HRV Analysis

Lesson 12a

Background
Heart Rate Variability

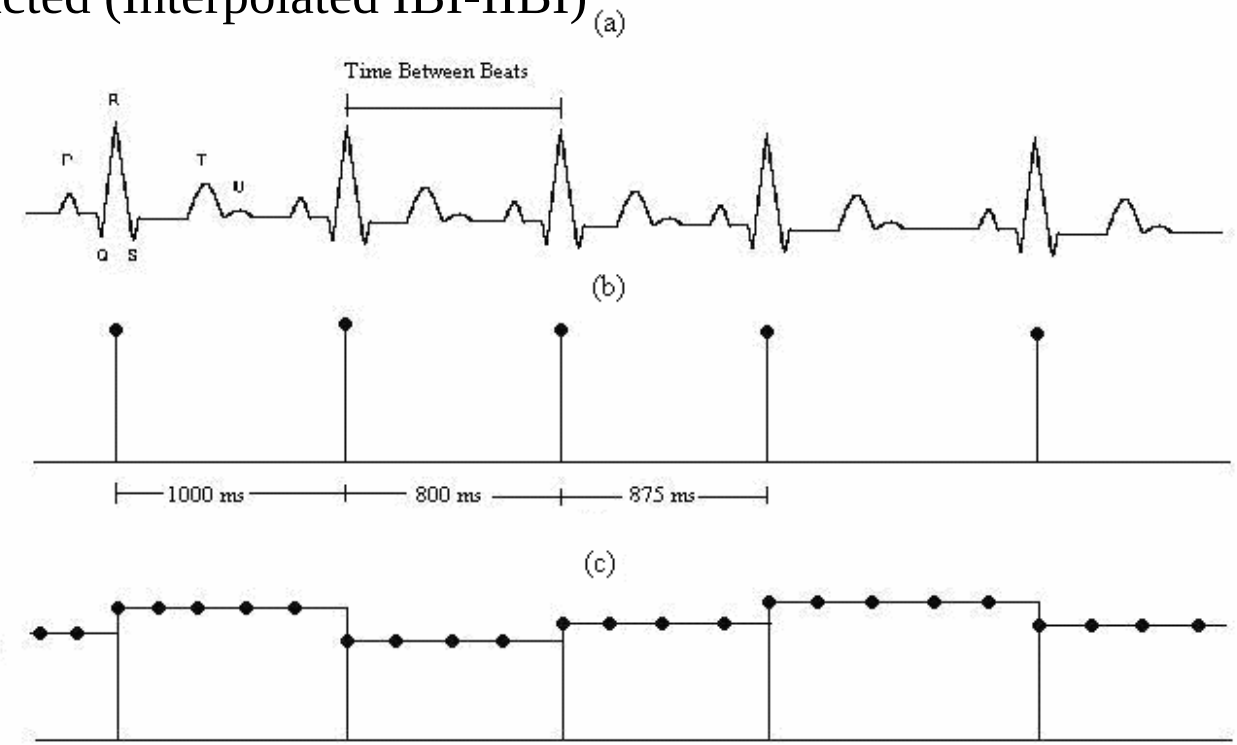
- Ability of the heart to handle the ever-present stresses and relaxations placed on the body
  - Stresses: Physical, Psychological
  - Relaxations: Recovery from these stresses
- One may conclude the greater the variability, the better the heart can keep up with changes and, therefore, healthier the person

Ways to Measure HRV

- From ECG R-wave intervals
  - Time Domain Analysis
    - Statistics of the R-R intervals
  - Frequency Domain Analysis
    - Power Spectrum calculated from the R-R intervals
  - Joint Time-Frequency Analysis

Background
HRV Power Spectrum

- From R-wave ECG intervals (Inter-Beat Interval-IBI) a special time sequence is constructed (Interpolated IBI-IIBI)

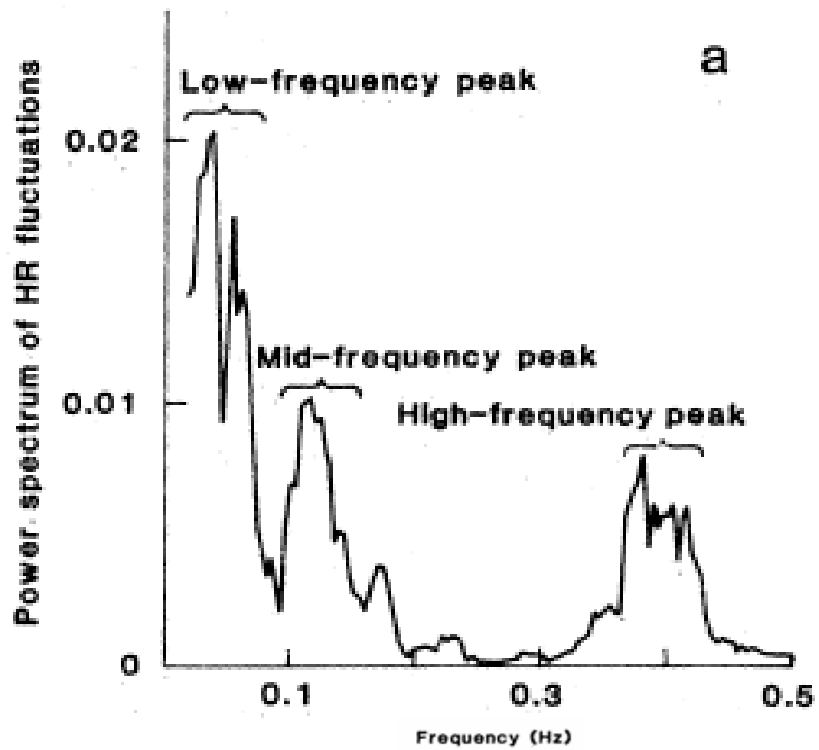


- From the IIBI, an HRV power spectrum can be obtained

From Pierre Asselin, *Relationship Between The Autonomic Nervous System and The Recovering Heart Post Exercise Using Heart Rate Variability*, NJIT Masters Thesis, May 2005 - Tools by Rockland and Asselin

Background
HRV Measurements

- From the IIBI, the HRV power spectrum is generated.



