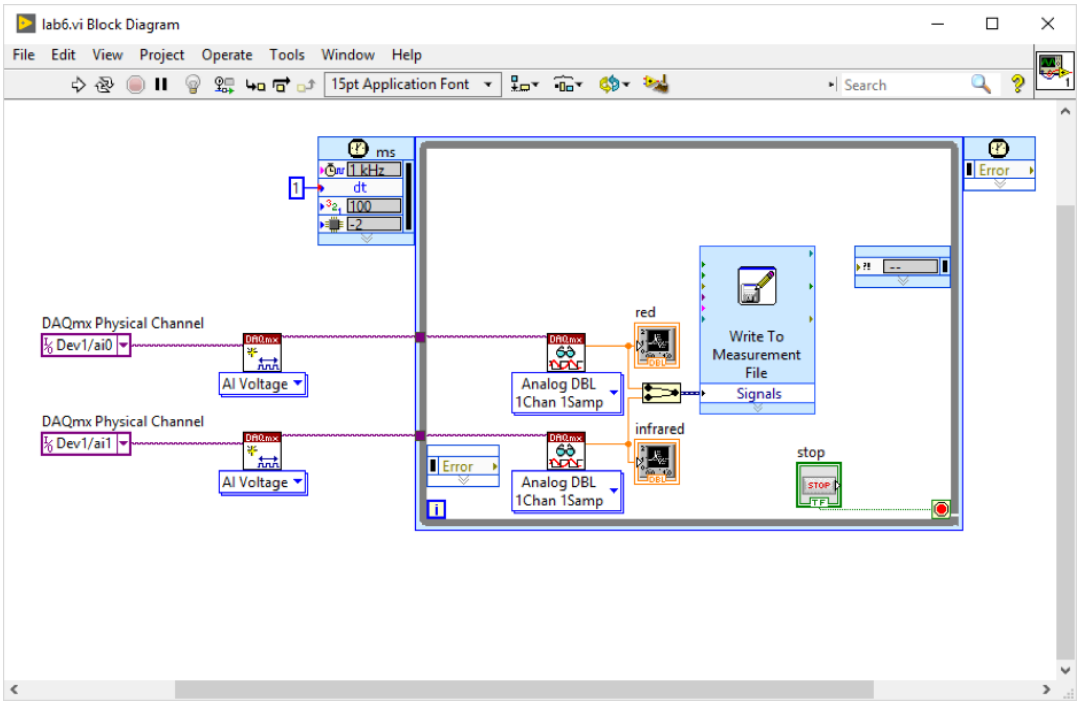
One advantage of the thresholding method is that it requires less data to identify the heart rate present. To eliminate slow frequency drift and baseline the data as needed for the thresholding method, only a couple cycles needed to be present. However, in many cases, the Fourier method required about 10 cycles to result in a clearly-identifiable peak in the frequency spectrum. In the clinic, a pulse oximeter that depends on thresholding would display a heart rate

that is more up-to-date with the subject's actual heart rate. Thus, if immediate changes in heart rate in response to an action such as standing up needed to be monitored, a pulse oximeter that relies on thresholding may be preferable.

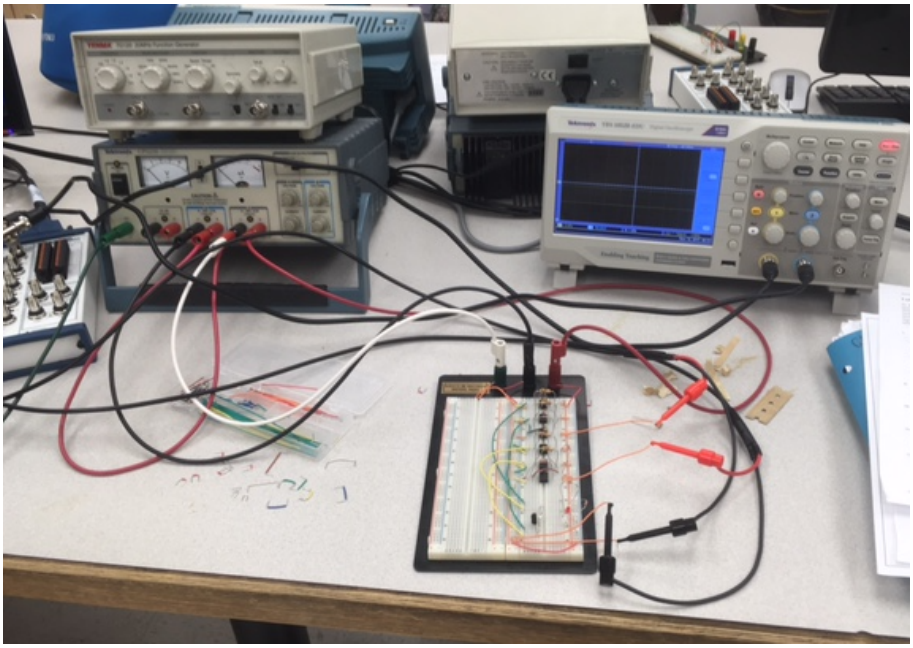
The standard deviations in heart rates found by subsetting the traces and taking the Fourier Transform revealed that each subject's heart beats occurred at fairly regular intervals. The largest standard deviation observed was 5.79 BPM. Considering that normal heart rates fluctuate over time, a 5-10 BPM change in heart rate over a period of several seconds to a minute is not abnormal, especially when considering that this subject was under the influence of an energy drink.

