Spectral Analysis and Heart Rate Variability: Principles and Biomedical Applications

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August 27, 2004

Why Spectral Analysis?

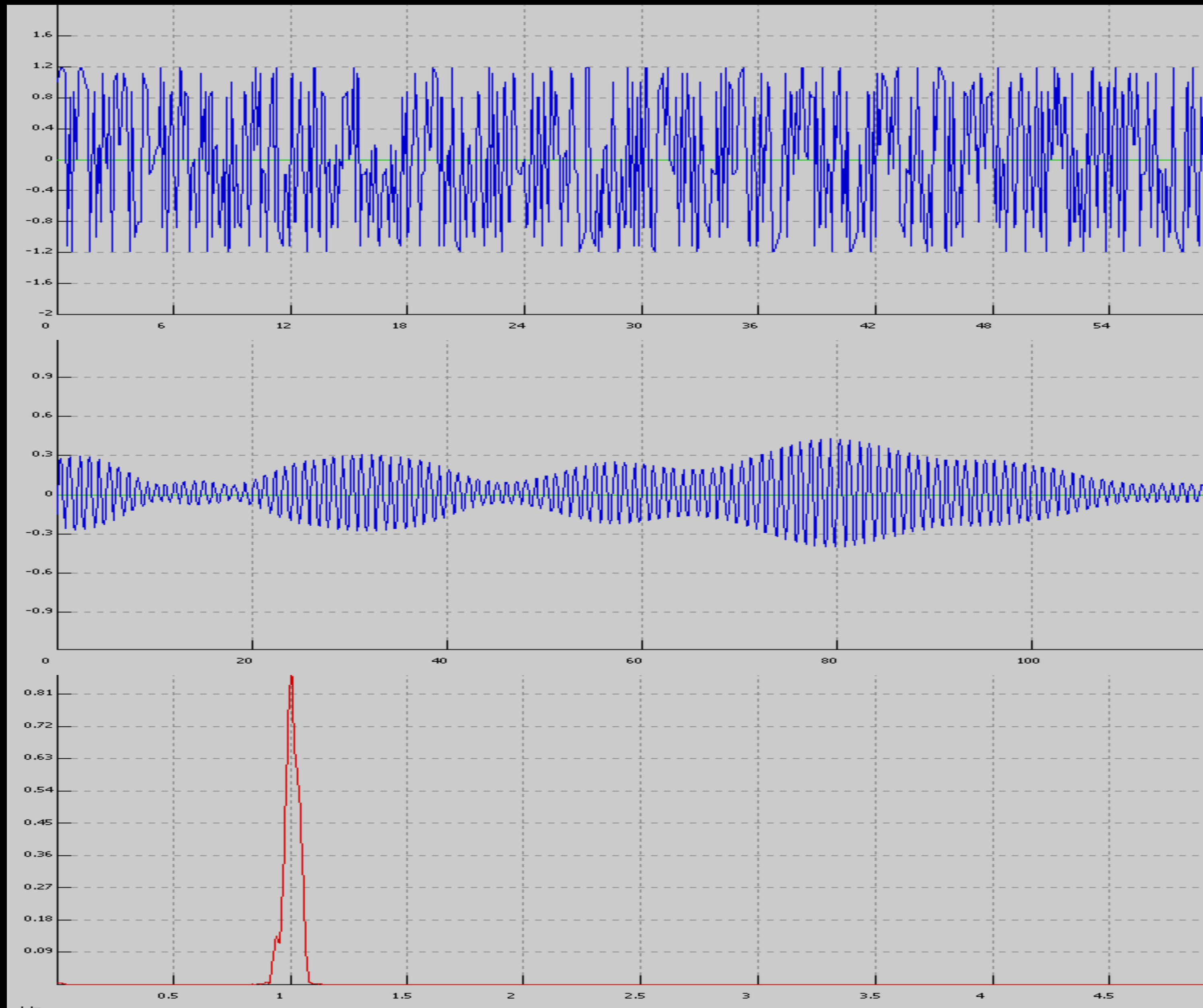
Detection and characterization of cyclical or periodic processes present in physiological signals

Rhythms are present in nearly all physiological signals - but not always evident to the ‘naked eye’!

Signal

Filtered

Spectrum



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Generating a time series signal from the Electrocardiogram

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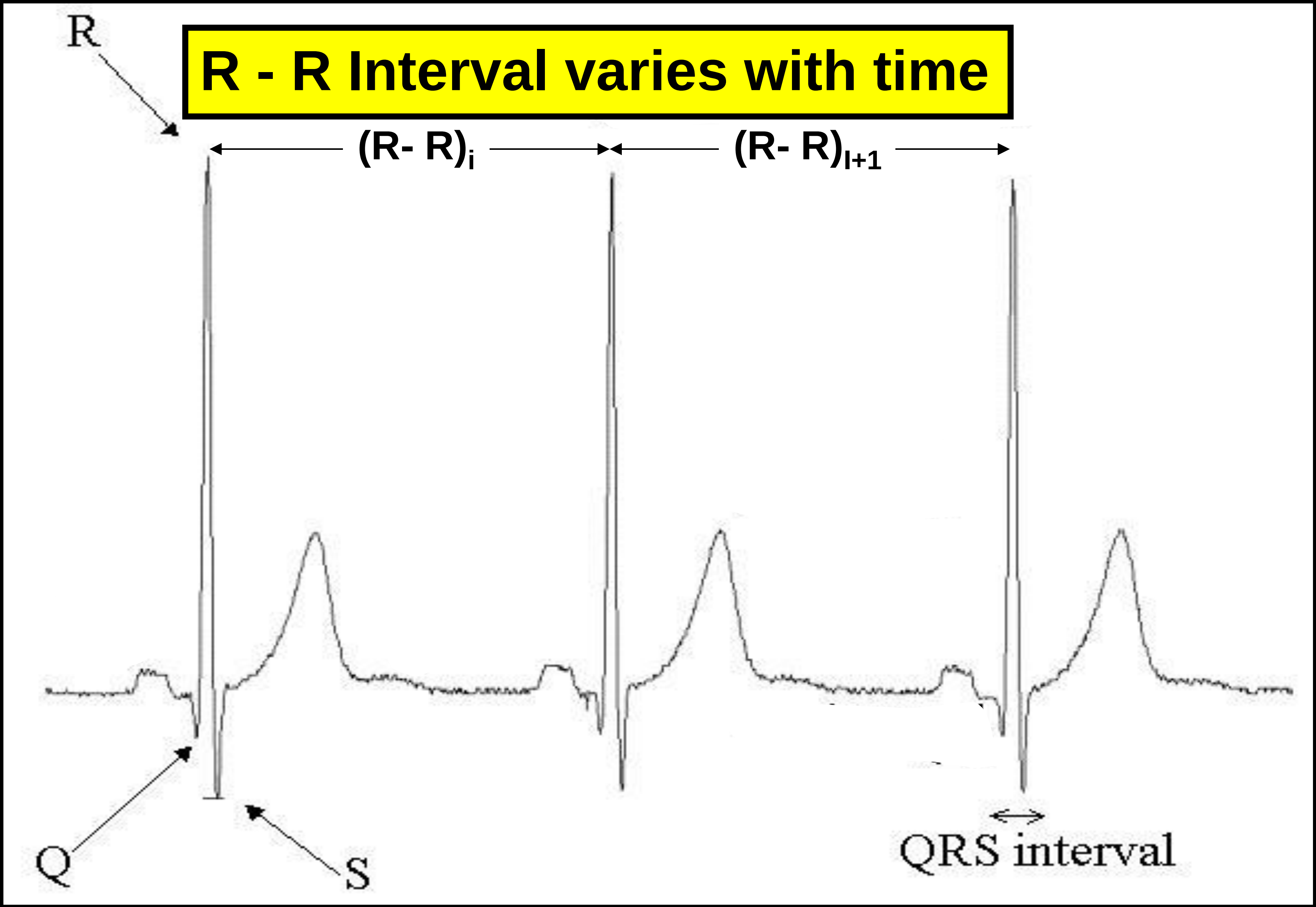
R- R Time Series



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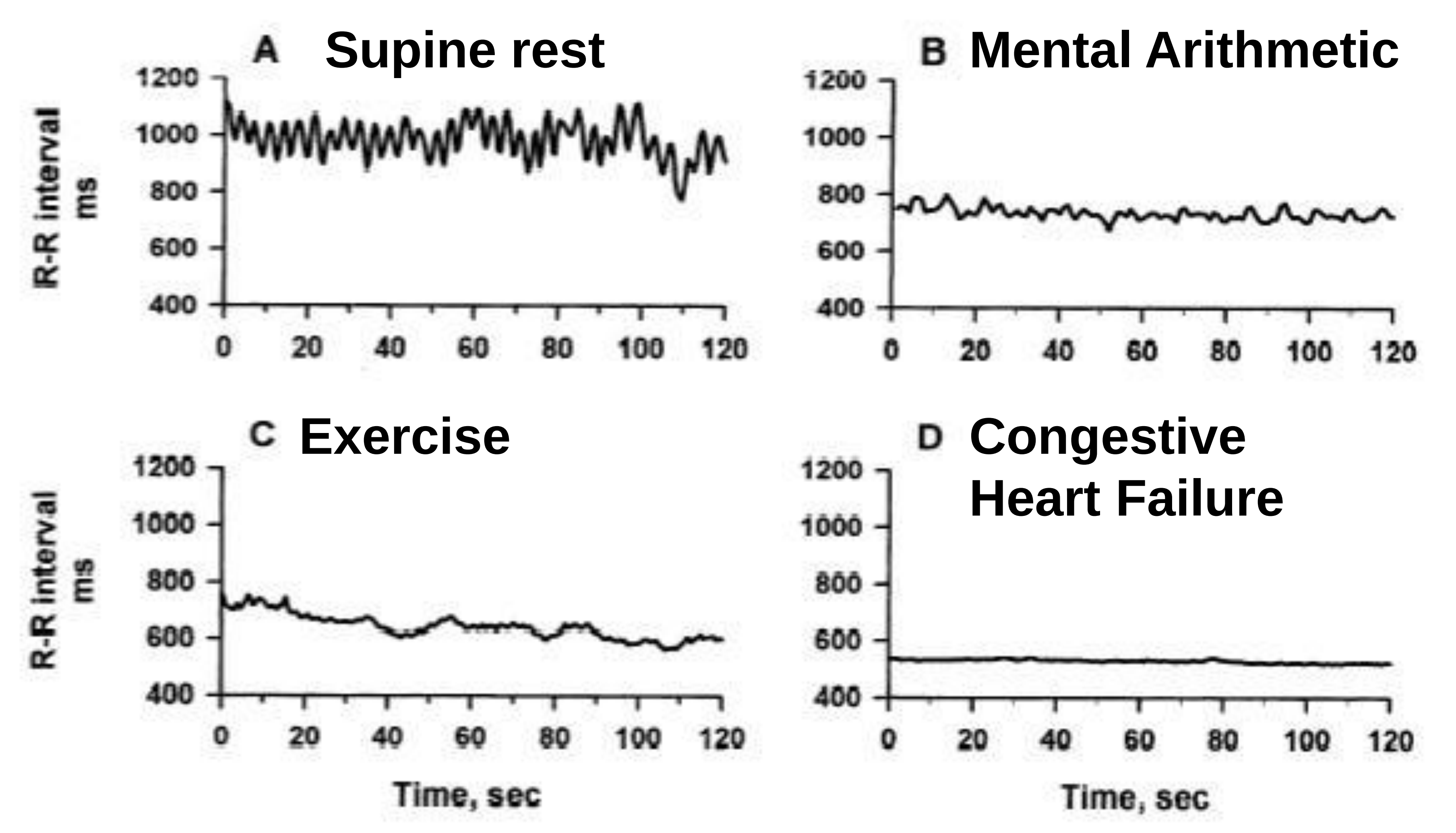
R- R Time Series