Borrowed from Power Spectrum Analysis of Heart Rate Fluctuation: A Quantitative Probe of Beat-To-Beat Cardiovascular Control, S. Akselrod, et.al. Science Vol. 213, 1981

Background
HRV Power Spectrum

- From the HRV Spectrum, there are two bands of interest:
  - The high frequency (HF) band (typically defined between 0.15 Hz and 0.7 Hz)
  - The low frequency (LF) band (typically defined between 0.04 Hz and 0.15 Hz)

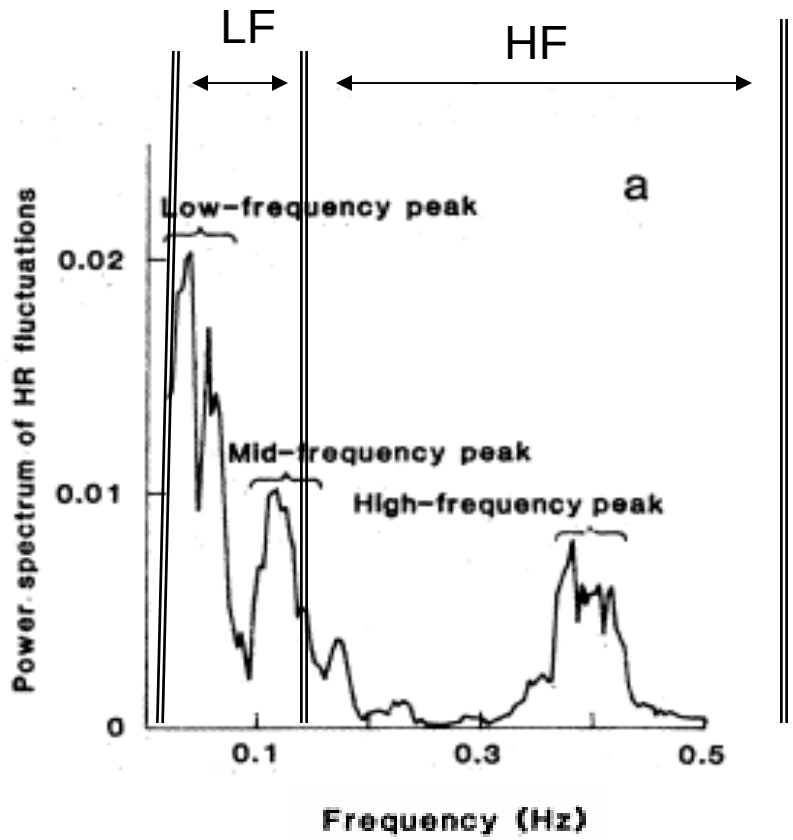


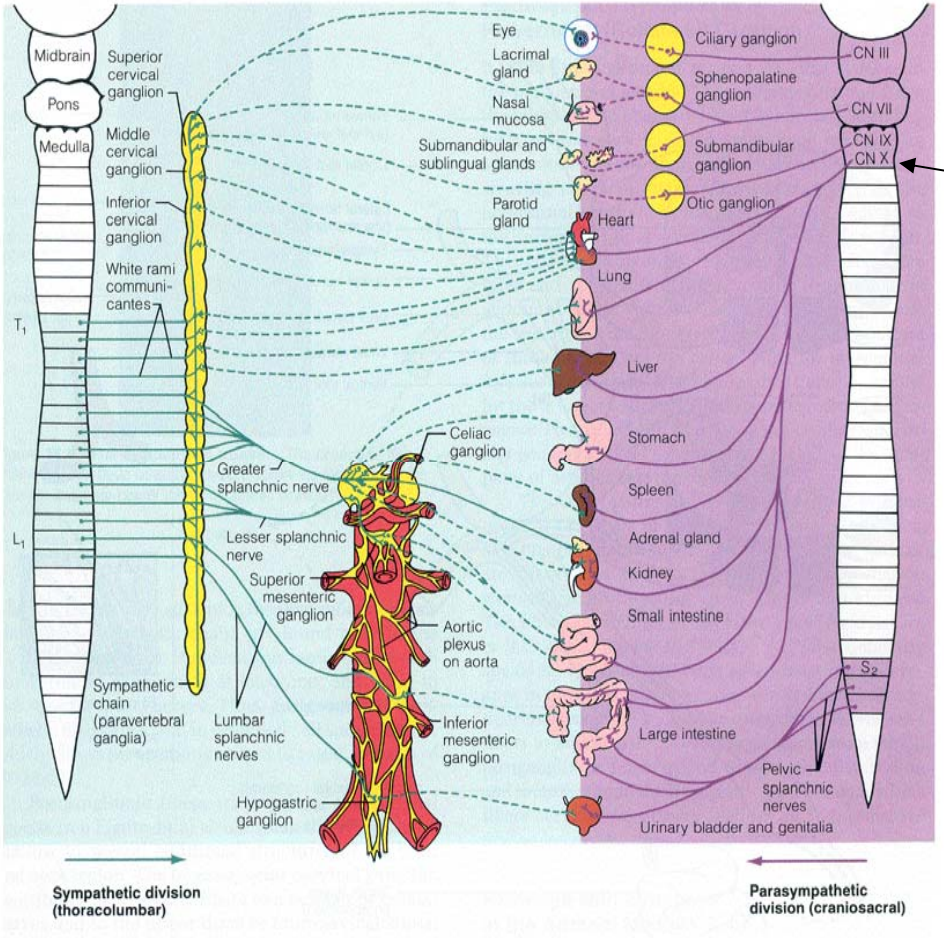
Figure borrowed from Power Spectrum Analysis of Heart Rate Fluctuation: A Quantitative Probe of Beat-To-Beat Cardiovascular Control, S. Akselrod, et.al. Science Vol. 213, 1981

Background

Autonomic Nervous System and HRV

- Sympathetic Branch – increases the heart rate as a result of stress
- Parasympathetic Branch – decreases the heart rate to recover from a stressful state
- It has been shown that:
  - The HF HRV frequency band is dependent on the Parasympathetic branch
  - The LF HRV frequency band is dependent on both the Parasympathetic and Sympathetic branches
  - Ratio of LF/HF measure of ANS balance