Appendix

LabVIEW:



Experimental Setup:



MATLAB Code:

```
%% Systems Lab 6
% Kristin SpO2
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=69);
el3 = el3(1);
el4 = find(t>=90);
```

```
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
a_hir = 690;    % all alpha (a) units in 1/(cm*M)
a_oir = 1200;
a_hred = 3200;
a_ored = 320;
n = 150;
for k = n+1:el2-el1-n
  vdc_red(k) = mean(red_normal(k-n:k+n));
  vac_red(k) = max(red_normal(k-n:k+n))-min(red_normal(k-n:k+n));

  vdc_ir(k) = mean(ir_normal(k-n:k+n));
  vac_ir(k) = max(ir_normal(k-n:k+n))-min(ir_normal(k-n:k+n));

  A(k) = abs(vac_red(k)/vdc_red(k)/(vac_ir(k)/vdc_ir(k)));

  SpO2(k) = (a_hir*A(k) - a_hred)./((a_hir-a_oir)*A(k) - (a_hred -
a_ored));
end
n2 = 100;
h = 1/n2*ones(1,n2);
SpO2_s = conv(SpO2,h,'same');
n3 = 50;
for k = n3+1:el4-el3-n3
  vdc_red_breath(k) = mean(red_breath(k-n3:k+n3));
  vac_red_breath(k) = max(red_breath(k-n3:k+n3))-min(red_breath(k-
n3:k+n3));

  vdc_ir_breath(k) = mean(ir_breath(k-n3:k+n3));
  vac_ir_breath(k) = max(ir_breath(k-n3:k+n3))-min(ir_breath(k-
n3:k+n3));

  A_breath(k) =
abs(vac_red_breath(k)/vdc_red_breath(k)/(vac_ir_breath(k)/vdc_ir_bre
ath(k)));

  SpO2_breath(k) = (a_hir*A_breath(k) - a_hred)./((a_hir-
a_oir)*A_breath(k) - (a_hred - a_ored));
end
n4 = 50;
h_breath = 1/n4*ones(1,n4);
SpO2_s_breath = conv(SpO2_breath,h_breath,'same');
SpO2_mean = mean(SpO2(n+1:end))
SpO2_breath_mean = mean(SpO2_breath(n3+1:end))
figure(20)
subplot(2,1,1)
hold on
t_s = 11.5;
plot(t_normal(n+1:el2-el1-n)-t_s,SpO2(n+1:end)*100,'LineWidth',1.5);
plot(t_normal(n+1:el2-el1-n)-
t_s,SpO2_s(n+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 1
Under Normal Breathing Conditions')
leg = legend('Normal Breathing SpO_2','Normal Breathing SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 35]);
ylim([50 75])
subplot(2,1,2)
hold on
t_s_breath = 70.5;
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_breath(n3+1:end)*100,'LineWidth',1.5);
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_s_breath(n3+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 1
Under Held-Breath Conditions')
leg = legend('Held-Breath SpO_2','Held-Breath SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 18])
ylim([50 75])
%% Merrill SpO2
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
normally
el1 = find(t >= 35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=74);
el3 = el3(1);
el4 = find(t>=96);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
a_hir = 690;    % all alpha (a) units in 1/(cm*M)
a_oir = 1200;
a_hred = 3200;
a_ored = 320;
n = 75;
for k = n+1:el2-el1-n
  vdc_red(k) = mean(red_normal(k-n:k+n));
  vac_red(k) = max(red_normal(k-n:k+n))-min(red_normal(k-n:k+n));

  vdc_ir(k) = mean(ir_normal(k-n:k+n));
  vac_ir(k) = max(ir_normal(k-n:k+n))-min(ir_normal(k-n:k+n));

  A(k) = abs(vac_red(k)/vdc_red(k)/(vac_ir(k)/vdc_ir(k)));

  SpO2(k) = (a_hir*A(k) - a_hred)./((a_hir-a_oir)*A(k) - (a_hred -
a_ored));
end
n2 = 50;
h = 1/n2*ones(1,n2);
SpO2_s = conv(SpO2,h,'same');
n3 = 50;
for k = n3+1:el4-el3-n3
  vdc_red_breath(k) = mean(red_breath(k-n3:k+n3));
  vac_red_breath(k) = max(red_breath(k-n3:k+n3))-min(red_breath(k-
n3:k+n3));

  vdc_ir_breath(k) = mean(ir_breath(k-n3:k+n3));
  vac_ir_breath(k) = max(ir_breath(k-n3:k+n3))-min(ir_breath(k-
n3:k+n3));

  A_breath(k) =
abs(vac_red_breath(k)/vdc_red_breath(k)/(vac_ir_breath(k)/vdc_ir_bre
ath(k)));

  SpO2_breath(k) = (a_hir*A_breath(k) - a_hred)./((a_hir-
a_oir)*A_breath(k) - (a_hred - a_ored));
end
n4 = 50;
h_breath = 1/n4*ones(1,n4);
SpO2_s_breath = conv(SpO2_breath,h_breath,'same');
SpO2_mean = mean(SpO2(n+1:end))
SpO2_breath_mean = mean(SpO2_breath(n3+1:end))
figure(20)
```

```
subplot(2,1,1)
hold on
t_s = 36.5;
plot(t_normal(n+1:el2-el1-n)-t_s,SpO2(n+1:end)*100,'LineWidth',1.5);
plot(t_normal(n+1:el2-el1-n)-
t_s,SpO2_s(n+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 2
Under Normal Breathing Conditions')
leg = legend('Normal Breathing SpO_2','Normal Breathing SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 25]);
ylim([70 90])
subplot(2,1,2)
hold on
t_s_breath = 77;
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_breath(n3+1:end)*100,'LineWidth',1.5);
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_s_breath(n3+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 2
Under Held-Breath Conditions')
leg = legend('Held-Breath SpO_2','Held-Breath SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 17])
ylim([70 90])
%% Steven (TA) SpO2
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=75);
el3 = el3(1);
el4 = find(t>=97);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
a_hir = 690;    % all alpha (a) units in 1/(cm*M)
a_oir = 1200;
a_hred = 3200;
a_ored = 320;
n = 60;
for k = n+1:el2-el1-n
   vdc_red(k) = mean(red_normal(k-n:k+n));
   vac_red(k) = max(red_normal(k-n:k+n))-min(red_normal(k-n:k+n));

   vdc_ir(k) = mean(ir_normal(k-n:k+n));
   vac_ir(k) = max(ir_normal(k-n:k+n))-min(ir_normal(k-n:k+n));

   A(k) = abs(vac_red(k)/vdc_red(k)/(vac_ir(k)/vdc_ir(k)));

   SpO2(k) = (a_hir*A(k) - a_hred)./((a_hir-a_oir)*A(k) - (a_hred -
a_ored));
end
n2 = 50;
h = 1/n2*ones(1,n2);
SpO2_s = conv(SpO2,h,'same');
n3 = 50;
for k = n3+1:el4-el3-n3