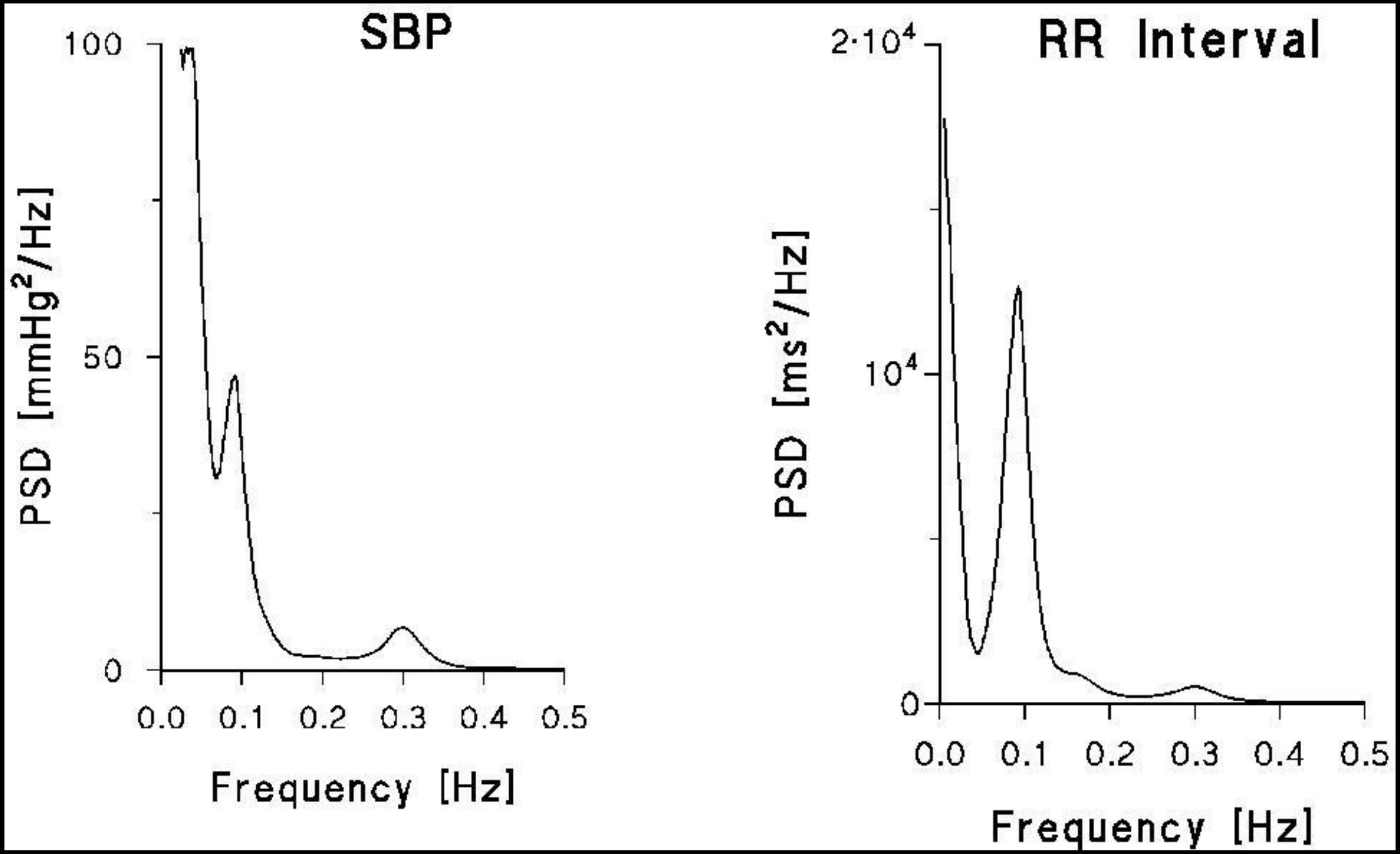


How do you extract spectral (frequency) components present in physiological signals?

Power Spectral Density

Amount of power per unit (density) of frequency (spectral) as a function of freqeuncy

PSD describes how the power (or variance) of a time series is distributed with frequency!



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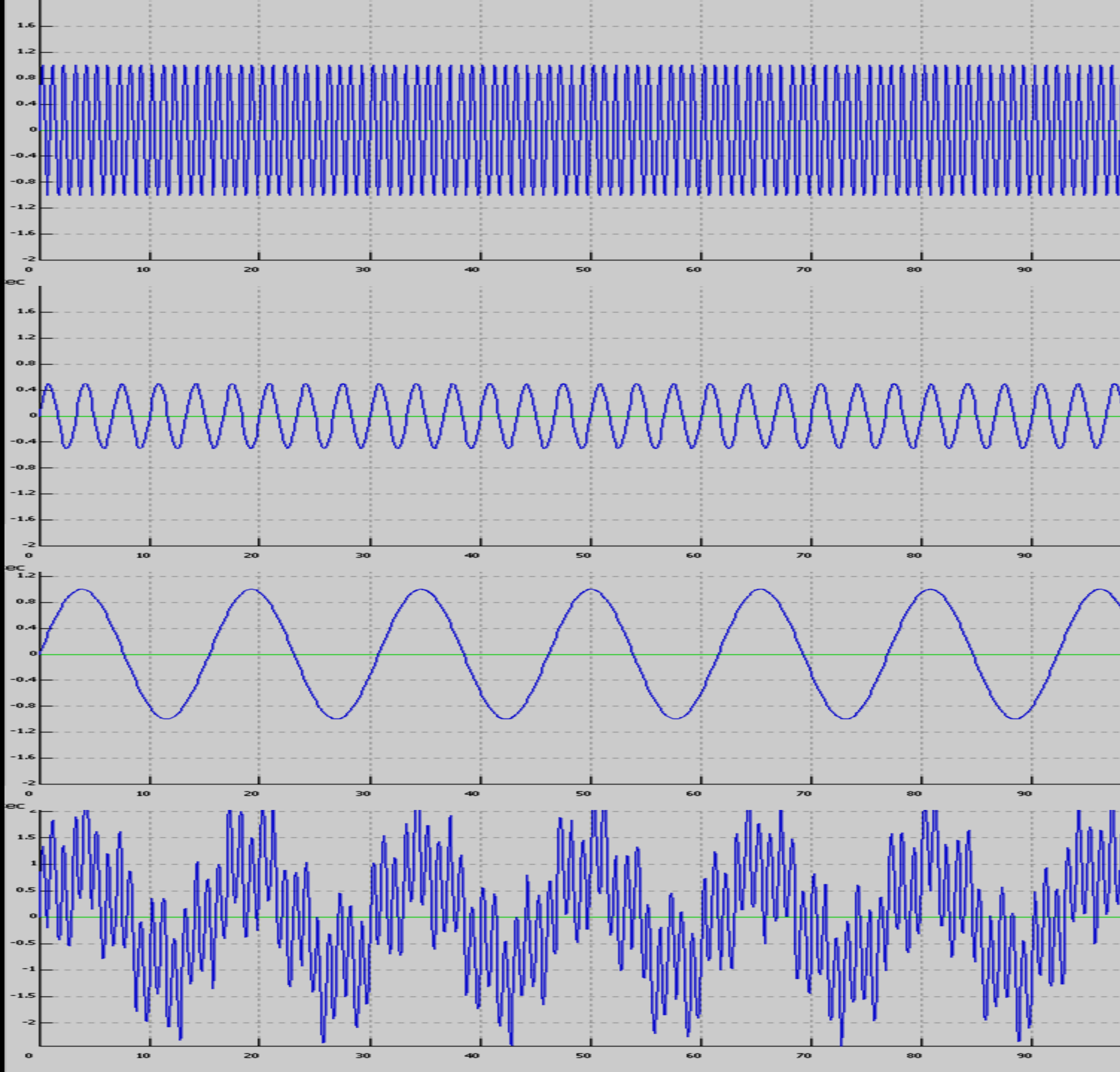
Example with Simulated Signals

A
1.0 Hz

B
0.3 Hz

C
0.065 Hz

A+ B+ C



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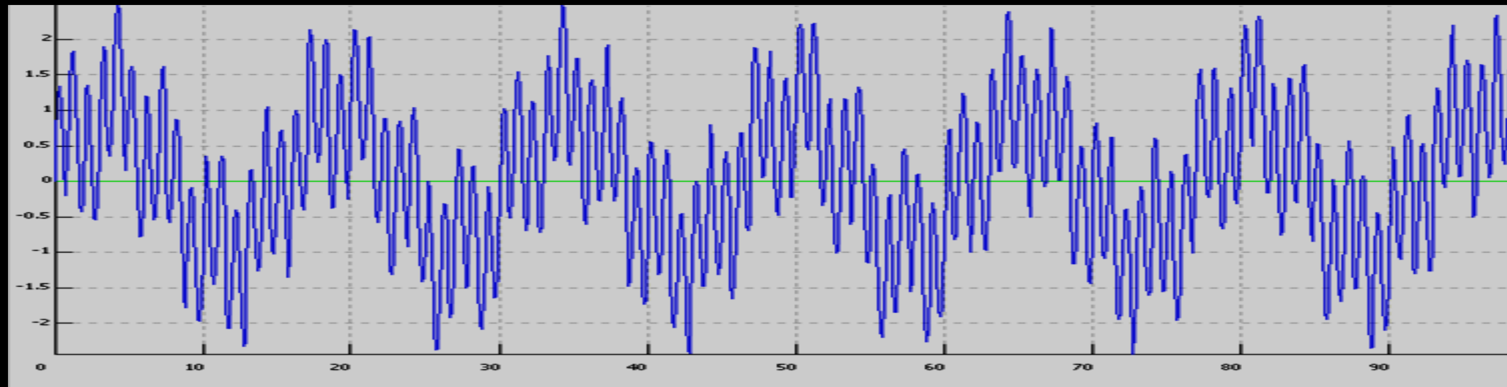
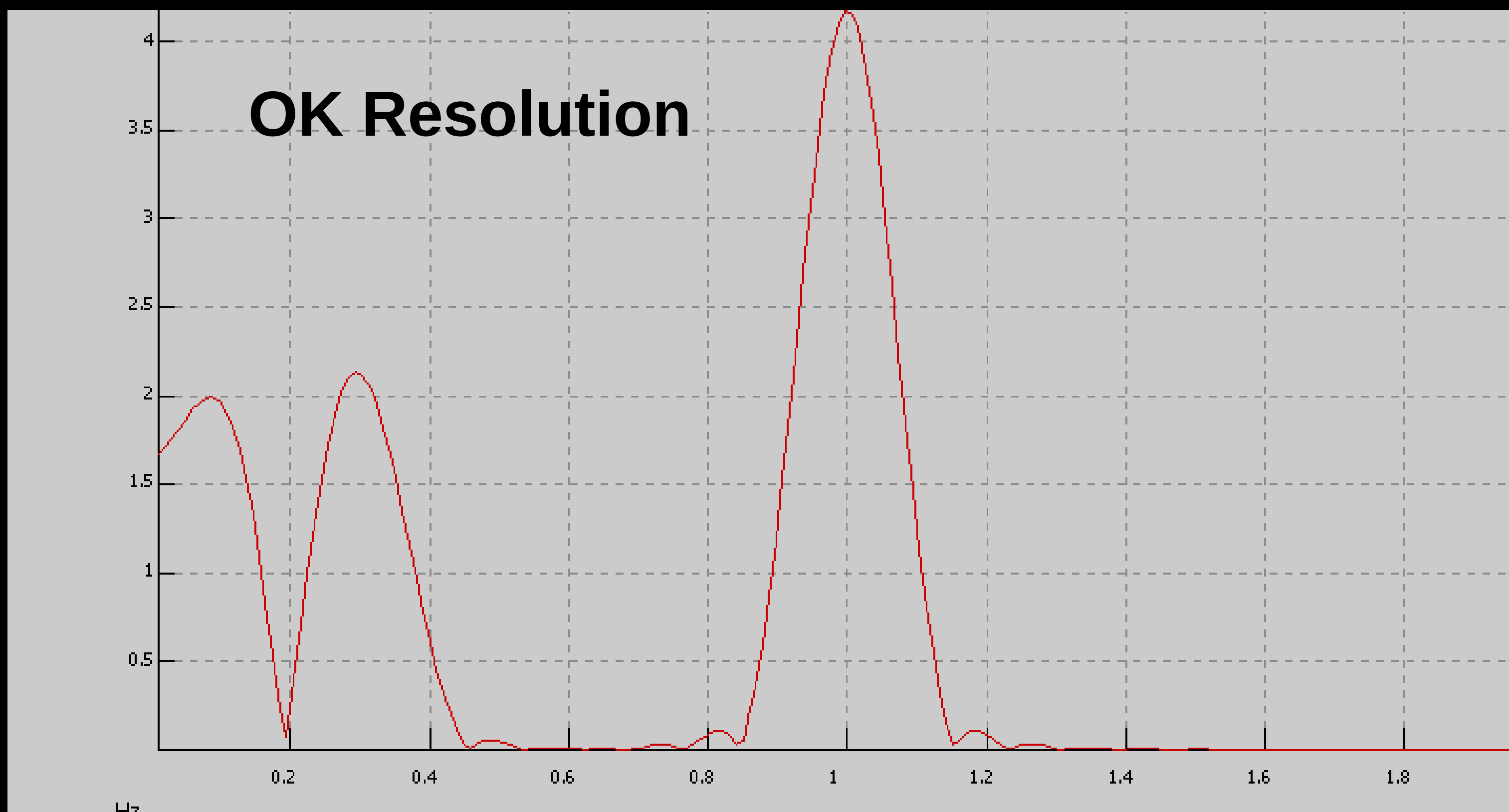
A+ B+ C