The sympathetic nervous system and parasympathetic nervous system

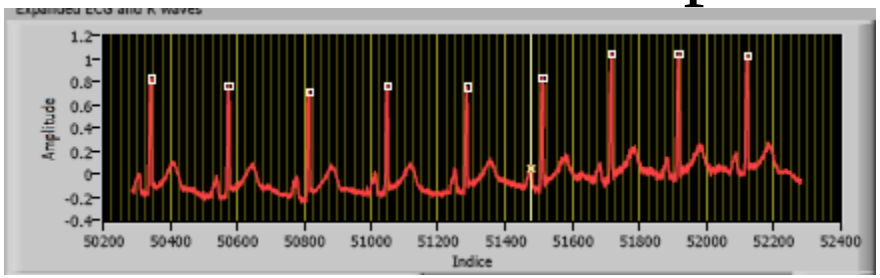


The Vagus Nerve
CN X

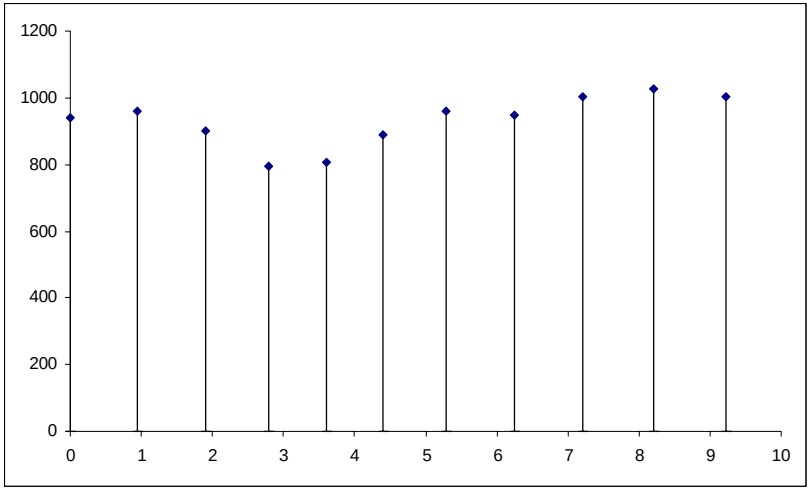
(From E. N. Marieb, Human Anatomy and Physiology, 3rd ed. New York: The Benjamin/Cummings Publishing Company, Inc., 1995.)

Obtaining the IIBI

- Partial data taken from a patient ECG



- IBI obtained using Labview



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1032
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852

Time Domain Techniques

- From this data we can calculate means, variances, standard deviations.

Mean	872.6
Variance	7254.4
SD	85.2
RMS	96.8
Number	360.0

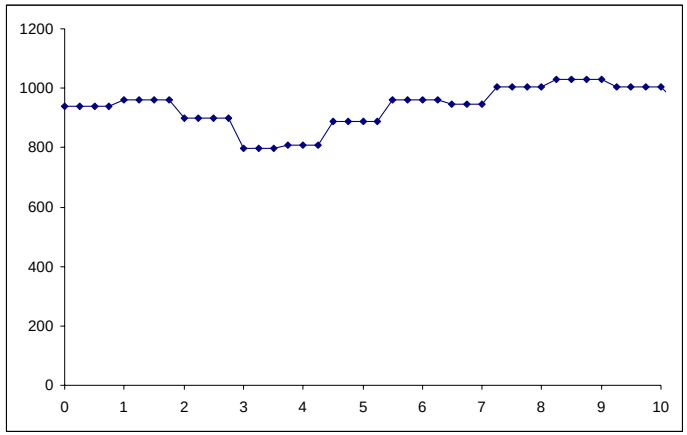
- What does this tell us?

Background
Frequency Domain Techniques

- Using the Fourier Transform to obtain the HRV Spectrum

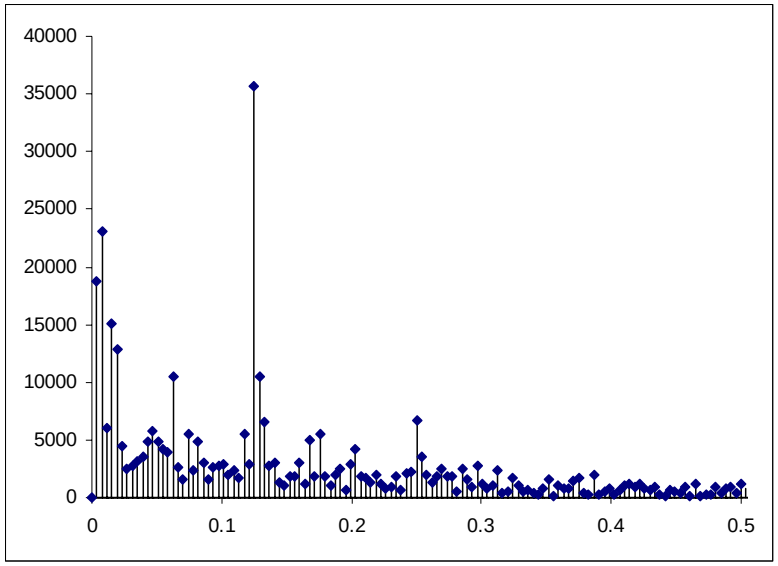
$$X(f) = \int_{-\infty}^{\infty} x(t) \cdot e^{-2j\pi ft} dt$$

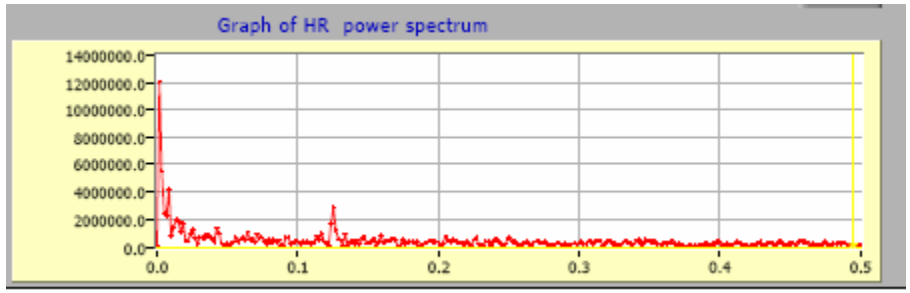
- IIBI obtained from IBI: sample rate 4s/s



FFT

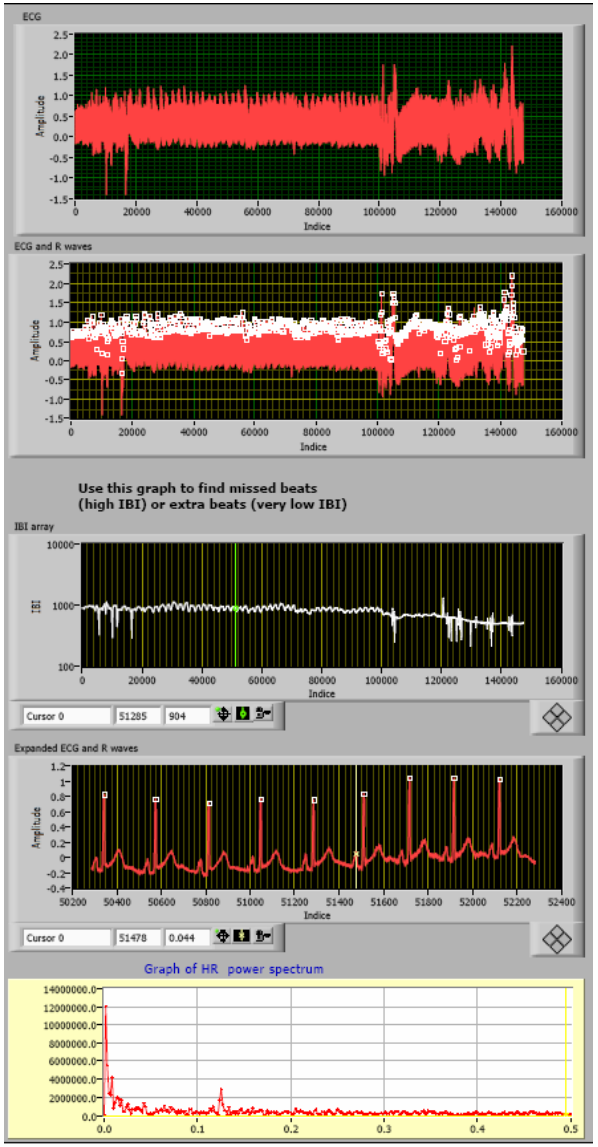
- Fast Fourier Transform of the IIBI sequence
- Note patient was supposed to be breathing at 12 breaths/min = 0.2 Hz





- This tells us more but is that enough?