   vdc_red_breath(k) = mean(red_breath(k-n3:k+n3));
   vac_red_breath(k) = max(red_breath(k-n3:k+n3))-min(red_breath(k-
n3:k+n3));

   vdc_ir_breath(k) = mean(ir_breath(k-n3:k+n3));
   vac_ir_breath(k) = max(ir_breath(k-n3:k+n3))-min(ir_breath(k-
n3:k+n3));

   A_breath(k) =
abs(vac_red_breath(k)/vdc_red_breath(k)/(vac_ir_breath(k)/vdc_ir_bre
ath(k)));

   SpO2_breath(k) = (a_hir*A_breath(k) - a_hred)./((a_hir-
a_oir)*A_breath(k) - (a_hred - a_ored));
end
n4 = 50;
h_breath = 1/n4*ones(1,n4);
SpO2_s_breath = conv(SpO2_breath,h_breath,'same');
SpO2_mean = mean(SpO2(n+1:end))
SpO2_breath_mean = mean(SpO2_breath(n3+1:end))
figure(20)
subplot(2,1,1)
hold on
t_s = 39.5;
plot(t_normal(n+1:el2-el1-n)-t_s,SpO2(n+1:end)*100,'LineWidth',1.5);
plot(t_normal(n+1:el2-el1-n)-
t_s,SpO2_s(n+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 3
Under Normal Breathing Conditions')
leg = legend('Normal Breathing SpO_2','Normal Breathing SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 25]);
ylim([10 80])
subplot(2,1,2)
hold on
t_s_breath = 76.5;
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_breath(n3+1:end)*100,'LineWidth',1.5);
plot(t_breath(n3+1:el4-el3-n3)-
t_s_breath,SpO2_s_breath(n3+1:end)*100,'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('SpO_2 (%)')
title('Instantaneous Blood Oxygen Saturation (SpO_2) for Subject 3
Under Held-Breath Conditions')
leg = legend('Held-Breath SpO_2','Held-Breath SpO_2
(Smoothed)','Location','southeast');
leg.FontSize = 11;
xlim([0 19])
ylim([10 80])
%% Thresholding known trace:
close all
clear all
clc
dt = .001;
t = [0:dt:5];
A = 10*sin(3*2*pi*t)+10;    % frequency of 3 Hz + DC (0 Hz) term
findpeaks(A,t)
[pks,loc] = findpeaks(A,t);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Thresholding Method Applied to Known Trace: y =
10\cdotsin(6\pit) + 10','FontSize',14)

%% K Thresholding
close all
```

```
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=69);
el3 = el3(1);
el4 = find(t>=90);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);

w = 100
for k = 1+w:length(t_normal)-w
  base(k-w) = mean(red_normal(k-w:k+w));
end
red_normal_b = red_normal(1+w:length(red_normal)-w) - base';
ts1 = 10.9;
ts2 = 69;
figure(1)
subplot(2,1,1)
[pks1,loc1] = findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-
w),'MinPeakHeight',.01)
hold on
findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-w)-
ts1,'MinPeakHeight',.01)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 1 Under
Normal Breathing Conditions','FontSize',14)
w = 100
for k = 1+w:length(t_normal)-w
  base(k-w) = mean(ir_normal(k-w:k+w));
end
ir_normal_b = ir_normal(1+w:length(ir_normal)-w) - base';
figure(2)
subplot(2,1,1)
[pks2,loc2] = findpeaks(ir_normal_b,t_normal(1+w:length(t_normal)-
w),'MinPeakHeight',.003,'MinPeakWidth',.1)
hold on
findpeaks(ir_normal_b,t_normal(1+w:length(t_normal)-w)-
ts1,'MinPeakHeight',.003,'MinPeakWidth',.1)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 1 Under
Normal Breathing Conditions','FontSize',14)
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=69);
el3 = el3(1);
el4 = find(t>=90);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
w3 = 20
for k = 1+w3:length(t_breath)-w3
  base3(k-w3) = mean(ir_breath(k-w3:k+w3));
end
figure(2)
subplot(2,1,2)
ir_breath_b = ir_breath(1+w3:length(ir_breath)-w3) - base3';
[pks3,loc3] = findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-
w3),'MinPeakHeight',.002,'MinPeakWidth',.1)
findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-w3)-
ts2,'MinPeakHeight',.002,'MinPeakWidth',.1)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 1 Under
Held-Breath Conditions','FontSize',14)
w4 = 20
for k = 1+w4:length(t_breath)-w4
  base4(k-w4) = mean(red_breath(k-w4:k+w4));
end
figure(1)
subplot(2,1,2)
red_breath_b = red_breath(1+w4:length(red_breath)-w4) - base4';
[pks4,loc4] = findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-
w4),'MinPeakHeight',.005,'MinPeakWidth',.1)
findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-w4)-
ts2,'MinPeakHeight',.005,'MinPeakWidth',.1)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 1 Under
Held-Breath Conditions','FontSize',14)
%% Merrill Thresholding
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=74);
el3 = el3(1);
el4 = find(t>=96);
el4 = el4(1);
ts1 = 35;
ts2 = 74;
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
w = 100
for k = 1+w:length(t_normal)-w
  base(k-w) = mean(red_normal(k-w:k+w));
end
red_normal_b = red_normal(1+w:length(red_normal)-w) - base';
figure(1)
subplot(2,1,1)
[pks1,loc1] = findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-
w),'MinPeakHeight',.004,'MinPeakWidth',.1)
hold on
```

```
findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-w)-
ts1,'MinPeakHeight',.004,'MinPeakWidth',.1)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 2 Under
Normal Breathing Conditions','FontSize',14)
w = 10
for k = 1+w:length(t_normal)-w
  base(k-w) = mean(ir_normal(k-w:k+w));
end
ir_normal_b = ir_normal(1+w:length(ir_normal)-w) - base';
figure(2)
subplot(2,1,1)
[pks2,loc2] = findpeaks(ir_normal_b,t_normal(1+w:length(t_normal)-
w),'MinPeakHeight',.001,'MinPeakWidth',.15)
hold on
findpeaks(ir_normal_b,t_normal(1+w:length(t_normal)-w)-