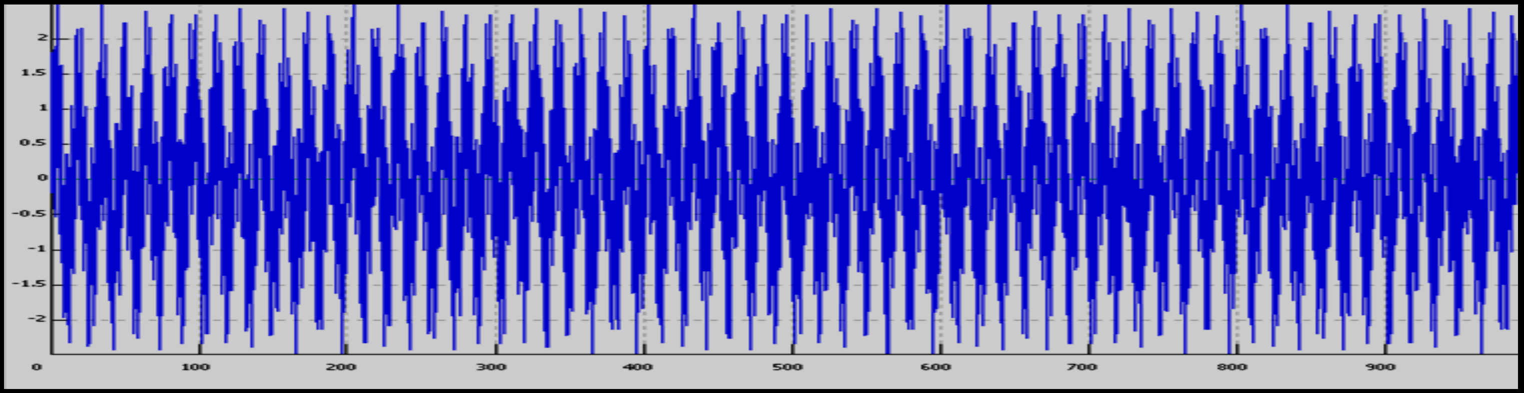
100 sec



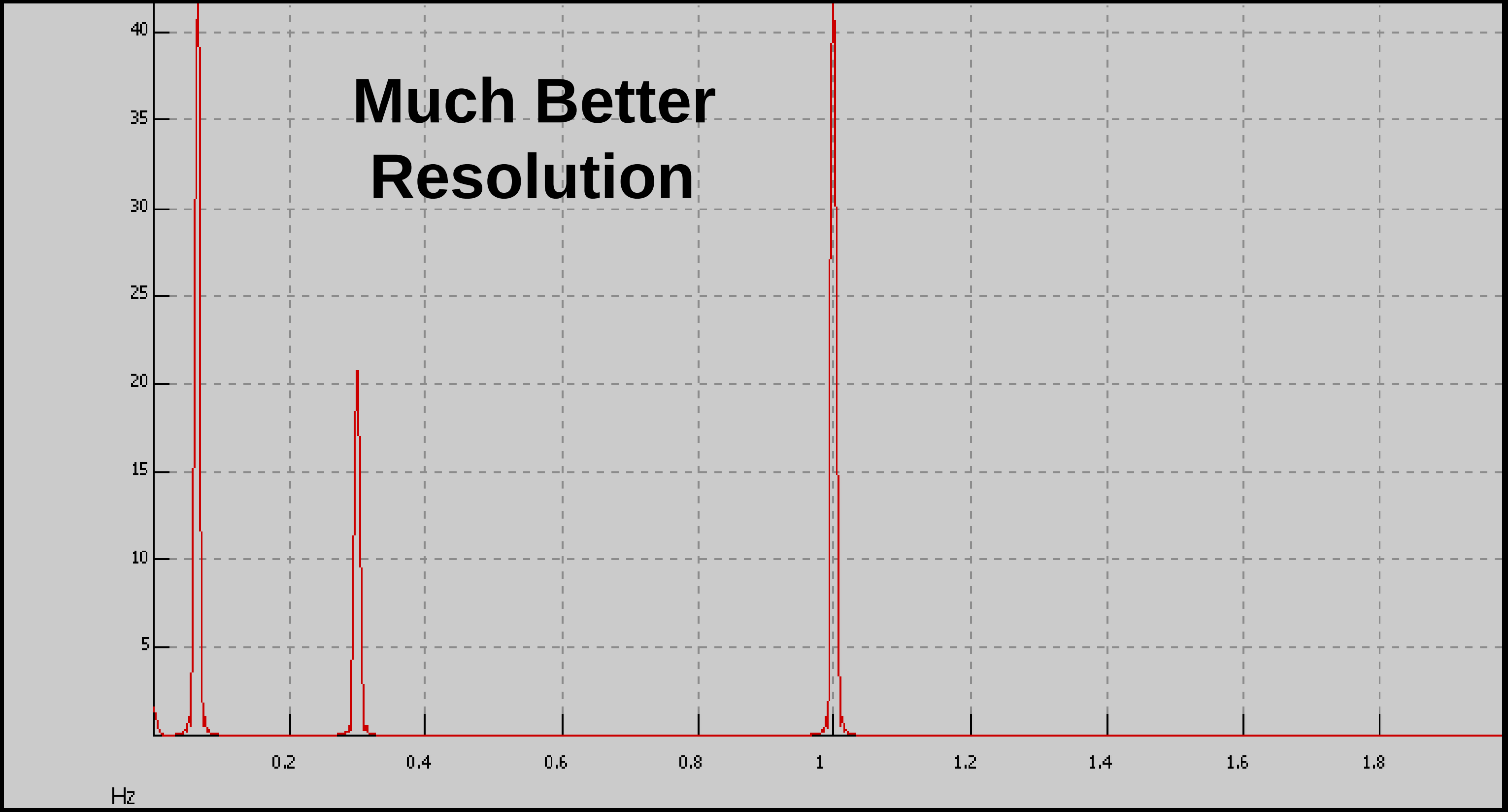


A+ B+ C

1000 sec



2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
700
800
900

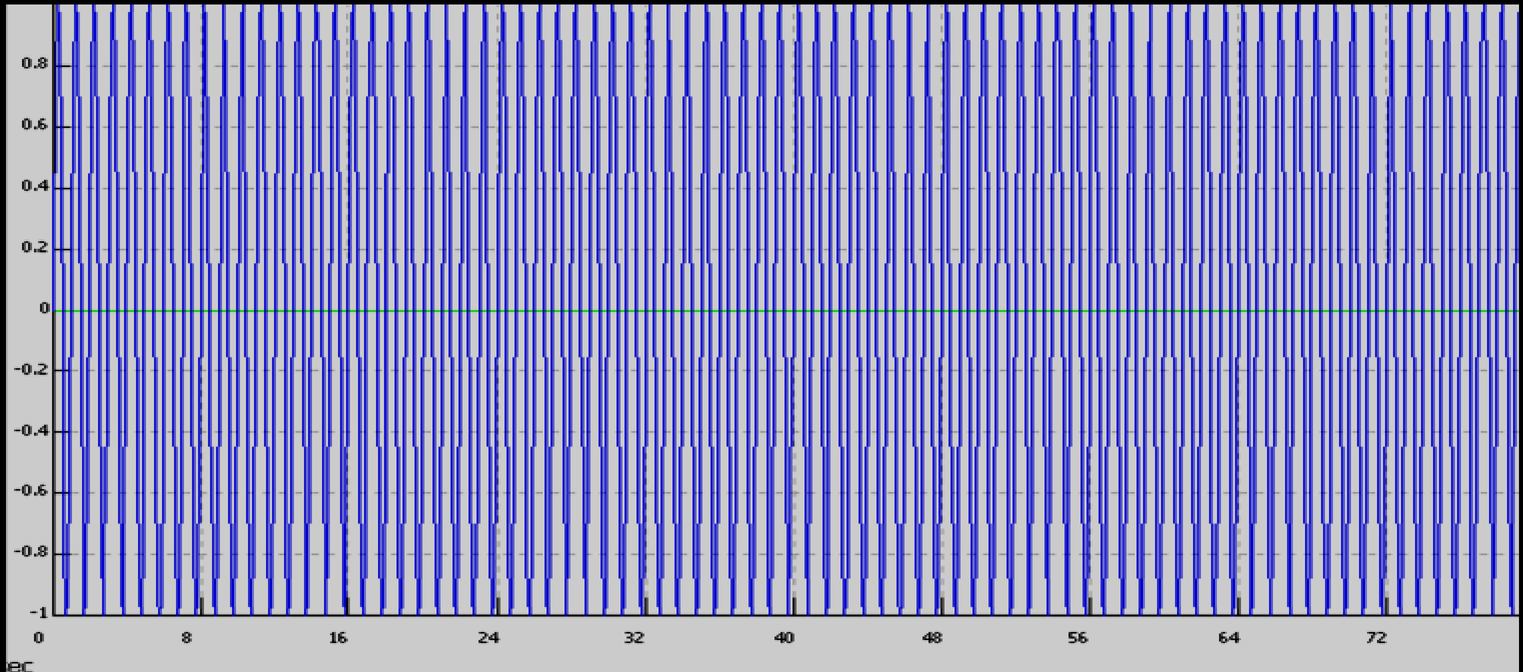


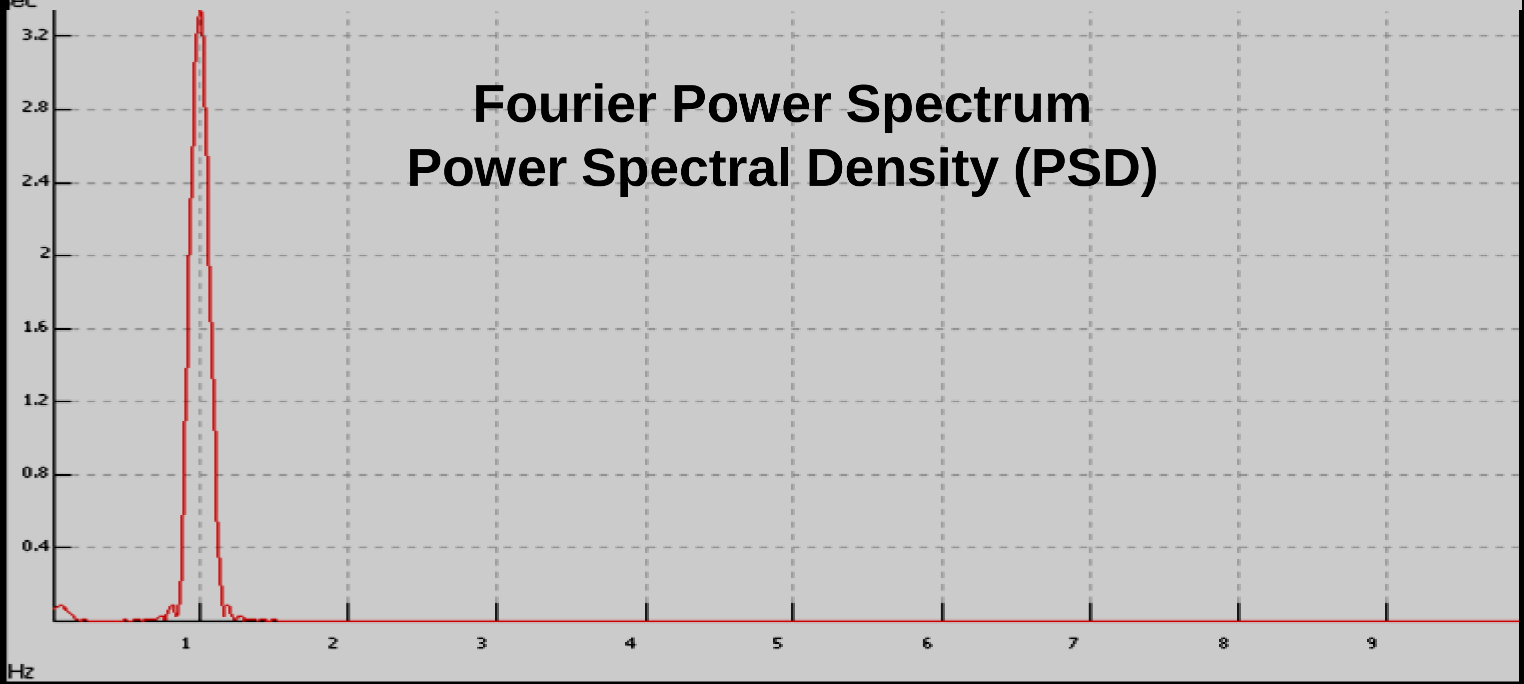
Much Better Resolution
40
35
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Hz

For a given sampling rate the length of time a signal is sampled sets the Frequency Resolution