Labview



Pane 1. ECG

Pane 2. R-wave Detection

Pane 3. IBI signal

Pane 4. Expanded ECG

Pane 5. HRV Spectrum

Background
Frequency Domain Techniques

- Integration is over time no information about frequency changes over time
- If we want to observe HRV as stresses and relaxations occur and how the ANS operates, we need a better method than the FT
- Use Joint Time-Frequency Analysis - JTFA

Background
JTFA Techniques

- Windowing and the FT (STFT)

$$STFT(\tau, f) = \int_{\tau-\Delta}^{\tau+\Delta} \left[x(t)\gamma^*(t-\tau) \right] \cdot e^{-j2\pi ft} dt$$

  - This method yields which frequencies are present over the span of time defined by the window
  - However, too short a window may miss lower frequencies while too long a window may miss any frequency changes in time
  - Hence we have a time and frequency resolution problem

Background
JTFA Techniques

- Wavelets

$$WT(s,\tau) = \int_{-\infty}^{\infty} |s|^{-1/2} x(t)\psi^*\left(\frac{t-\tau}{s}\right)dt$$

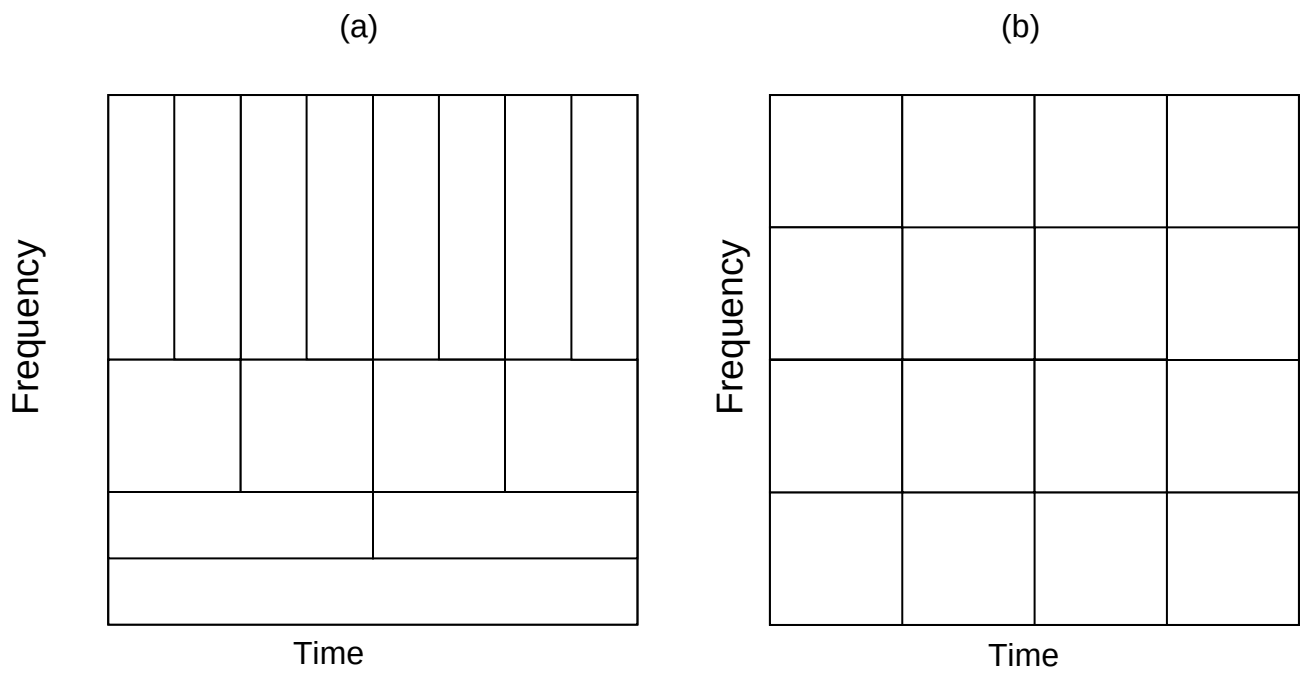
  - Wavelets tries to overcome the such problems techniques
  - The signal is multiplied by a “window/transformation” function where the window can be both
    - Widened and narrowed (scale parameter: s)
    - Time shifted (time shift parameter: τ)
  - For example, for a given τ, several calculations of WT can be made for various values of s
  - As a result a 3D plot is obtained

Background
JTFA Techniques

- Wavelets
  - Since it can be shown that frequency and the scale parameter are inversely related, then we can build a 3D plot of frequency changes in time
  - However, we still have resolution problem due to the Heisenberg Uncertainty Principle – a tradeoff between time and frequency resolution