ts1,'MinPeakHeight',.001,'MinPeakWidth',.15)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 2 Under
Normal Breathing Conditions','FontSize',14)
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=74);
el3 = el3(1);
el4 = find(t>=96);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
w3 = 20
for k = 1+w3:length(t_breath)-w3
  base3(k-w3) = mean(ir_breath(k-w3:k+w3));
end
figure(2)
subplot(2,1,2)
ir_breath_b = ir_breath(1+w3:length(ir_breath)-w3) - base3';
[pks3,loc3] = findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-
w3),'MinPeakHeight',.001,'MinPeakWidth',.12)
findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-w3)-
ts2,'MinPeakHeight',.001,'MinPeakWidth',.12)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 2 Under
Held-Breath Conditions','FontSize',14)
w4 = 20
for k = 1+w4:length(t_breath)-w4
  base4(k-w4) = mean(red_breath(k-w4:k+w4));
end
figure(1)
subplot(2,1,2)
red_breath_b = red_breath(1+w4:length(red_breath)-w4) - base4';
[pks4,loc4] = findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-
w4),'MinPeakHeight',.004,'MinPeakWidth',.1)
findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-w4)-
ts2,'MinPeakHeight',.004,'MinPeakWidth',.1)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 2 Under
Held-Breath Conditions','FontSize',14)
%% Steven (TA) Thresholding
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=75);
el3 = el3(1);
el4 = find(t>=97);
el4 = el4(1);
ts1 = 38;
ts2 = 75;
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
w = 20
for k = 1+w:length(t_normal)-w
  base(k-w) = mean(red_normal(k-w:k+w));
end
red_normal_b = red_normal(1+w:length(red_normal)-w) - base';
figure(1)
subplot(2,1,1)
[pks1,loc1] = findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-
w),'MinPeakHeight',.006,'MinPeakWidth',.115)
hold on
findpeaks(red_normal_b,t_normal(1+w:length(t_normal)-w)-
ts1,'MinPeakHeight',.006,'MinPeakWidth',.115)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 3 Under
Normal Breathing Conditions','FontSize',14)
w2 = 20
for k = 1+w2:length(t_normal)-w2
  base2(k-w2) = mean(ir_normal(k-w2:k+w2));
end
ir_normal_b = ir_normal(1+w2:length(ir_normal)-w2) - base2';
figure(2)
subplot(2,1,1)
[pks2,loc2] = findpeaks(ir_normal_b,t_normal(1+w2:length(t_normal)-
w2),'MinPeakHeight',.0006,'MinPeakWidth',.115)
findpeaks(ir_normal_b,t_normal(1+w2:length(t_normal)-w2)-
ts1,'MinPeakHeight',.0006,'MinPeakWidth',.115)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 2 Under
Normal Breathing Conditions','FontSize',14)
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
normally
el1 = find(t >= 38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=75);
el3 = el3(1);
el4 = find(t>=97);
el4 = el4(1);
```

```
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
w3 = 20
for k = 1+w3:length(t_breath)-w3
  base3(k-w3) = mean(ir_breath(k-w3:k+w3));
end
figure(2)
subplot(2,1,2)
ir_breath_b = ir_breath(1+w3:length(ir_breath)-w3) - base3';
[pks3,loc3] = findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-
w3),'MinPeakHeight',.001,'MinPeakWidth',.12)
findpeaks(ir_breath_b,t_breath(1+w3:length(t_breath)-w3)-
ts2,'MinPeakHeight',.001,'MinPeakWidth',.12)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to IR Trace of Subject 3 Under
Held-Breath Conditions','FontSize',14)
w4 = 20
for k = 1+w4:length(t_breath)-w4
  base4(k-w4) = mean(red_breath(k-w4:k+w4));
end
figure(1)
subplot(2,1,2)
red_breath_b = red_breath(1+w4:length(red_breath)-w4) - base4';
[pks4,loc4] = findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-
w4),'MinPeakHeight',.008,'MinPeakWidth',.1)
findpeaks(red_breath_b,t_breath(1+w4:length(t_breath)-w4)-
ts2,'MinPeakHeight',.008,'MinPeakWidth',.1)
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Thresholding Method Applied to Red Trace of Subject 3 Under
Held-Breath Conditions','FontSize',14)
%% Fourier Method for Known Trace
close all
clear all
clc
dt = .001;
fs = 1/dt;
t = [0:dt:20];
A = 10*sin(3*2*pi*t)+10;    % frequency of 3 Hz + DC (0 Hz) term
f = [0:length(t)-1]*fs/length(t);
figure(1)
subplot(2,1,1)
plot(t,A,'k','LineWidth',1.5)
xlim([0 3])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude')
title('Simulated Known Trace: y = 10\cdotsin(6\pit) + 10','FontSize',14)
subplot(2,1,2)
freq = fftshift(abs(fft(A)))/length(t);
plot(f-fs/2,freq,'LineWidth',1.5)
xlim([-10,10])
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of Known Trace: y = 10\cdotsin(6\pit) +
10','FontSize',14)
%% Representative Overview of FT of Traces
% 1. Full FT (DC predominates)
% 2. Pos freqs without DC
% 3. Freqs. in physiological range
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
  el = find(t >= dt*k);
  el = el(1);
  els(k) = el;
end
f = fs*[0:length(els)-1]/length(els);
figure(1)
subplot(3,1,1)
hold on
plot(f-fs/2,fftshift(abs(fft(red(els)))/length(t)),'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Representative Full Fourier Transform (FT) of Experimental
Trace','FontSize',14)
ylim([0 3])
subplot(3,1,2)
plot(f,abs(fft(red(els)))/length(t),'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('FT from Above with DC Component Removed (Positive
Frequencies Only)','FontSize',14)
xlim([0.5 100])
subplot(3,1,3)
plot(f,abs(fft(red(els)))/length(t),'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('FT from Above Viewed in Physiological Frequency Range (0.5