Signal

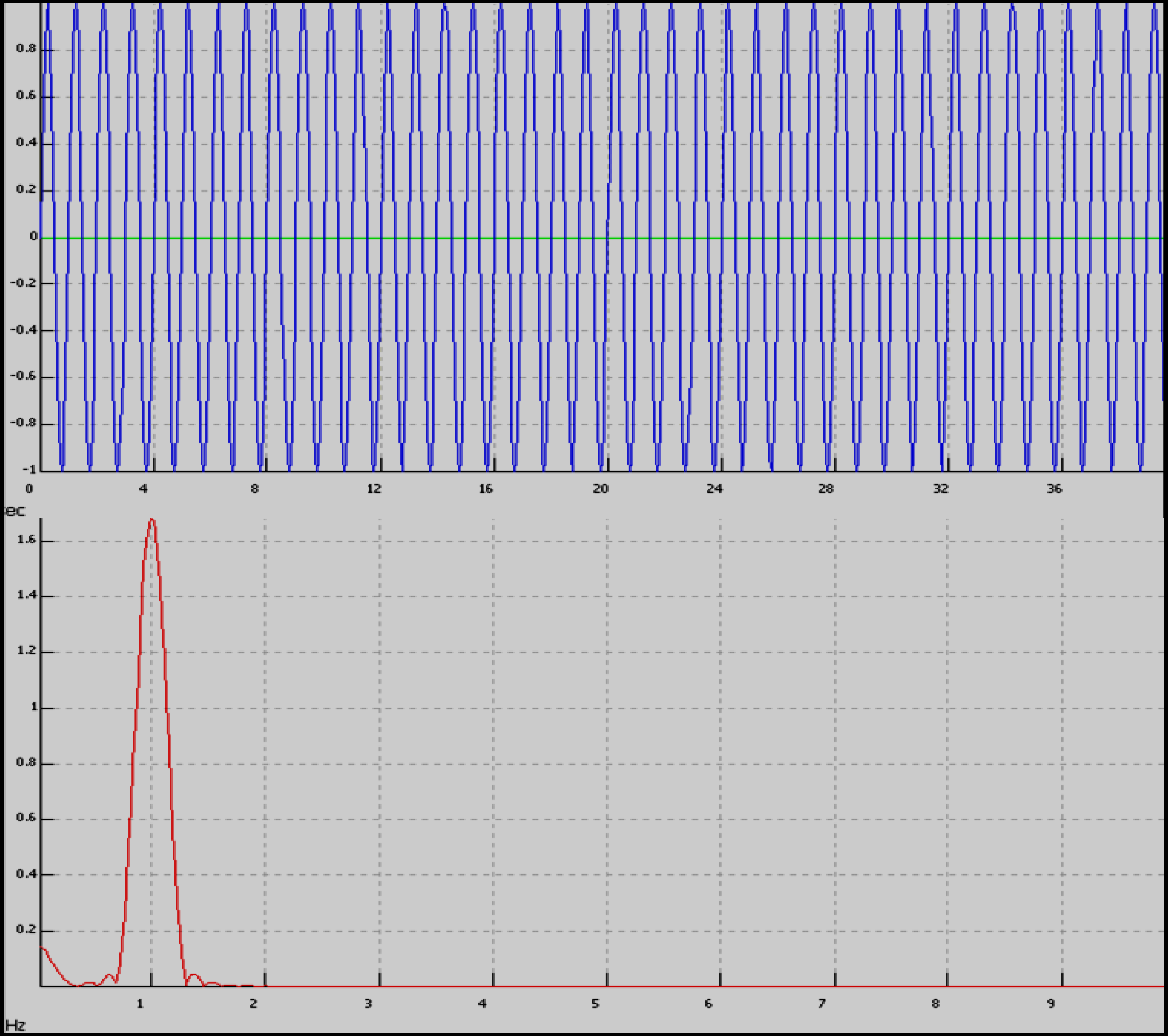
80 cycles of a 1 Hz sine wave





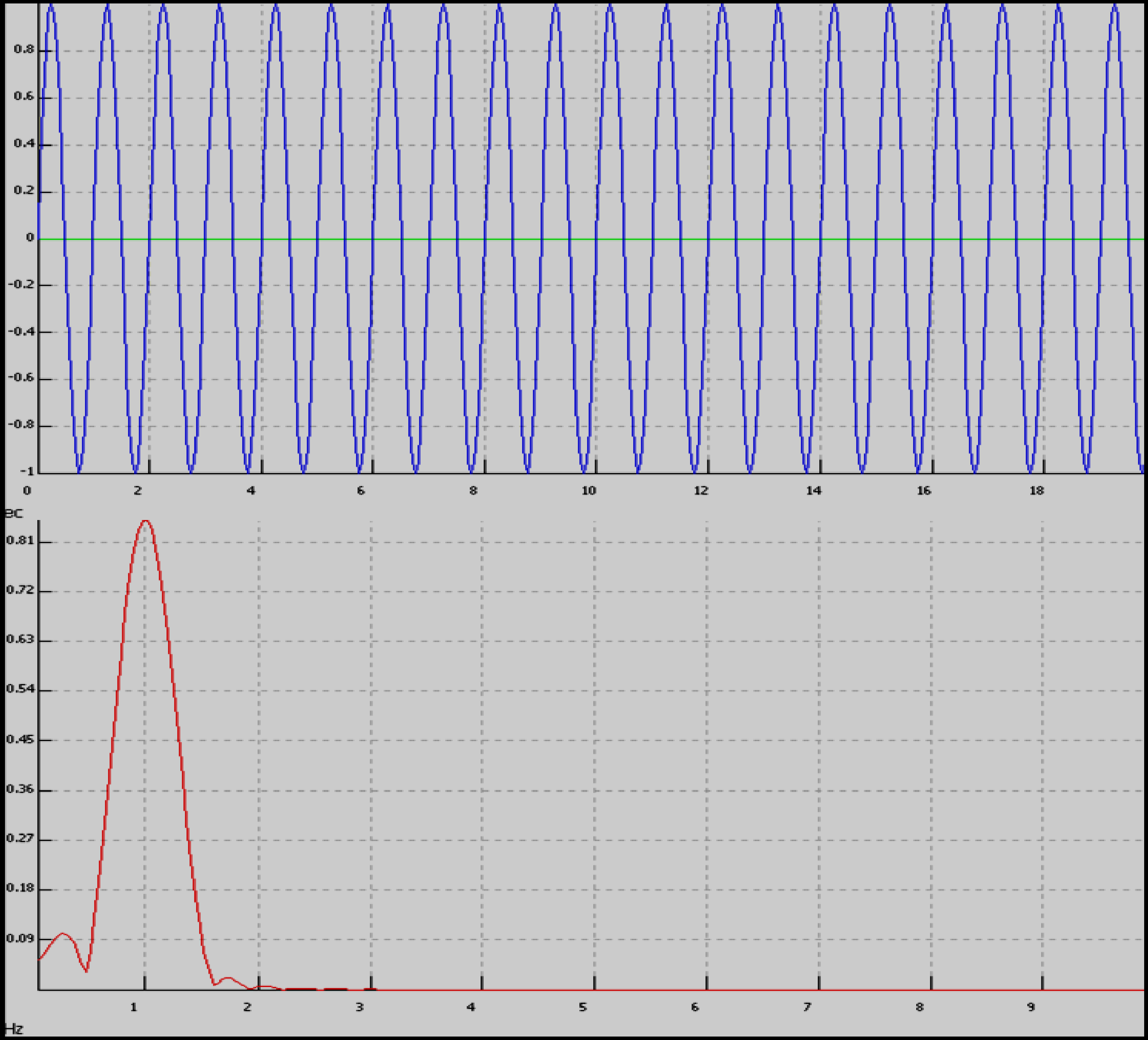
Signal

40 cycles of a 1 Hz sine wave



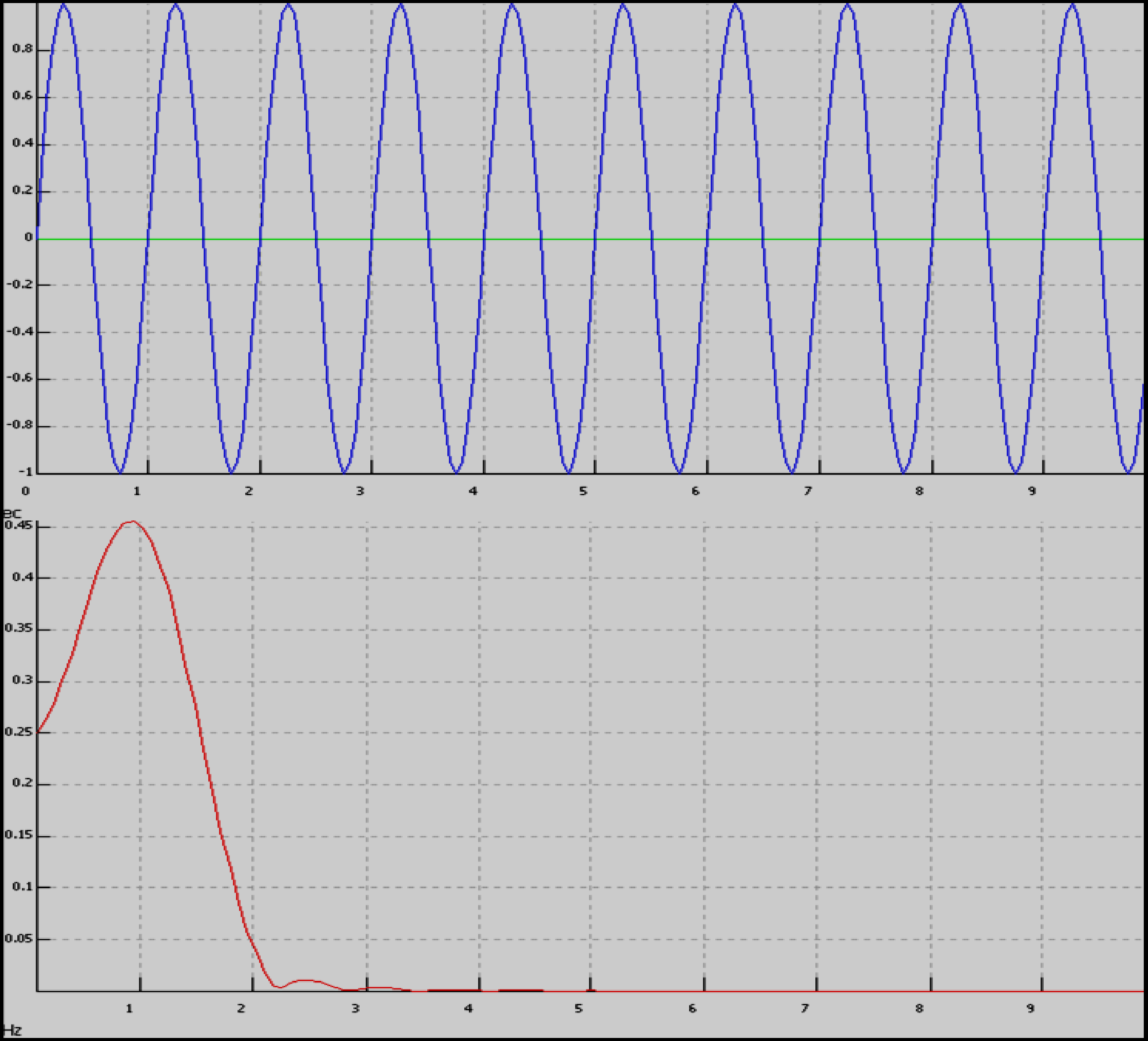
Signal

20 cycles of a 1 Hz sine wave



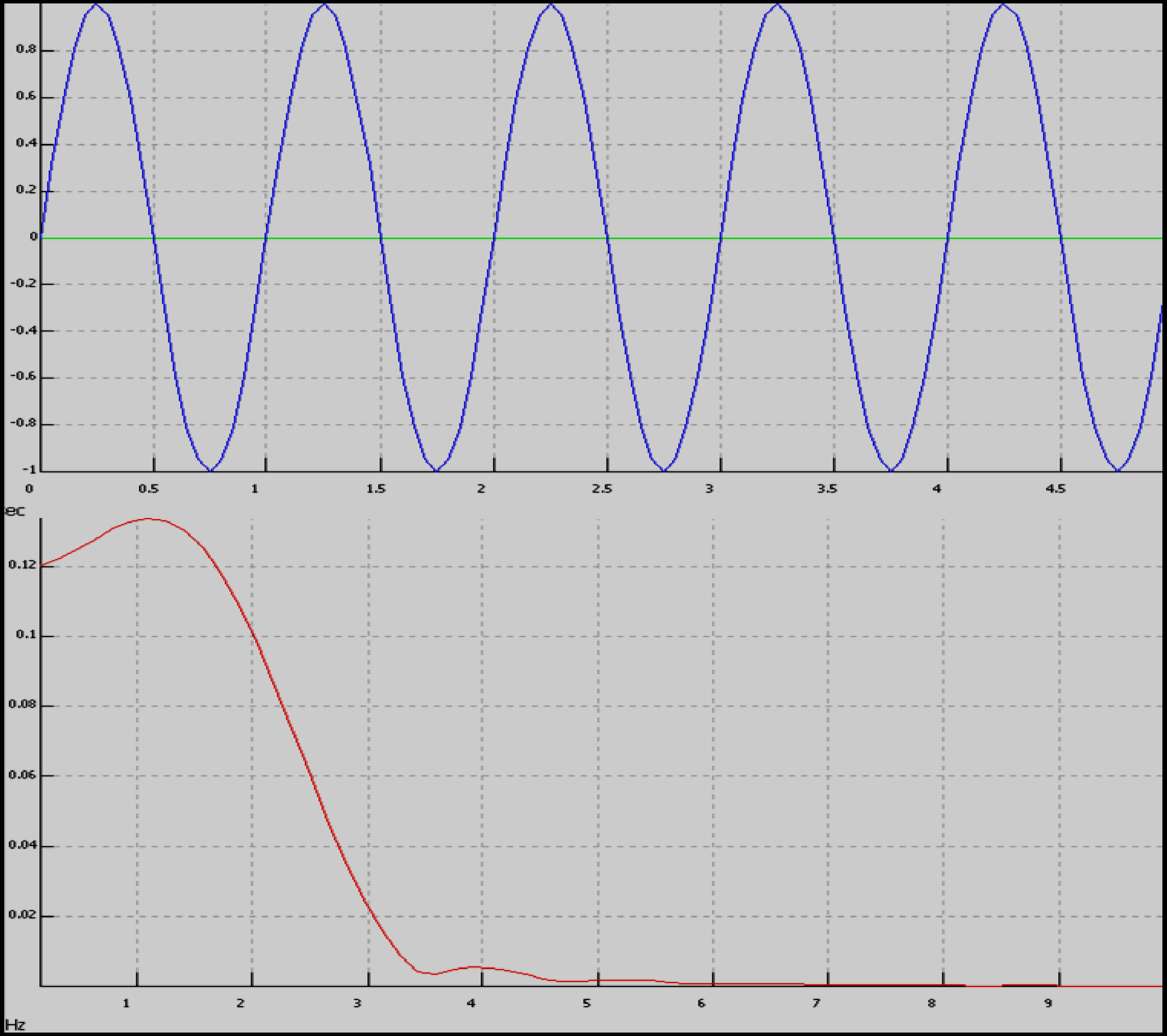
Signal

10 cycles of a 1 Hz sine wave