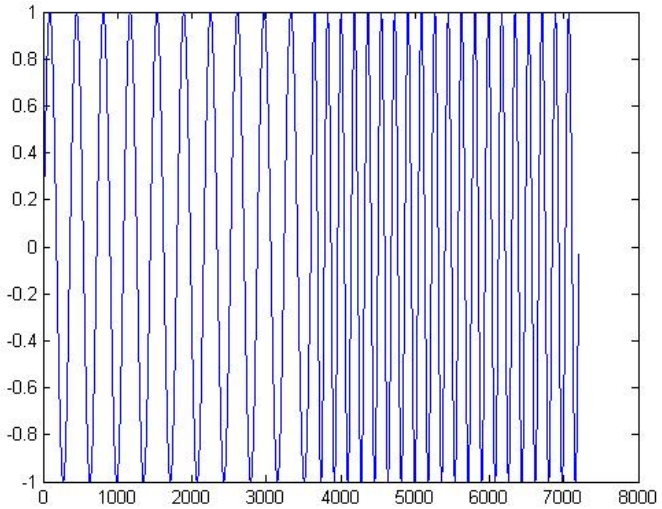
Heisenberg Uncertainty Principle

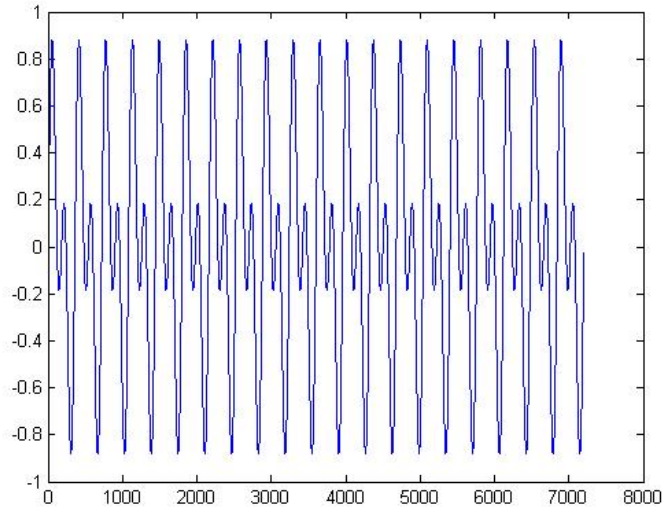
- Figure (a) for Wavelets, (b) for STFT



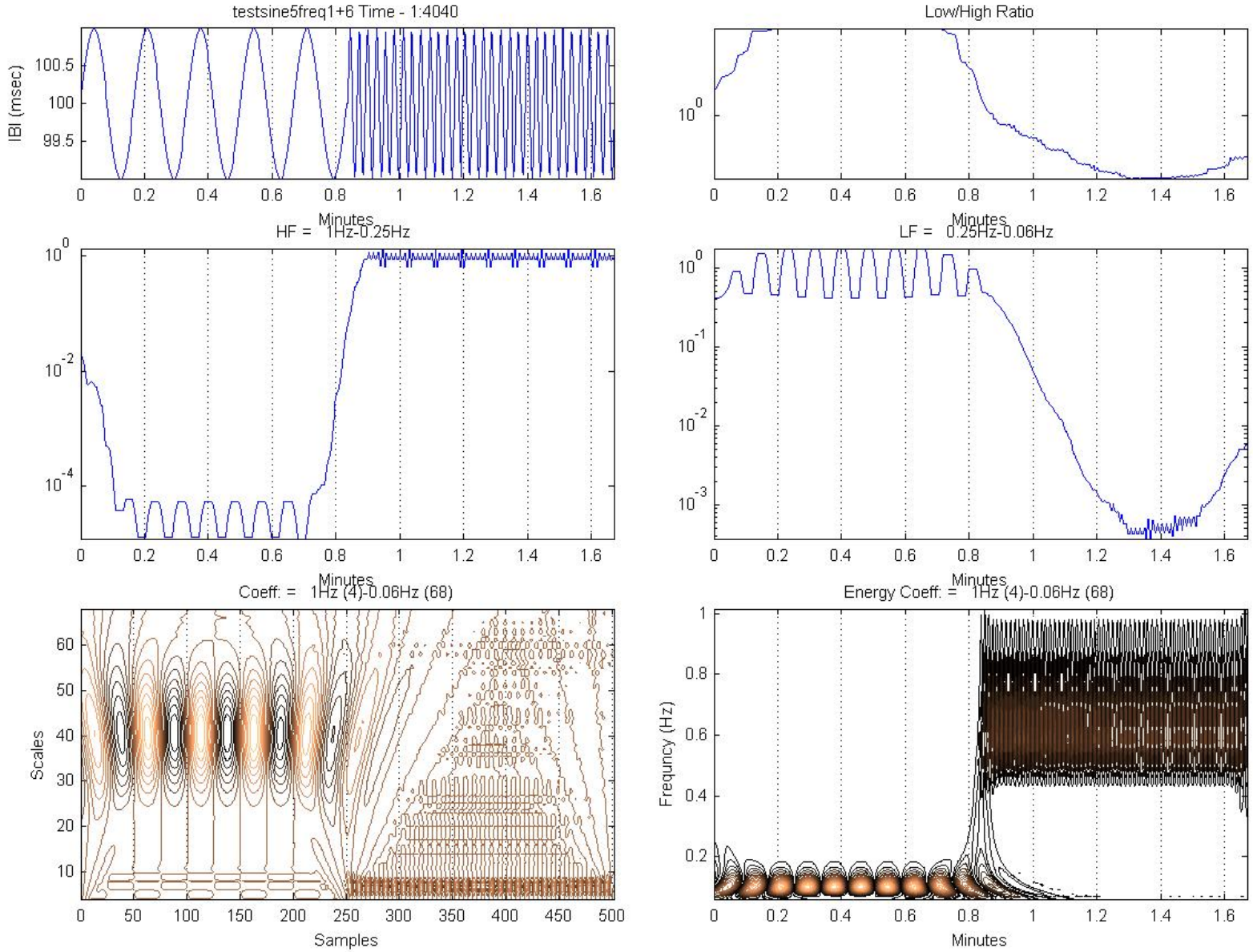
Background
A Classic Test

- How do we distinguish between sequential series of frequencies vs concurrent series of frequencies