Hz to 3 Hz)','FontSize',14)
xlim([0.5 3])
%% K normal breathing + hold breath RED & normal breathing + hold
breath IR
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
% Normal Breathing part of trace
el1 = find(t>=10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
  el = find(t >= dt*k);
  el = el(1);
  els(k) = el;
end
f = fs*[0:length(els)-1]/length(els);
% K hold breath part of trace
% RED
[tb,redb,irb] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=68);
el1b = el1b(1);
el2b = find(tb>=90);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
```

```
for k = 1:round(tb(end)/dt)-1
  elb = find(tb >= dt*k);
  elb = elb(1);
  elsb(k) = elb;
end
figure(1)
subplot(2,1,1)
hold on
plot(f,abs(fft(red(els)))/length(t),'Color',[.85 0 0],'LineWidth',1.5)
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(redb(elsb)))/length(tb),'Color',[0.6 0.3
0.6],'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of Red Traces for Subject 1','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath Conditions');
leg.FontSize = 12;
xlim([0.5 3])
% K normal breathing + hold breath IR
% IR
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
  el = find(t >= dt*k);
  el = el(1);
  els(k) = el;
end
[tb,redb,irb] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=68);
el1b = el1b(1);
el2b = find(tb>=90);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
for k = 1:round(tb(end)/dt)-1
  elb = find(tb >= dt*k);
  elb = elb(1);
  elsb(k) = elb;
end
subplot(2,1,2)
hold on
f = fs*[0:length(els)-1]/length(els);
plot(f,abs(fft(ir(els)))/length(t),'Color',[0 0 .85],'LineWidth',1.5)
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(irb(elsb)))/length(tb),'Color',[0 .5 1],'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of IR Traces for Subject 1','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath Conditions');
leg.FontSize = 12;
xlim([0.5 3])
%% M normal breathing + hold breath RED & normal breathing + hold
breath IR
% RED
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
  el = find(t >= dt*k);
  el = el(1);
  els(k) = el;
end
[tb,redb,irb] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=74);
el1b = el1b(1);
el2b = find(tb>=96);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
for k = 1:round(tb(end)/dt)-1
  elb = find(tb >= dt*k);
  elb = elb(1);
  elsb(k) = elb;
end
figure(1)
subplot(2,1,1)
hold on
f = fs*[0:length(els)-1]/length(els);
plot(f,abs(fft(red(els))/length(els)),'Color',[.85 0 0],'LineWidth',1.5)
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(redb(elsb))/length(elsb)),'Color',[0.6 0.3
0.6],'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of Red Traces for Subject 2','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath Conditions');
leg.FontSize = 12;
xlim([0.5 3])
% M normal breathing IR
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
  el = find(t >= dt*k);
  el = el(1);
  els(k) = el;
end
% M hold breath IR
[tb,redb,irb] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=74);
el1b = el1b(1);
el2b = find(tb>=96);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
for k = 1:round(tb(end)/dt)-1
  elb = find(tb >= dt*k);
```

```
   elb = elb(1);
   elsb(k) = elb;
end
subplot(2,1,2)
hold on
f = fs*[0:length(els)-1]/length(els);
plot(f,abs(fft(ir(els)))/length(els),'Color',[0 0 .85],'LineWidth',1.5)
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(irb(elsb)))/length(elsb),'Color',[0 .5 1],'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of IR Traces for Subject 2','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath Conditions');
leg.FontSize = 12;
xlim([0.5 3])
ylim([0 4e-4])
%% TA Steven normal breathing + held breath red & NB + HB IR
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005;
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
   el = find(t >= dt*k);
   el = el(1);
   els(k) = el;
end
% hold breath RED
[tb,redb,irb] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=75);
el1b = el1b(1);
el2b = find(tb>=97);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
for k = 1:round(tb(end)/dt)-1
   elb = find(tb >= dt*k);
   elb = elb(1);
   elsb(k) = elb;
end
figure(1)
subplot(2,1,1)
hold on
f = fs*[0:length(els)-1]/length(els);
plot(f,abs(fft(red(els)))/length(els),'Color',[.85 0 0],'LineWidth',1.5);
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(redb(elsb)))/length(elsb),'Color',[0.6 0.3
0.6],'LineWidth',1.5)
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of Red Traces for Subject 3','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath
Conditions','Location','northwest');
leg.FontSize = 12;
xlim([0.6 3])
% normal breathing IR
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
dt = .005
fs = 1/dt;
for k = 1:round(t(end)/dt)-1
   el = find(t >= dt*k);
   el = el(1);
   els(k) = el;
end
% hold breath IR
[tb,redb,irb] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=75);
el1b = el1b(1);
el2b = find(tb>=97);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
dt = .005
fs = 1/dt;
for k = 1:round(tb(end)/dt)-1
   elb = find(tb >= dt*k);
   elb = elb(1);
   elsb(k) = elb;
end
subplot(2,1,2)
hold on
spec  = abs(fft(ir(els)));
f = fs*[0:length(els)-1]/length(els);