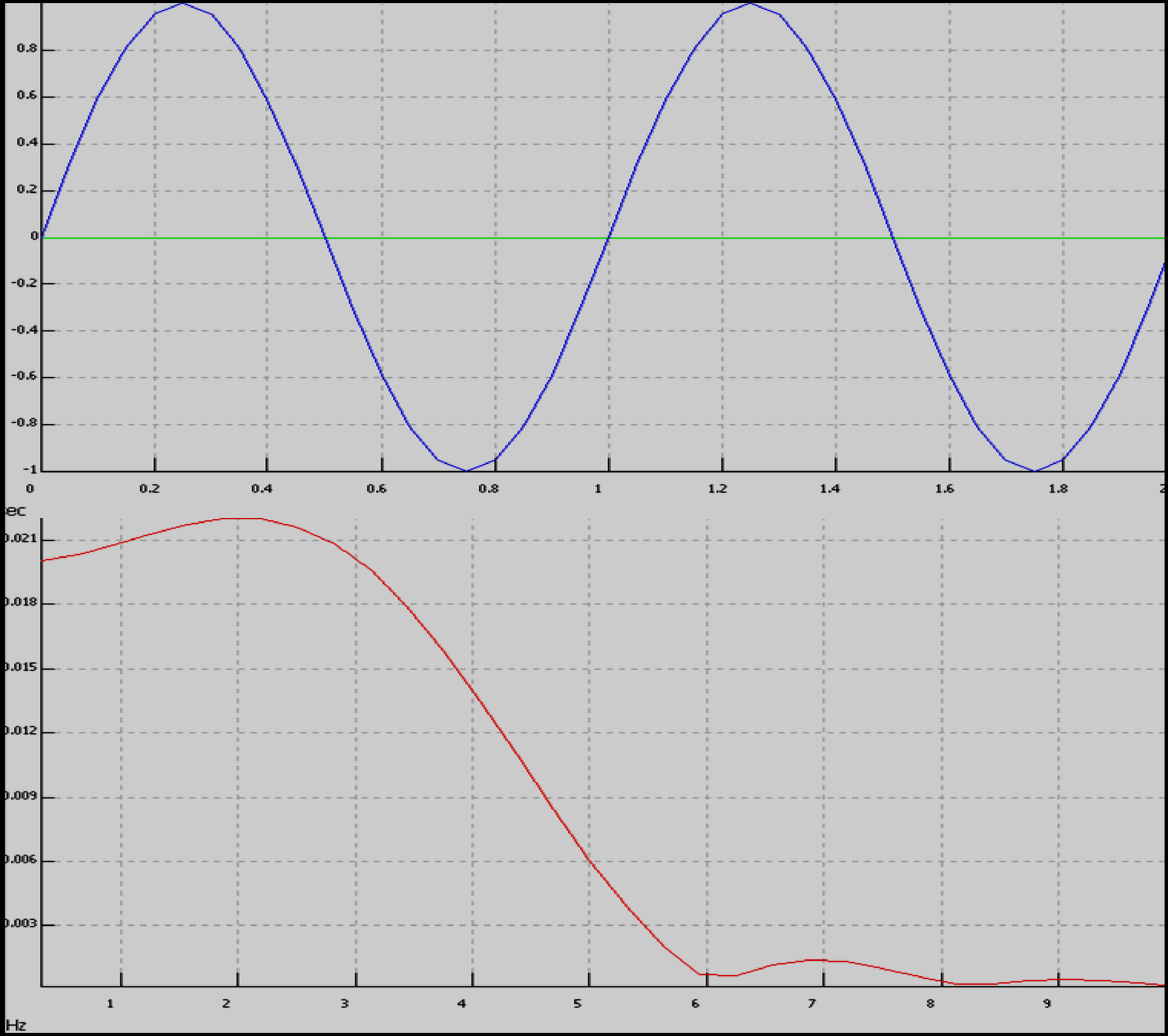
Signal

5 cycles of a 1 Hz sine wave



Signal

2 cycles of a 1 Hz sine wave



Real Physiological Signals

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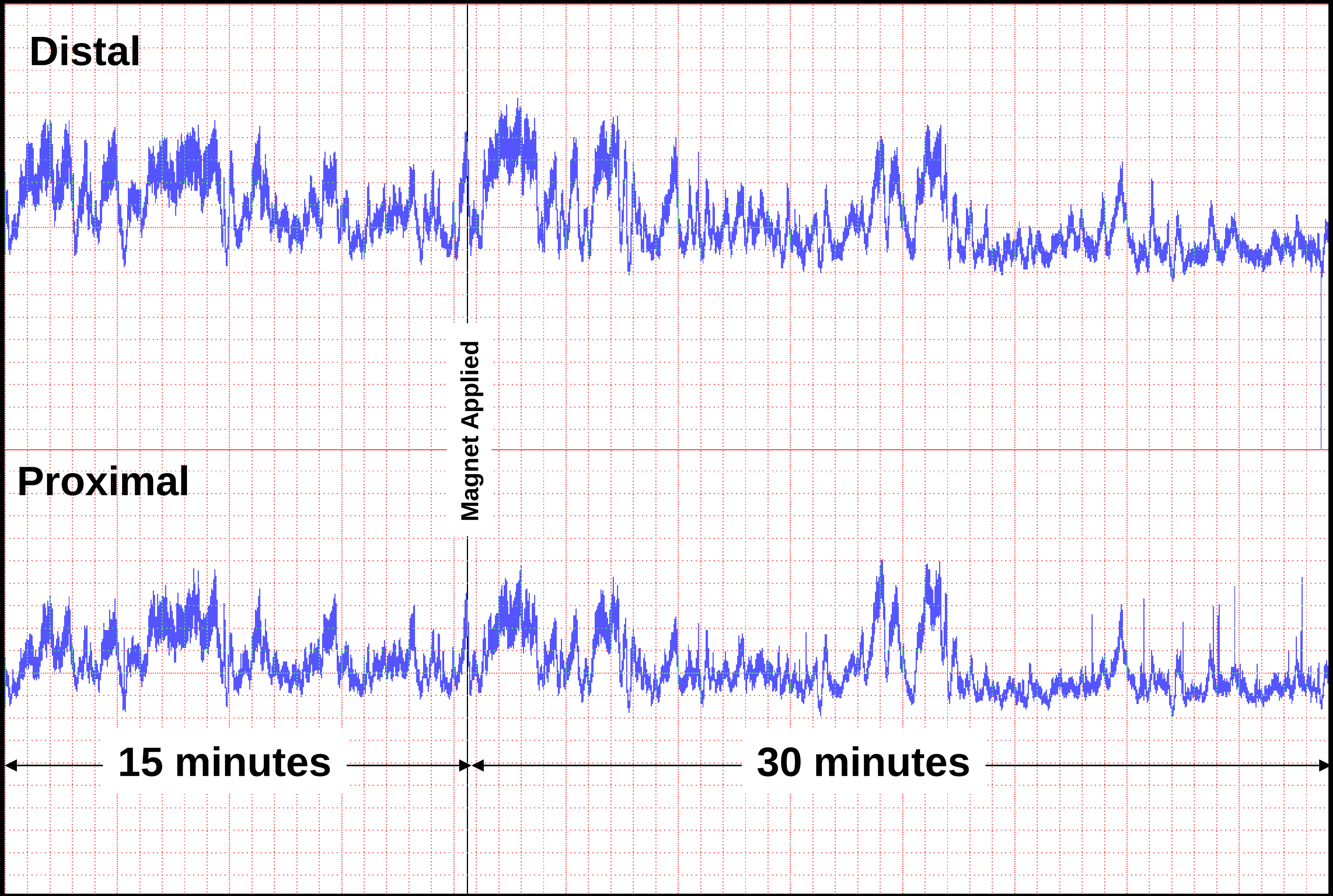
Blood Flow Signals



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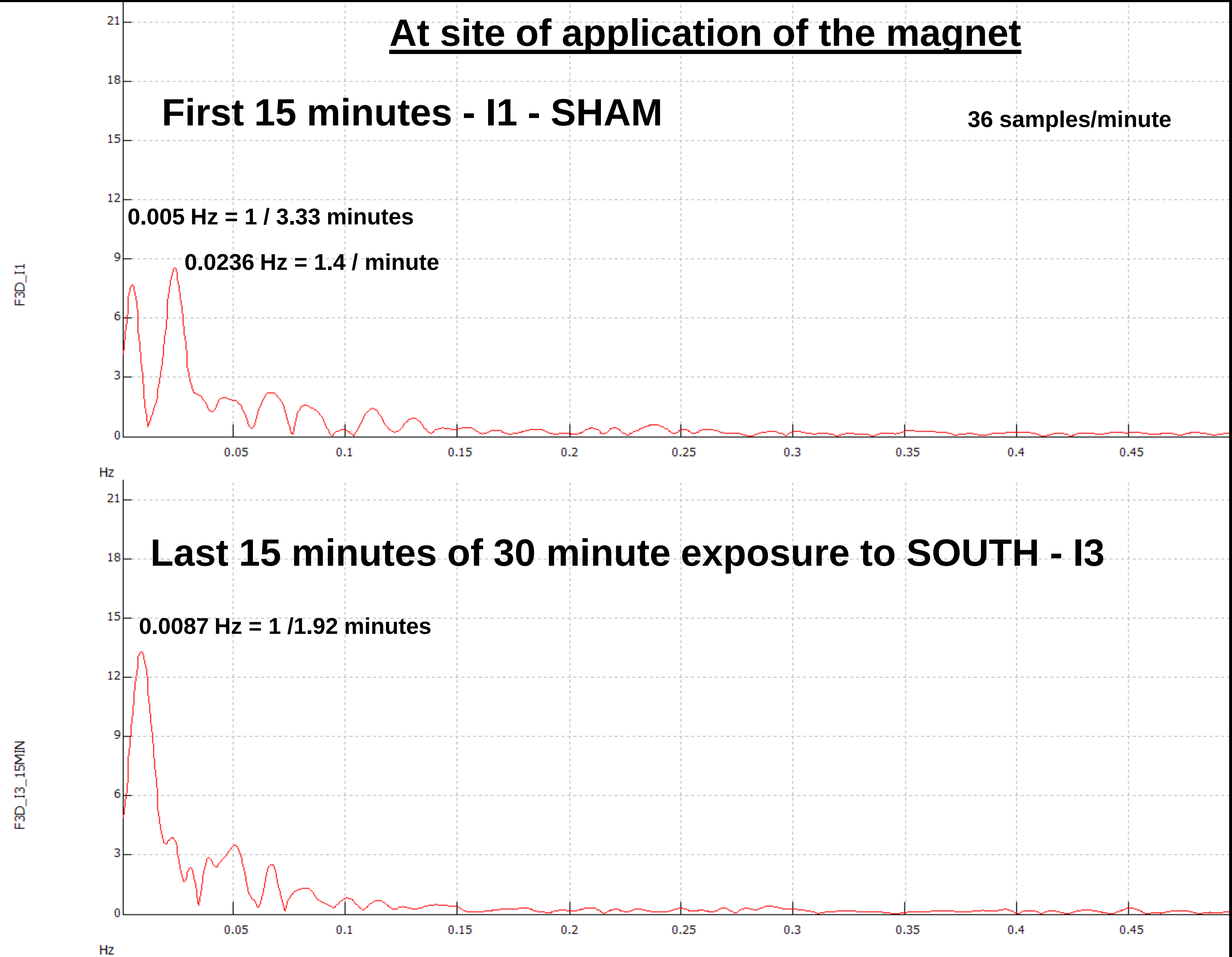