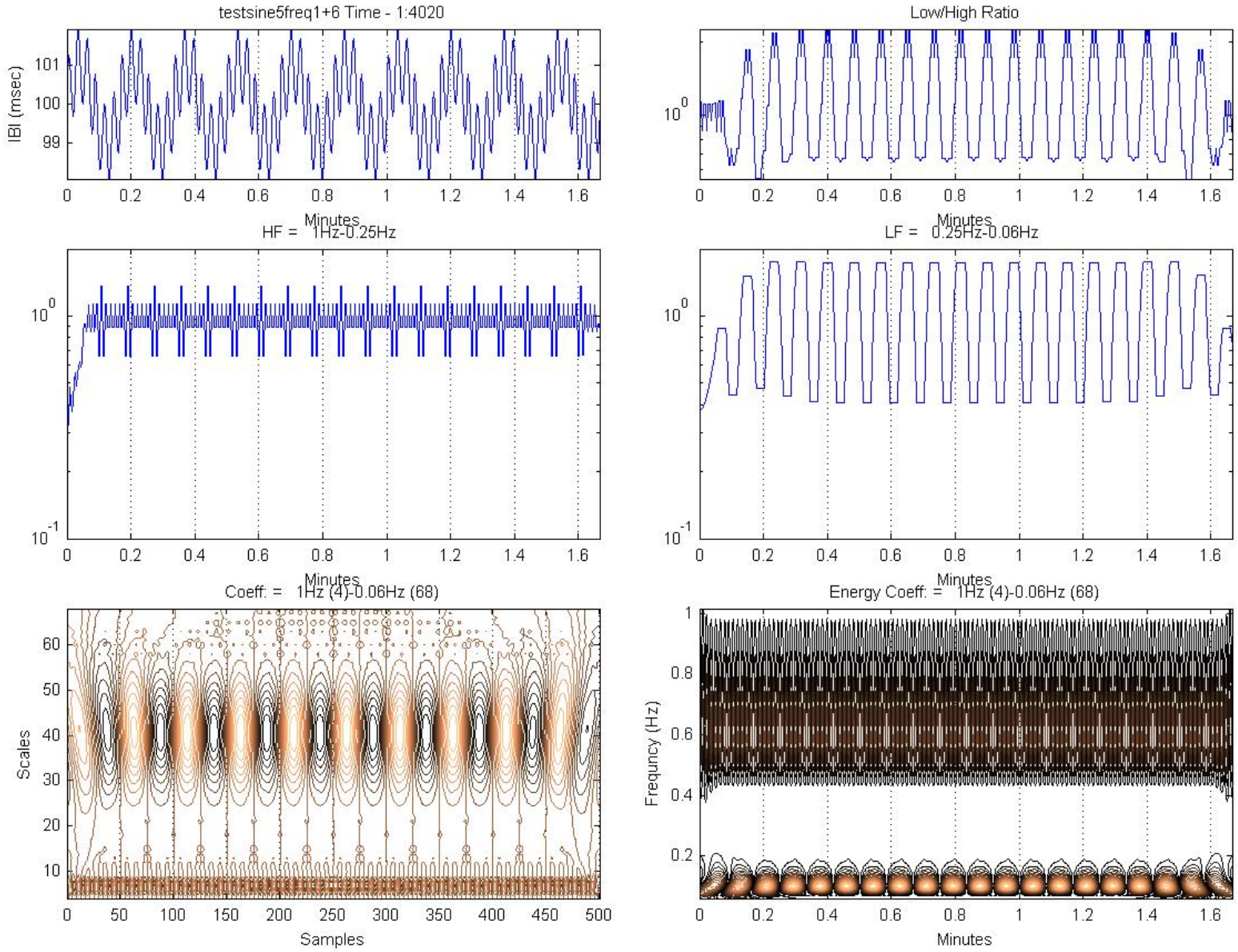




Wavelet Tool



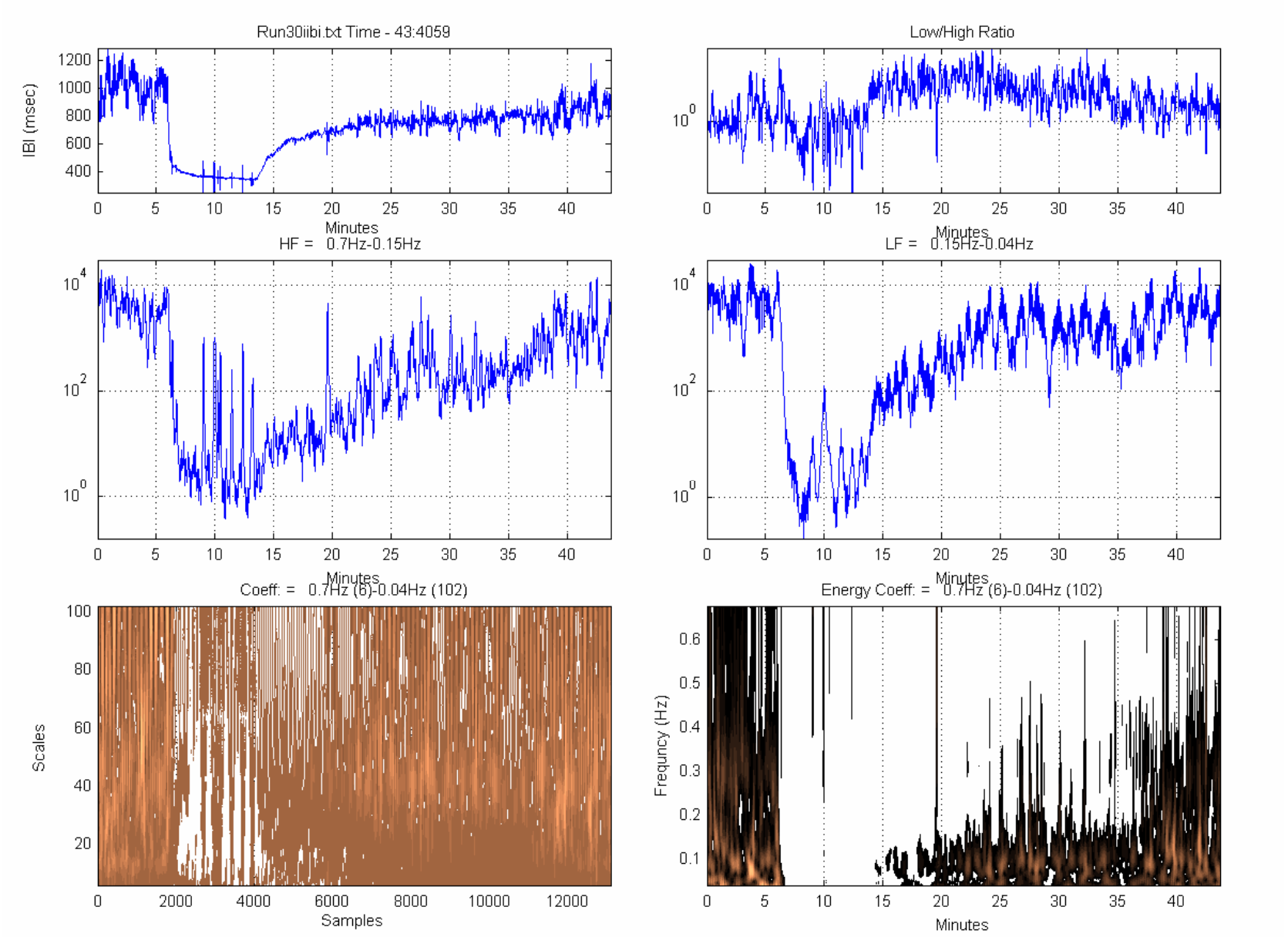
Wavelet Tool



An Experiment

- Monitor the HRV of subjects undergoing an exercise regime.
- The three phases of concern were
  - a resting phase prior to the exercise,
  - the exercise phase,
  - a recovery phase.
- HRV Spectrum and the average energy in the HF and LF bands during each of the three phases were calculated.
  - The IBI of various subjects was obtained using a Polar® S810i watch.

Typical Results



Our Expectations

- Our expectations were simple.
  1. ANS takes on a nominal value
  2. During the exercise phase, when the heart rate increases,
     - Sympathetic Enhancement
  3. Finally, during the recovery phase, when the heart rate decreases,
     - Parasympathetic Enhancement

Class 1: ***Indicate a shift toward relative vagal enhancement***[1]

a) LF decreases and HF is unchanged or increased. This indicates a reduction in sympathetic activity. If HF is increased, then vagal activity is increased.

b) LF is unchanged and HF increases, indicating a reduction in sympathetic activity and an increase in vagal activity.

c) Both LF and HF increase, but their ratio (LF/HF) is unchanged or reduced, indicating increased vagal activity (HF increasing more would reduce the ratio) and unchanged or reduced sympathetic activity.

d) Both LF and HF decrease and their ratio decreases, indicating decreased vagal and sympathetic activity, with a shift in balance towards relative vagal enhancement.