plot(f,abs(fft(ir(els)))/length(els),'Color',[0 0 .85],'LineWidth',1.5);
fb = fs*[0:length(elsb)-1]/length(elsb);
plot(fb,abs(fft(irb(elsb)))/length(elsb),'Color',[0 .5 1],'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Fourier Transform of IR Traces for Subject 3','FontSize',14)
leg = legend('Normal Breathing Conditions','Held-Breath
Conditions','location','northwest');
leg.FontSize = 12;
xlim([0.6 3])
%% frequency of max peak of spectrum code:
spec  = abs(fft(ir(els)));
f = fs*[0:length(els)-1]/length(els);
plot(f,spec);
l1 = find(f>=0.5);
l1 = l1(1);
l2 = find(f>=3);
l2 = l2(1);
[a,b] = max(spec(l1:l2));
freq = f(b+l1-1)
xlim([0.5 3]);
%% Hz to BPM
hz = [1.76 1.455 1.369 1.229 1.882 1.784 1.76 1.444 1.369 1.229 1.882
1.794];
bpm = 60*hz
%% K normal breathing & holding breath subsets RED + IR
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
l = length(red);
N = 8;
x = floor(l/N);
```

```
for n = 1:N
   red_sub(n,:) = red(1+(n-1)*x:n*x);
   t_sub(n,:) = t(1+(n-1)*x:n*x);
   dt_sub(n) = (t_sub(n,end)-t_sub(n,1))/x;
   fs_sub(n) = 1/dt_sub(n);
   f_sub(n,:) = fs_sub(n)*[0:x-1]/x;
   spec(n,:) = abs(fft(red_sub(n,:)))/length(t_sub(n,:));
end
figure(9)
subplot(2,2,1)
hold on
plot(f_sub(1,:),spec(1,:),'LineWidth',1.5);
plot(f_sub(2,:),spec(2,:),'LineWidth',1.5);
plot(f_sub(3,:),spec(3,:),'LineWidth',1.5);
plot(f_sub(4,:),spec(4,:),'LineWidth',1.5);
plot(f_sub(5,:),spec(5,:),'LineWidth',1.5);
plot(f_sub(6,:),spec(6,:),'LineWidth',1.5);
plot(f_sub(7,:),spec(7,:),'LineWidth',1.5);
plot(f_sub(8,:),spec(8,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 1', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','6','7','8');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tb,redb,irb] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=70);
el1b = el1b(1);
el2b = find(tb>=90);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
plot(tb,redb)
lb = length(redb);
Nb = 4;
xb = floor(lb/Nb);
for n = 1:Nb
   red_subb(n,:) = redb(1+(n-1)*xb:n*xb);
   t_subb(n,:) = tb(1+(n-1)*xb:n*xb);
   dt_subb(n) = (t_subb(n,end)-t_subb(n,1))/xb;
   fs_subb(n) = 1/dt_subb(n);
   f_subb(n,:) = fs_subb(n)*[0:xb-1]/xb;
   specb(n,:) = abs(fft(red_subb(n,:)))/length(red_subb(n,:));
end
subplot(2,2,2)
hold on
plot(f_subb(1,:),specb(1,:),'LineWidth',1.5);
plot(f_subb(2,:),specb(2,:),'LineWidth',1.5);
plot(f_subb(3,:),specb(3,:),'LineWidth',1.5);
plot(f_subb(4,:),specb(4,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 1', 'Under Held-
Breath Conditions'},'FontSize',14)
leg = legend('1','2','3','4');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tc,redc,irc] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1c = find(tc>=10);
el1c = el1c(1);
el2c = find(tc>=50);
el2c = el2c(1)
tc = tc(el1c:el2c);
redc = redc(el1c:el2c);
irc = irc(el1c:el2c);
lc = length(redc);
Nc = 8;
xc = floor(lc/Nc);
for n = 1:Nc
   ir_subc(n,:) = irc(1+(n-1)*xc:n*xc);
   t_subc(n,:) = tc(1+(n-1)*xc:n*xc);
   dt_subc(n) = (t_subc(n,end)-t_subc(n,1))/xc;
   fs_subc(n) = 1/dt_subc(n);
   f_subc(n,:) = fs_subc(n)*[0:xc-1]/xc;
   specc(n,:) = abs(fft(ir_subc(n,:)))/length(ir_subc(n,:));
end
subplot(2,2,3)
hold on
plot(f_subc(1,:),specc(1,:),'LineWidth',1.5);
plot(f_subc(2,:),specc(2,:),'LineWidth',1.5);
plot(f_subc(3,:),specc(3,:),'LineWidth',1.5);
plot(f_subc(4,:),specc(4,:),'LineWidth',1.5);
plot(f_subc(5,:),specc(5,:),'LineWidth',1.5);
plot(f_subc(6,:),specc(6,:),'LineWidth',1.5);
plot(f_subc(7,:),specc(7,:),'LineWidth',1.5);
plot(f_subc(8,:),specc(8,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 1', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','6','7','8');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[td,redd,ird] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
el1d = find(td>=70);
el1d = el1d(1);
el2d = find(td>=90);
el2d = el2d(1)
td = td(el1d:el2d);
redd = redd(el1d:el2d);
ird = ird(el1d:el2d);
ld = length(redd);
Nd = 4;
xd = floor(ld/Nd);
for n = 1:Nd
   ir_subd(n,:) = ird(1+(n-1)*xd:n*xd);
   t_subd(n,:) = td(1+(n-1)*xd:n*xd);
   dt_subd(n) = (t_subd(n,end)-t_subd(n,1))/xd;
   fs_subd(n) = 1/dt_subd(n);
   f_subd(n,:) = fs_subd(n)*[0:xd-1]/xd;
   specd(n,:) = abs(fft(ir_subd(n,:)))/length(ir_subd(n,:));
end
subplot(2,2,4)
hold on
plot(f_subd(1,:),specd(1,:),'LineWidth',1.5);
plot(f_subd(2,:),specd(2,:),'LineWidth',1.5);
plot(f_subd(3,:),specd(3,:),'LineWidth',1.5);
plot(f_subd(4,:),specd(4,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 1', 'Under Held-Breath
Conditions'},'FontSize',14)
leg = legend('1','2','3','4');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
%% M normal breathing & hold breath subsets RED + IR
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=35);
el1 = el1(1);
```

```
el2 = find(t>=65);
el2 = el2(1)
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
l = length(red);
N = 5;
x = floor(l/N);
for n = 1:N
  red_sub(n,:) = red(1+(n-1)*x:n*x);
  t_sub(n,:) = t(1+(n-1)*x:n*x);
  dt_sub(n) = (t_sub(n,end)-t_sub(n,1))/x;
  fs_sub(n) = 1/dt_sub(n);
  f_sub(n,:) = fs_sub(n)*[0:x-1]/x;
  spec(n,:) = abs(fft(red_sub(n,:)))/length(red_sub(n,:));
end
subplot(2,2,1)
hold on
plot(f_sub(1,:),spec(1,:),'LineWidth',1.5);
plot(f_sub(2,:),spec(2,:),'LineWidth',1.5);
plot(f_sub(3,:),spec(3,:),'LineWidth',1.5);