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Another Type of Experiment
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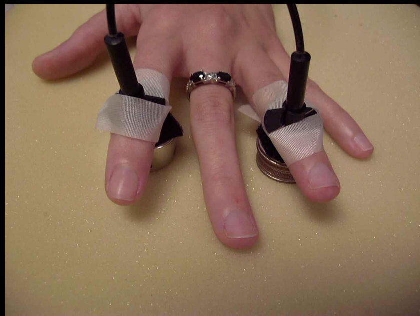
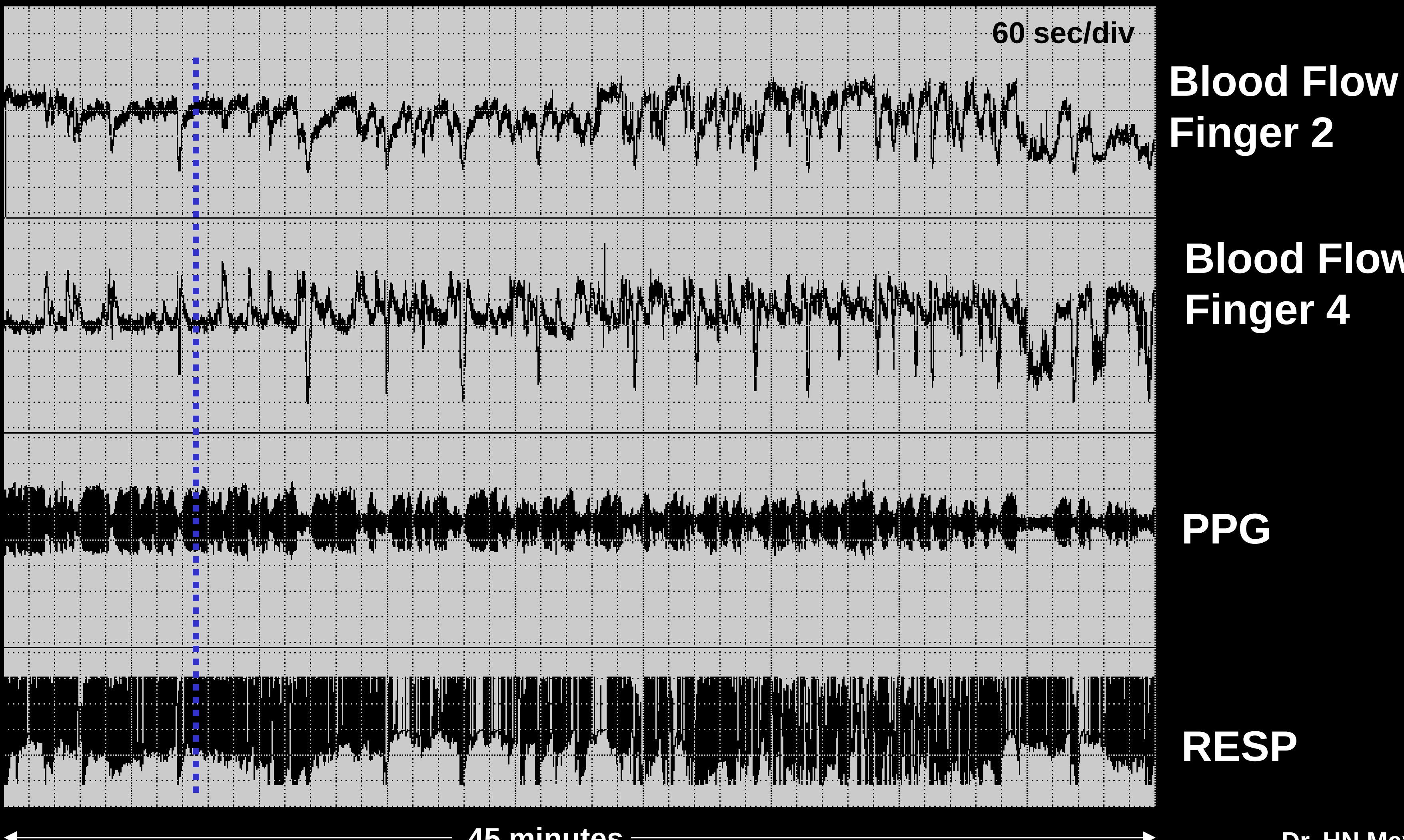
Experiment





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Experiment

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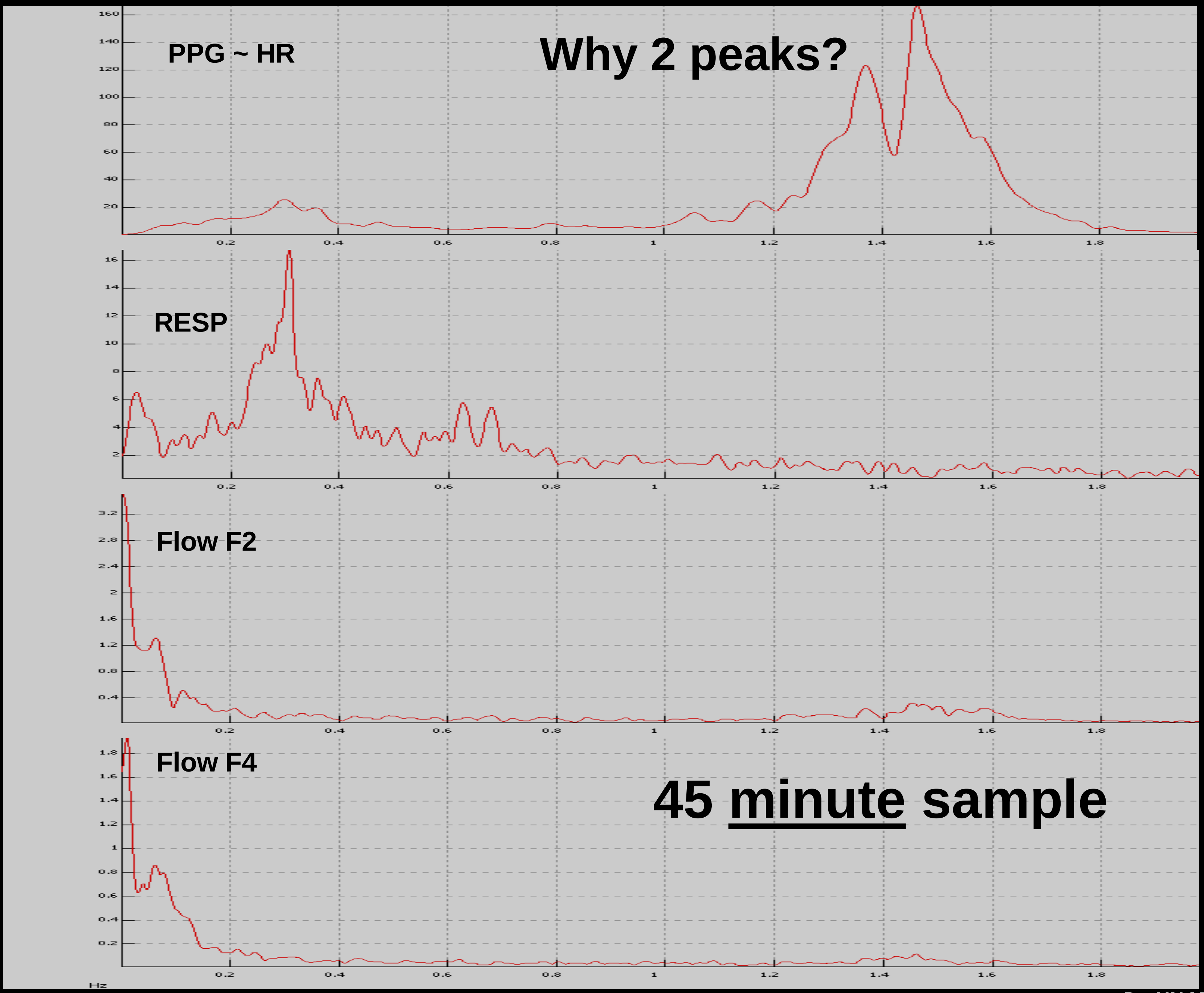

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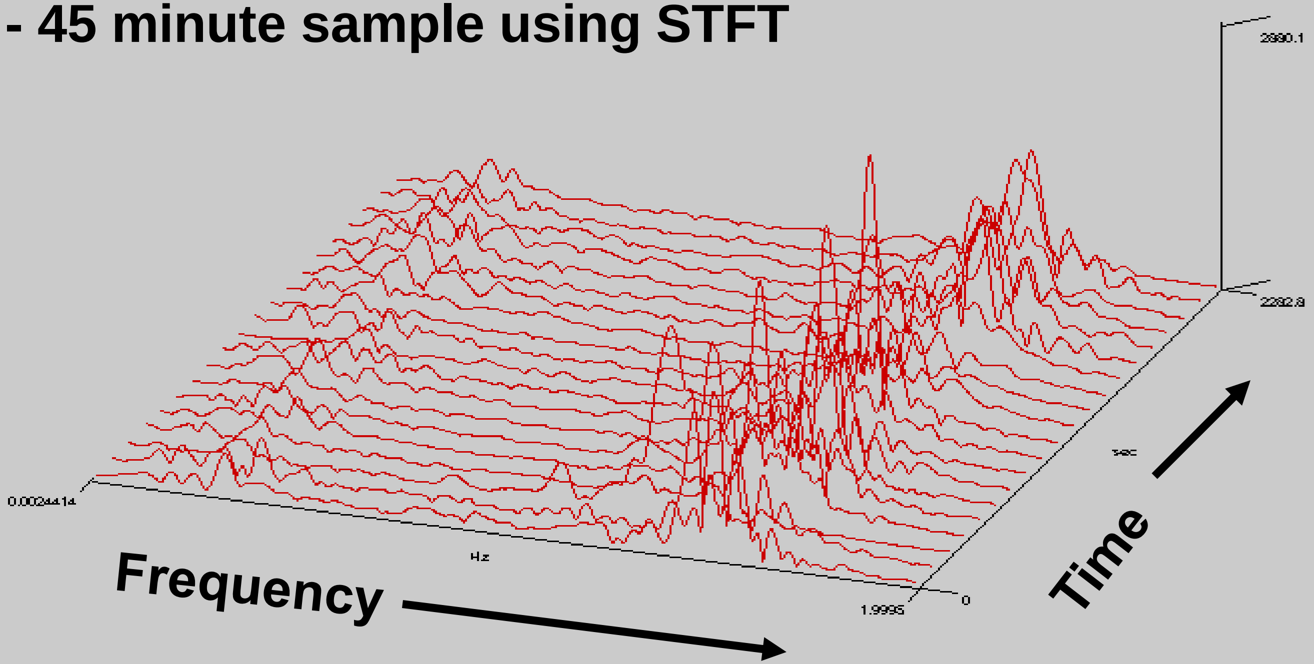
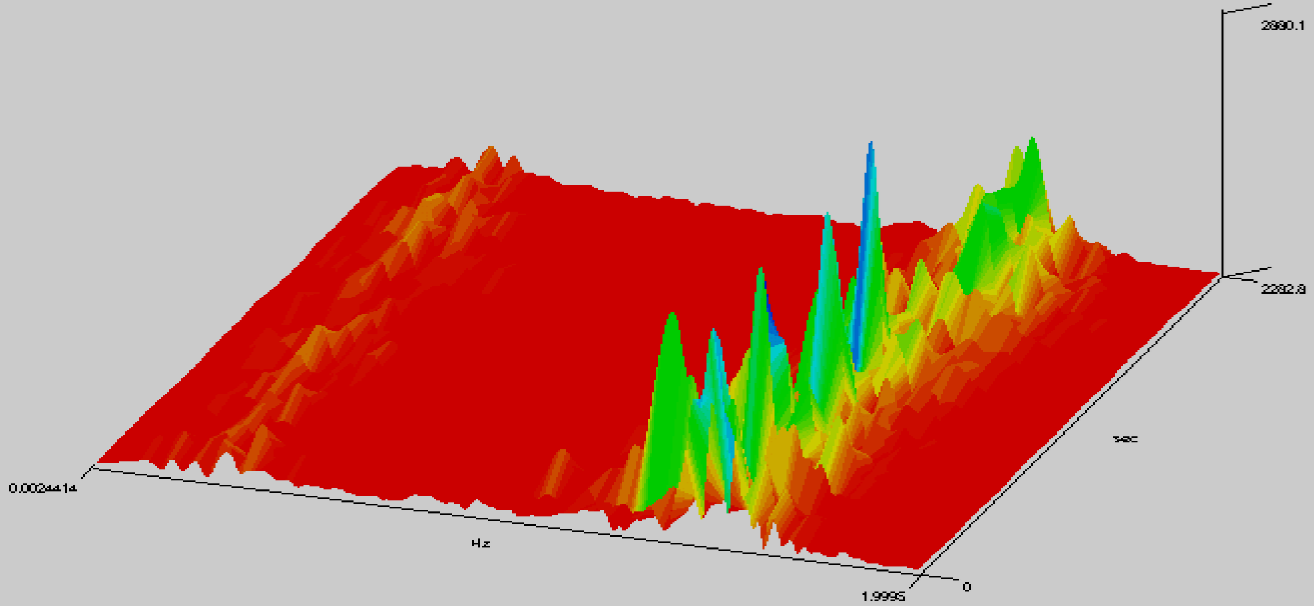
Physiological signals whose spectral content changes with time