Class 2: ***Indicate a shift in balance toward relative sympathetic enhancement[1]***

a) HF decreases and LF increases or is unchanged, indicating a reduction in vagal activity and increase in sympathetic activity.

b) LF increases and HF unchanged, indicating increased sympathetic activity and unchanged vagal activity

c) Both LF and HF decrease and their ratio is unchanged, indicating reduction of vagal activity without considerable change of sympathetic activity.

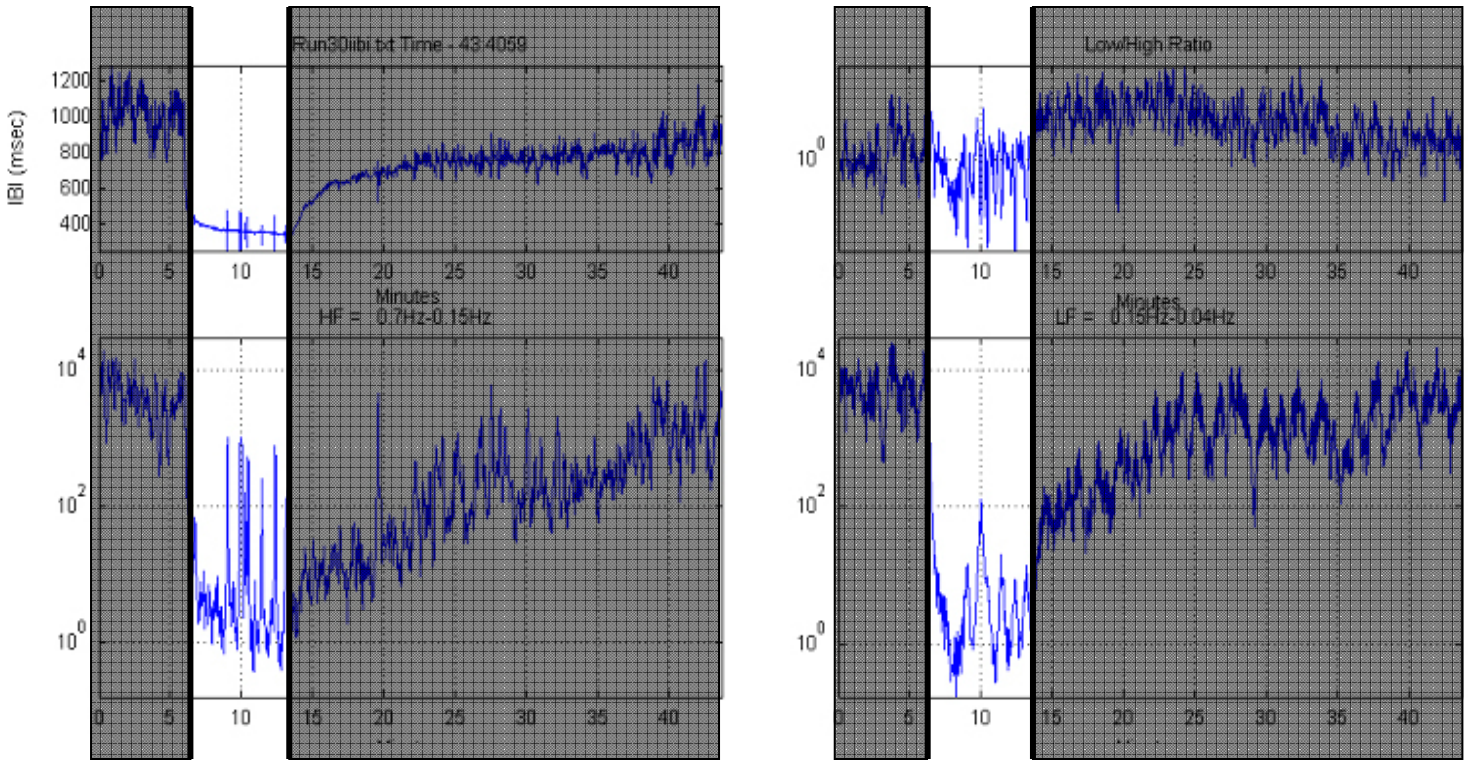
d) Both LF and HF increase and their ratio increases, indicating increased vagal and sympathetic activities, with a shift in balance toward relative sympathetic enhancement.

Expectations

1. During the resting phase, HF and LF would individually take on a nominal value.
2. During the exercise phase, when the heart rate increases,
   - parasympathetic activity would diminish, and perhaps the sympathetic activity would increase.
   - Therefore, it was expected that HF would diminish while the ratio of LF/HF would increase.
3. Finally, during the recovery phase, when the heart rate decreases,
   - parasympathetic activity should increase and/or sympathetic activity would diminish.
   - This would mean that HF would increase and LF/HF ratio would decrease.