plot(f_sub(4,:),spec(4,:),'LineWidth',1.5);
plot(f_sub(5,:),spec(5,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 2', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tb,redb,irb] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=74);
el1b = el1b(1);
el2b = find(tb>=96);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);
lb = length(redb);
Nb = 3;
xb = floor(lb/Nb);
for n = 1:Nb
  red_subb(n,:) = redb(1+(n-1)*xb:n*xb);
  t_subb(n,:) = tb(1+(n-1)*xb:n*xb);
  dt_subb(n) = (t_subb(n,end)-t_subb(n,1))/xb;
  fs_subb(n) = 1/dt_subb(n);
  f_subb(n,:) = fs_subb(n)*[0:xb-1]/xb;
  specb(n,:) = abs(fft(red_subb(n,:)))/length(red_subb(n,:));
end
subplot(2,2,2)
hold on
plot(f_subb(1,:),specb(1,:),'LineWidth',1.5);
plot(f_subb(2,:),specb(2,:),'LineWidth',1.5);
plot(f_subb(3,:),specb(3,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 2', 'Under Held-
Breath Conditions'},'FontSize',14)
leg = legend('1','2','3','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tc,redc,irc] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1c = find(tc>=35);
el1c = el1c(1);
el2c = find(tc>=65);
el2c = el2c(1)
tc = tc(el1c:el2c);
redc = redc(el1c:el2c);
irc = irc(el1c:el2c);
lc = length(redc);
Nc = 5;
xc = floor(lc/Nc);
for n = 1:Nc
  ir_subc(n,:) = irc(1+(n-1)*xc:n*xc);
  t_subc(n,:) = tc(1+(n-1)*xc:n*xc);
  dt_subc(n) = (t_subc(n,end)-t_subc(n,1))/xc;
  fs_subc(n) = 1/dt_subc(n);
  f_subc(n,:) = fs_subc(n)*[0:xc-1]/xc;
  specc(n,:) = abs(fft(ir_subc(n,:)))/length(ir_subc(n,:));
end
subplot(2,2,3)
hold on
plot(f_subc(1,:),specc(1,:),'LineWidth',1.5);
plot(f_subc(2,:),specc(2,:),'LineWidth',1.5);
plot(f_subc(3,:),specc(3,:),'LineWidth',1.5);
plot(f_subc(4,:),specc(4,:),'LineWidth',1.5);
plot(f_subc(5,:),specc(5,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 2', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[td,redd,ird] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
el1d = find(td>=74);
el1d = el1d(1);
el2d = find(td>=96);
el2d = el2d(1)
td = td(el1d:el2d);
redd = redd(el1d:el2d);
ird = ird(el1d:el2d);
ld = length(redd);
Nd = 3;
xd = floor(ld/Nd);
for n = 1:Nd
  ir_subd(n,:) = ird(1+(n-1)*xd:n*xd);
  t_subd(n,:) = td(1+(n-1)*xd:n*xd);
  dt_subd(n) = (t_subd(n,end)-t_subd(n,1))/xd;
  fs_subd(n) = 1/dt_subd(n);
  f_subd(n,:) = fs_subd(n)*[0:xd-1]/xd;
  specd(n,:) = abs(fft(ir_subd(n,:)))/length(ir_subd(:,n));
end
subplot(2,2,4)
hold on
plot(f_subd(1,:),specd(1,:),'LineWidth',1.5);
plot(f_subd(2,:),specd(2,:),'LineWidth',1.5);
plot(f_subd(3,:),specd(3,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 2', 'Under Held-Breath
Conditions'},'FontSize',14)
leg = legend('1','2','3','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
%% S normal breathing & hold breath subsets RED + IR
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1 = find(t>=38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1)
```

```
t = t(el1:el2);
red = red(el1:el2);
ir = ir(el1:el2);
l = length(red);
N = 7;
x = floor(l/N);
for n = 1:N
  red_sub(n,:) = red(1+(n-1)*x:n*x);
  t_sub(n,:) = t(1+(n-1)*x:n*x);
  dt_sub(n) = (t_sub(n,end)-t_sub(n,1))/x;
  fs_sub(n) = 1/dt_sub(n);
  f_sub(n,:) = fs_sub(n)*[0:x-1]/x;
  spec(n,:) = abs(fft(red_sub(n,:)))/length(red_sub(n,:));
end
subplot(2,2,1)
hold on
plot(f_sub(1,:),spec(1,:),'LineWidth',1.5);
plot(f_sub(2,:),spec(2,:),'LineWidth',1.5);
plot(f_sub(3,:),spec(3,:),'LineWidth',1.5);
plot(f_sub(4,:),spec(4,:),'LineWidth',1.5);
plot(f_sub(5,:),spec(5,:),'LineWidth',1.5);
plot(f_sub(6,:),spec(6,:),'LineWidth',1.5);
plot(f_sub(7,:),spec(7,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 3', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','6','7','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tb,redb,irb] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1b = find(tb>=75);
el1b = el1b(1);
el2b = find(tb>=97);
el2b = el2b(1)
tb = tb(el1b:el2b);
redb = redb(el1b:el2b);
irb = irb(el1b:el2b);

lb = length(redb);
Nb = 5;
xb = floor(lb/Nb);
for n = 1:Nb
  red_subb(n,:) = redb(1+(n-1)*xb:n*xb);
  t_subb(n,:) = tb(1+(n-1)*xb:n*xb);
  dt_subb(n) = (t_subb(n,end)-t_subb(n,1))/xb;
  fs_subb(n) = 1/dt_subb(n);
  f_subb(n,:) = fs_subb(n)*[0:xb-1]/xb;
  specb(n,:) = abs(fft(red_subb(n,:)))/length(red_subb(n,:));
end
subplot(2,2,2)
hold on
plot(f_subb(1,:),specb(1,:),'LineWidth',1.5);
plot(f_subb(2,:),specb(2,:),'LineWidth',1.5);
plot(f_subb(3,:),specb(3,:),'LineWidth',1.5);
plot(f_subb(4,:),specb(4,:),'LineWidth',1.5);
plot(f_subb(5,:),specb(5,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of Red Trace for Subject 3', 'Under Held-
Breath Conditions'},'FontSize',14)
leg = legend('1','2','3','4','5','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[tc,redc,irc] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1c = find(tc>=38);
el1c = el1c(1);
el2c = find(tc>=68);
el2c = el2c(1)
tc = tc(el1c:el2c);
redc = redc(el1c:el2c);
irc = irc(el1c:el2c);
lc = length(redc);
Nc = 3;
xc = floor(lc/Nc);
for n = 1:Nc
  ir_subc(n,:) = irc(1+(n-1)*xc:n*xc);
  t_subc(n,:) = tc(1+(n-1)*xc:n*xc);
  dt_subc(n) = (t_subc(n,end)-t_subc(n,1))/xc;
  fs_subc(n) = 1/dt_subc(n);
  f_subc(n,:) = fs_subc(n)*[0:xc-1]/xc;
  specc(n,:) = abs(fft(ir_subc(n,:)))/length(ir_subc(n,:));
end
subplot(2,2,3)
hold on