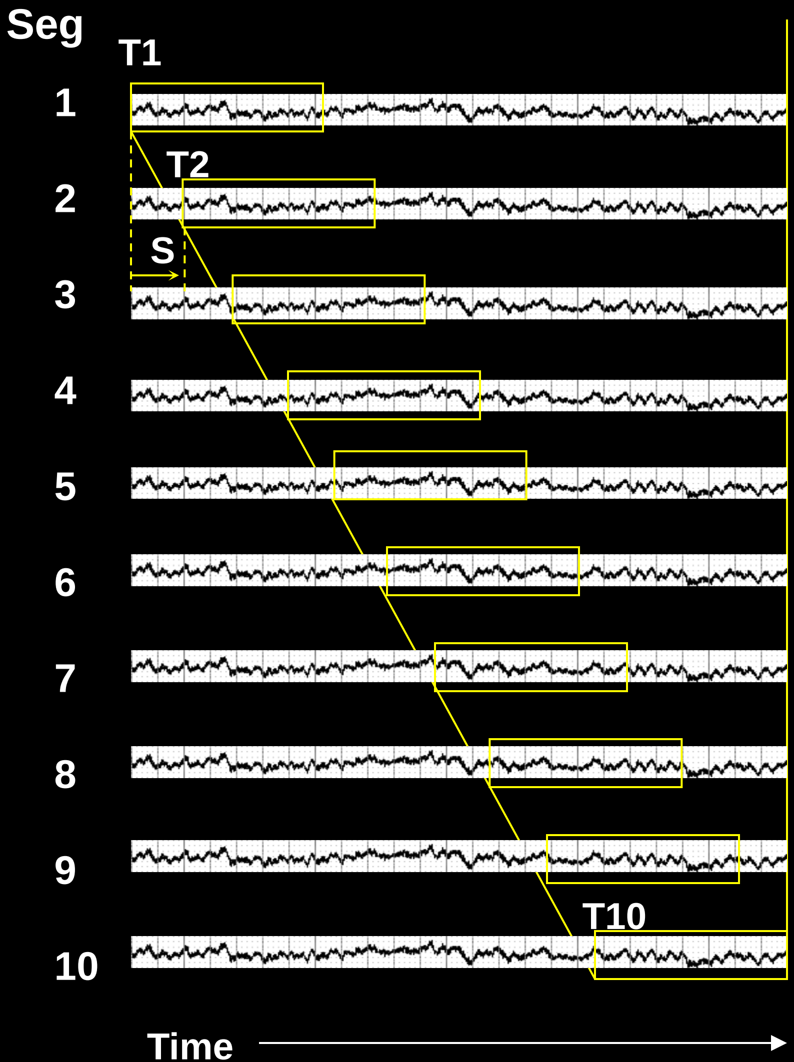
Principle of STFT
Short Time Fourier Transform

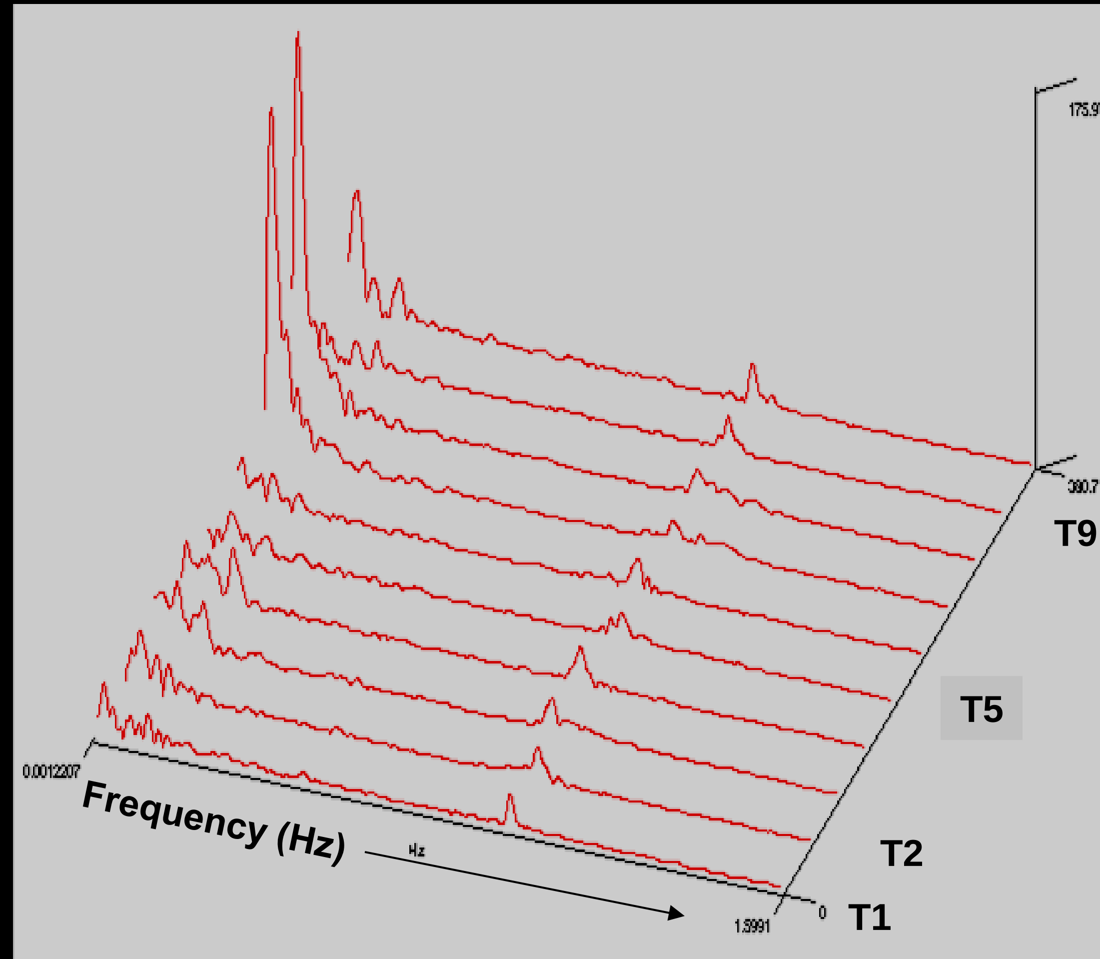
PPG - 45 minute sample using STFT





Principles of Short Time Fourier Transform Analysis





T10 = T_{total} - $N_{precision}/F_S$
= 1200 - 819.2 = 380.7 sec
= (N_{segs}-1) x S = 9 x 846/20 = 9 x 42.3 sec = 380.7 sec

T_{total} = 20 minutes =1200 sec, F_S =20 s/sec
$N_{precision}$ = 16384 = 16384/20 = 819.2 sec
$F_{precision}$=(1/819.2) = 0.0012 Hz

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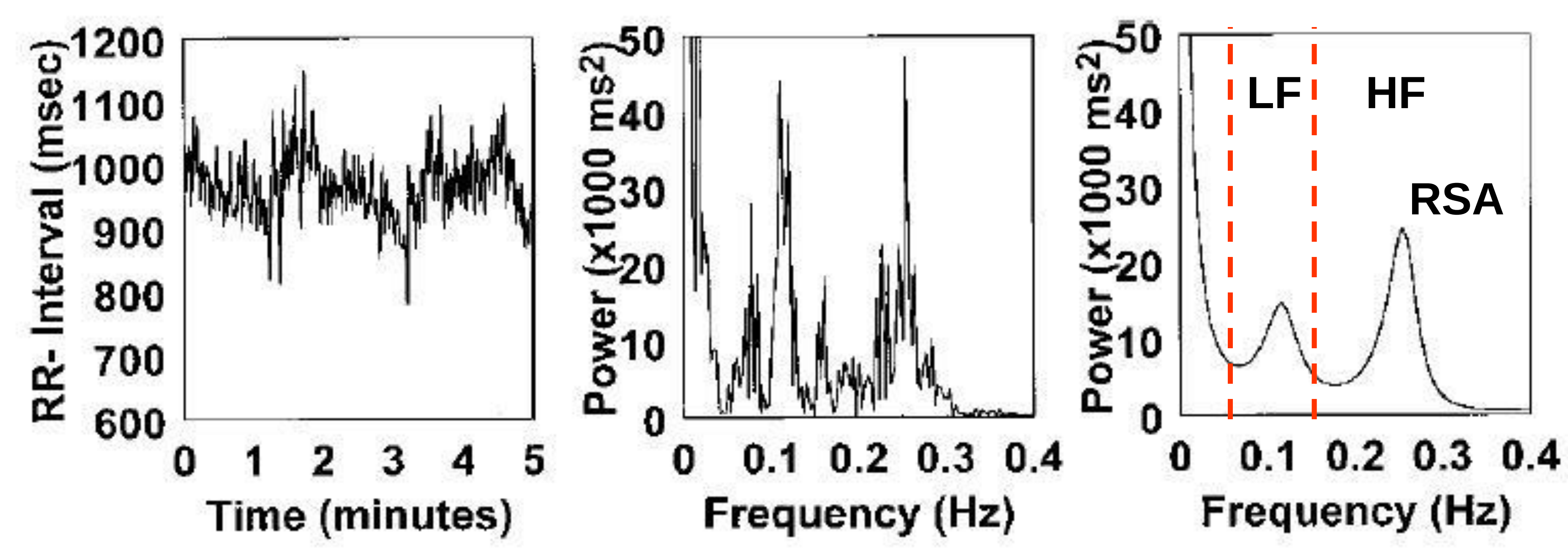
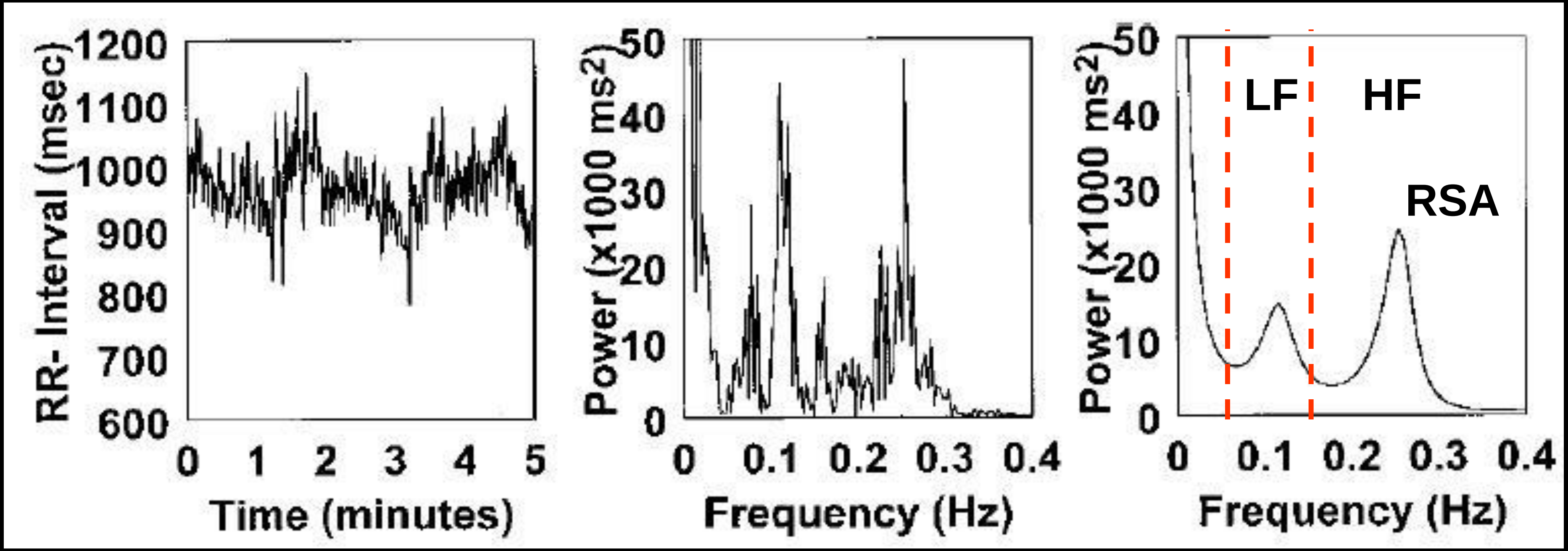
Heart Rate Variability

Heart Rate Variability (HRV)



Heart Rate Variability (HRV)

		ULF: <0.003 Hz
Peripheral Vascular & Thermoregulatory	→	VLF: 0.003 - 0.04 Hz
Baroreceptors phase delay Sympathetic & Parsympathetic	→	LF: 0.04 - 0.15 Hz
Respiratory Sinus Arrythmia (RSA) Cardiac Vagal Activity Change	→	HF: 0.15 - 0.40* Hz