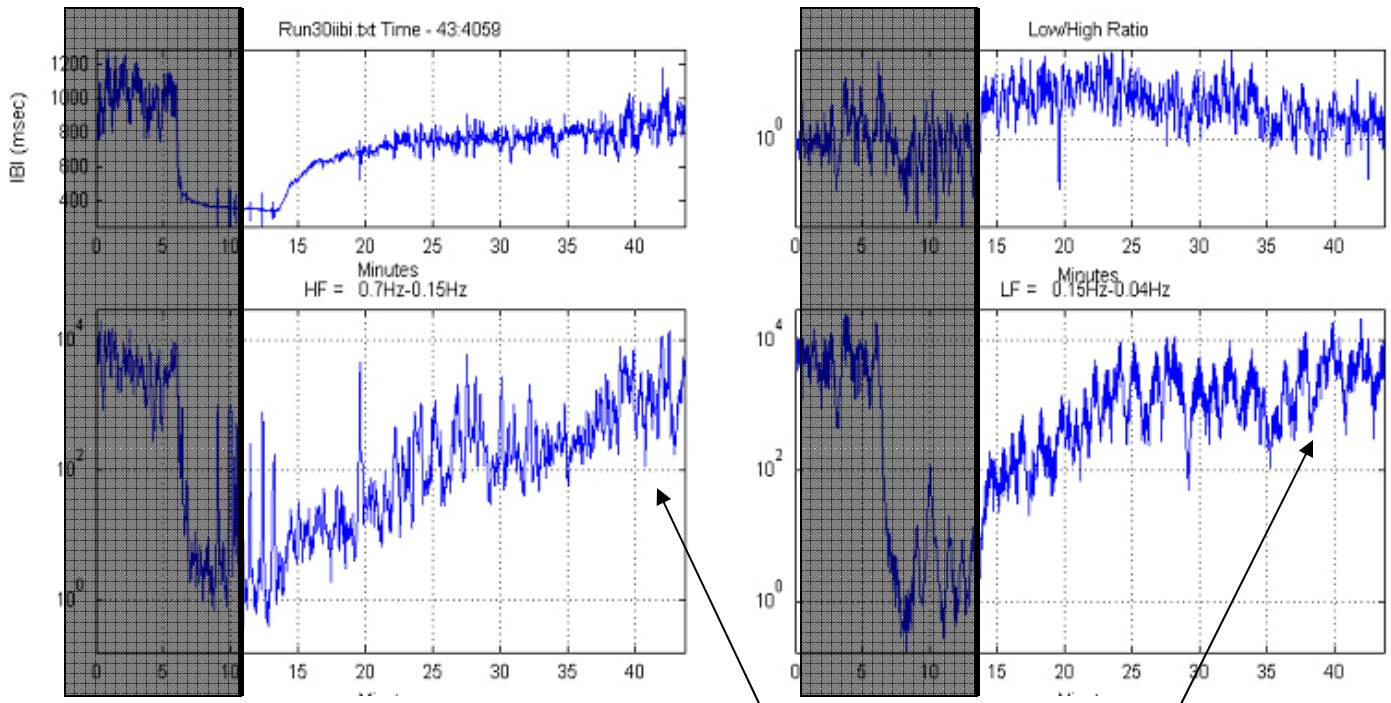
Problems

- Note there are some glaring inconsistencies during the exercise and recovery phases.
- At the start of the exercise phase both HF and LF drop but the LF/HF ratio initially <u>decreases</u> and then rises but never to a value greater than its resting phase value.



Problems

- Finally, during the recovery phase (> 13 min) <u>LF rises first</u> while <u>HF lags behind</u>.



HF catches to LF up here

What could be wrong?

- Wavelets are not suitable for HRV analysis.
- Bad Data
- The MATLAB® tool developed for this study had a defect.
- A new HRV-ANS dynamic was being observed.

As A Result

- Rigorously, test the tool
  - Tested other Subjects
  - Calibration Testing
    1. Single sine waves at HF and LF frequencies
    2. Multi-sine waves in the HF and LF bands
       - Sequential: multiple signals at different frequencies but occurring at different times
       - Simultaneous: multiple signals at different frequencies but occurring at the same time
    3. Repeat of tests 1 and 2 using square waves
  - Stylized IBI signals: simple IBI waveform amplitude modulated with a single sine wave or square wave.
- Result:
  - Same sort of dynamics with other subjects
  - Some bugs found but none which explained these problems

As A Result

- Subject the same data to other JTFA tools.
  - To assess the applicability of Wavelet Analysis, the following JTFA tools were used:
    - Short Term Fourier Transforms (STFT)
    - Gabor, Choi-Williams and Smoothed Pseudo-Wigner Ville distributions.
    - A frequency based (rather than scale based) Wavelet Tool* obtained as a result of our literature search.
- Result:
  - We learned about how the Matlab tools worked and how care must be taken to use them
    - At first we saw the STFT testing was producing consist results with our understanding of HRV-ANS physiology.
  - Although each obviously produced a different Spectrum using the above mentioned tools, the calculation of the LF and HF bands showed the same inconsistent dynamic behavior in the exercise and recovery phases.

*Tool From E.Toledo, O. Gurevitz, H. Hod, M. Eldar and S. Akselrod, "Wavelet analysis of instantaneous heart rate: a study in autonomic control during thrombolysis" in *Am J Physiol Regul Intefr Comp Physiol*, vol. 284; p. R1079-R1091, 2003.- Testing by Rockland, Asselin, & Donnely

As A Result

- Literature search was performed
- Two areas of interest were uncovered.
  1. Other investigators[1] have applied wavelet analysis with satisfactory results.
  2. Other investigators [2,3,4] have documented the inconsistencies seen by the authors.
- Result:
  - One possibility to explain these inconsistencies may be due saturation of the HRV. As reported in these papers, saturation of the ANS can occur during higher levers of exercise intensity or at elevated temperature.

HRV Saturation[1,5]

- Shutdown: A decrease in both LF and HF may occur as a result of HR reduction which is usually associated with a parasympathetic withdrawal
  - In our case, this withdrawal may be as a result of the exercise phase.
- Turn on: A increase in both LF and HF associated with a strong parasympathetic activation
  - In our case, this activation may be as a result of the recovery phase

Conclusions

- Make sure your results are consistent and can be explained
- If not develop an methodological approach to determine the root cause of any inconsistencies.

Where does one go from here?

- Completely understand and characterize the HR Saturation phenomenon
  - Is saturation a function of the intensity of exercise?
  - What is the relationship of the delay to this process?
- The desire to understand the recovery process
  - Others has stated that good cardiovascular health may be related to how well the heart recovers from stress.
  - Abnormal recovery has been defined[6] as a reduction of 12 beats/min or less
  - Our desire is to improve this metric by characterizing recovery using joint time-frequency analysis.

Bibliography

[1]E.Toledo, O. Gurevitz, H. Hod, M. Eldar and S. Akselrod, “Wavelet analysis of instantaneous heart rate: a study in autonomic control during thrombolysis” in *Am J Physiol Regul Intefr Comp Physiol*, vol. 284; p. R1079-R1091, 2003.

[2]E.Toledo, O. Gurevitz, H. Hod, M. Eldar and S. Akselrod, “Thrombolysis in the Eyes of the Continous Wavelet Transform”, in *Computers in Cardiology*, vol.29, p. 657-660, 2002

[3]A. P. Pichon, C. DeBisschop, M. Roulaud, A. Denjean, and Y. Papelier, “Spectral Analysis of Heart Rate Variability during Exercise I Trained Subjects” in *Medical & Science In Sports & Exercise®*, p. 1702-1708, 2004

[4]I. K. M. Brenner, S. Thomas, and R. J. Shepard, “Autonomic Regulation of the Circulation During Exercise and Heat Exposure Inferences from Heart Rate Variability”, vol. 2, p. 85-99, Aug. 28 1998.

[5]E.Toledo, O. Gurevitz, H. Hod, M. Eldar and S. Akselrod, “Wavelet analysis of instantaneous heart rate: a study in autonomic control during thrombolysis” in *Am J Physiol Regul Intefr Comp Physiol*, vol. 284; p. R1079-R1091, 2003.

[6]C. Cole, E.H. Blackstone, F. J. Pashkow, C.E. Snader, and M.S. Lauer, “Heart-Rate Recovery Immediately After Exercise As A Predictor of Mortality”, New England Journal of Medicine, vol. 341; 18, p. 1351-1357. 1999.

Homework

1. Obtain the IBI from web page and calculate time domain measures
2. Generate the IIBI (assume f_s = 4s/s)
3. Calculate the Fourier Transform of the IIBI
4. Plot the HRV spectrum