plot(f_subc(1,:),specc(1,:),'LineWidth',1.5);
plot(f_subc(2,:),specc(2,:),'LineWidth',1.5);
plot(f_subc(3,:),specc(3,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 3', 'Under Normal
Breathing Conditions'},'FontSize',14)
leg = legend('1','2','3','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
[td,redd,ird] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
el1d = find(td>=75);
el1d = el1d(1);
el2d = find(td>=97);
el2d = el2d(1)
td = td(el1d:el2d);
redd = redd(el1d:el2d);
ird = ird(el1d:el2d);

ld = length(redd);
Nd = 5;
xd = floor(ld/Nd);
for n = 1:Nd
  ir_subd(n,:) = ird(1+(n-1)*xd:n*xd);
  t_subd(n,:) = td(1+(n-1)*xd:n*xd);
  dt_subd(n) = (t_subd(n,end)-t_subd(n,1))/xd;
  fs_subd(n) = 1/dt_subd(n);
  f_subd(n,:) = fs_subd(n)*[0:xd-1]/xd;
  specd(n,:) = abs(fft(ir_subd(n,:)))/length(ir_subd(n,:));
end
subplot(2,2,4)
hold on
plot(f_subd(1,:),specd(1,:),'LineWidth',1.5);
plot(f_subd(2,:),specd(2,:),'LineWidth',1.5);
plot(f_subd(3,:),specd(3,:),'LineWidth',1.5);
plot(f_subd(4,:),specd(4,:),'LineWidth',1.5);
set(gca,'FontSize',12)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title({'FT of Each Subset of IR Trace for Subject 3', 'Under Held-Breath
Conditions'},'FontSize',14)
leg = legend('1','2','3','4','Location','northwest');
leg.FontSize = 10;
t = get(leg,'title');
set(t,'string','Subsets');
xlim([0.5 3]);
%% standard deviations
close all
clear all
clc
submaxes{1} = [1.696 1.842 1.737 1.667 1.717 1.74 1.829 1.782]; % K
R NB
submaxes{2} = [1.344 1.39 1.419 1.476]; % K R HB
```

```
submaxes{3} = [1.696 1.842 1.737 1.667 1.717 1.74 1.829 1.782]; % K
IR NB
submaxes{4} = [1.419 1.39 1.476 1.344]; % K IR HB
submaxes{5} = [1.337 1.457 1.402 1.456 1.378]; % M R NB
submaxes{6} = [1.246 1.162 1.292]; % M R HB
submaxes{7} = [1.337 1.402 1.457 1.378 1.456]; % M IR NB
submaxes{8} = [1.292 1.246 1.291]; % M IR HB
submaxes{9} = [1.815 1.889 2.005 1.999 1.922 1.935 2.057]; % S R
NB
submaxes{10} = [1.899 1.994 1.957 1.845 1.879]; % S R HB
submaxes{11} = [1.871 2.051 1.901]; % S IR NB
submaxes{12} = [1.899 1.845 1.879 1.994]; % S IR HB
for k = 1:12
  d = submaxes{k};
  st_dev(k) = std(d);
  subset_bpm{k} = 60*d;
end
st_dev
st_dev_bpm = 60*st_dev
subset_bpm
%% K raw data plot
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_13.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 10);
el1 = el1(1);
el2 = find(t>=50);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=69);
el3 = el3(1);
el4 = find(t>=90);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
subplot(4,1,1)
plot(t_normal-10,red_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 1 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,2)
plot(t_breath-69,red_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 1 Under Held-Breath
Conditions','FontSize',14)
subplot(4,1,3)
plot(t_normal-10,ir_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 1 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,4)
plot(t_breath-69,ir_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 1 Under Held-Breath
Conditions','FontSize',14)
%% M raw data plot
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_14.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 35);
el1 = el1(1);
el2 = find(t>=65);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=74);
el3 = el3(1);
el4 = find(t>=96);
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
subplot(4,1,1)
plot(t_normal-35,red_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 2 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,2)
plot(t_breath-74,red_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 2 Under Held-Breath
Conditions','FontSize',14)
subplot(4,1,3)
plot(t_normal-35,ir_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 2 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,4)
plot(t_breath-74,ir_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 2 Under Held-Breath
Conditions','FontSize',14)
%% S (TA) raw data plot
close all
clear all
clc
[t,red,ir] = textread('rominger_datwyler_lab6_15.lvm', '%n %n
%n','headerlines',22);
% el1 to el2 correspond to part of trial where subject was breathing
 normally
el1 = find(t >= 38);
el1 = el1(1);
el2 = find(t>=68);
el2 = el2(1);
% el3 to el4 correspond to part of trial where subject was holding
 breath (once steady state was reached)
el3 = find(t>=75);
el3 = el3(1);
el4 = find(t>=97);
```

```
el4 = el4(1);
t_normal = t(el1:el2);
t_breath = t(el3:el4);
red_normal = red(el1:el2);
red_breath = red(el3:el4);
ir_normal = ir(el1:el2);
ir_breath = ir(el3:el4);
subplot(4,1,1)
plot(t_normal-38,red_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 3 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,2)
plot(t_breath-75,red_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('Red Trace of Subject 3 Under Held-Breath
Conditions','FontSize',14)
subplot(4,1,3)
plot(t_normal-38,ir_normal)
xlim([0 30]);
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 3 Under Normal Breathing
Conditions','FontSize',14)
subplot(4,1,4)
plot(t_breath-75,ir_breath)
xlim([0 21])
set(gca,'FontSize',12)
xlabel('Time (s)')
ylabel('Amplitude (V)')
title('IR Trace of Subject 3 Under Held-Breath
Conditions','FontSize',14)
```

Bibliography

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