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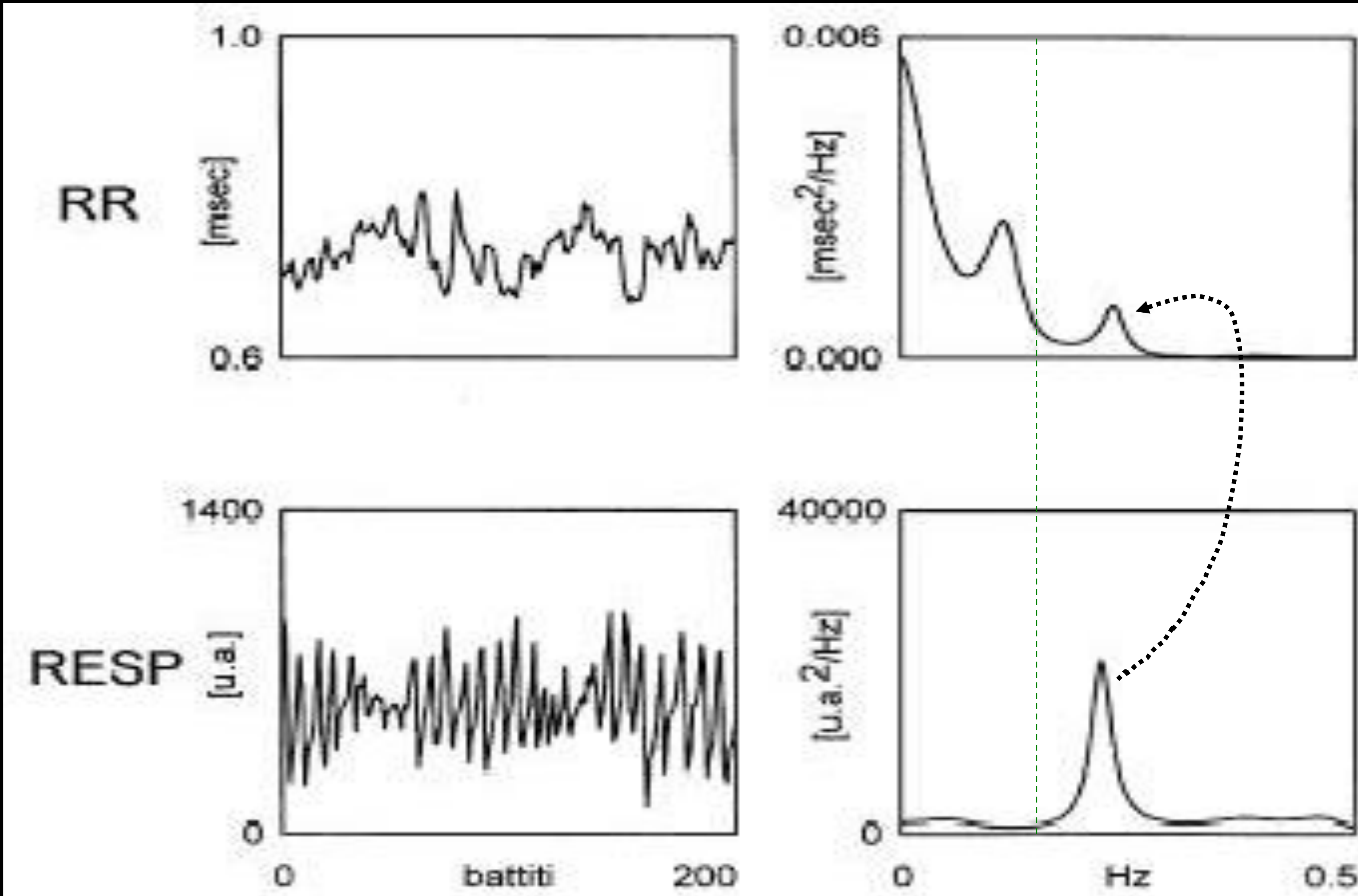
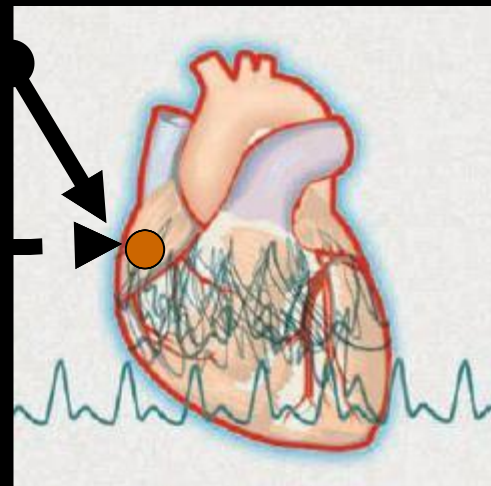
RSA Main Source of HF peak



Respiratory Linkage to HF & LF

Parasympathetic
(Vagus)
Heart Rate Brake



HR
Increases

Inspiration
(inhibits
vagus nerve
outflow impulses)

- Centrally?
- Increased
venous return

Baroreflex

Vagus ~ Fast ~ HF

Sympathetic

Sympathetic ~ Slow ~ Phase Delay ~ LF

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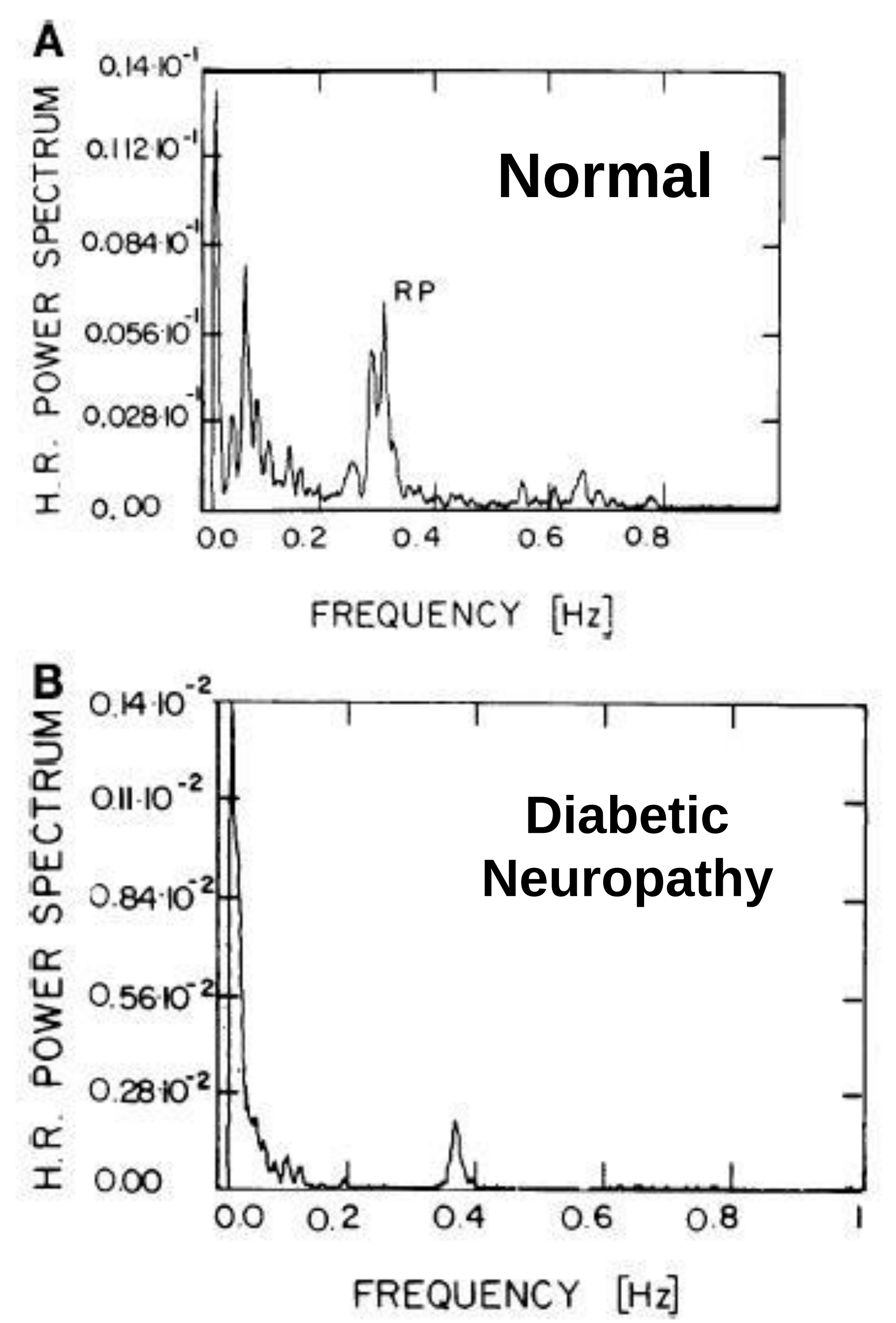
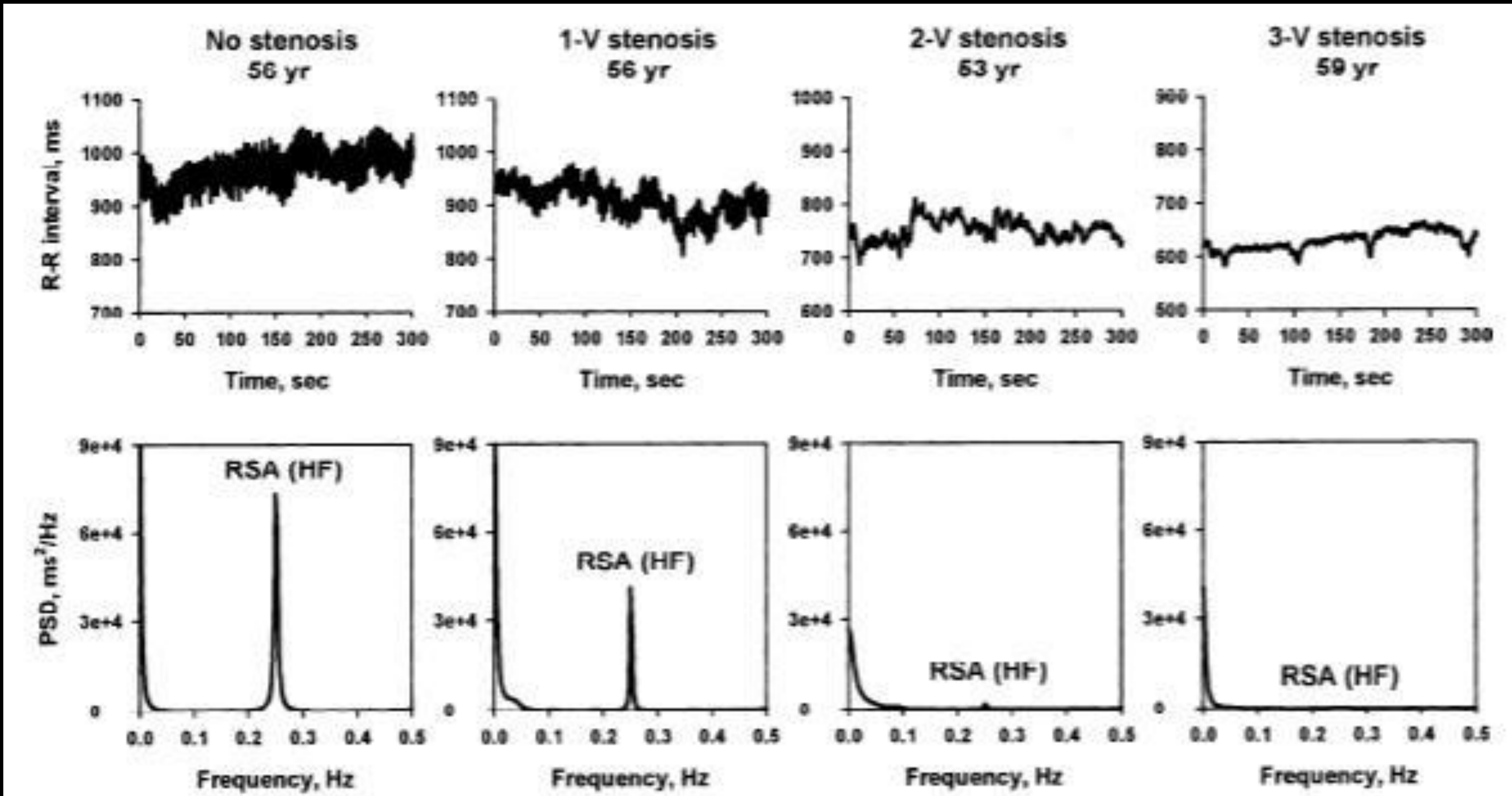
Clinical Findings & Applications



Lishner et al.
J Auton Nerv Syst
1987;19:119-125

Hypothesis: respiratory sinus arrhythmia is an intrinsic resting function of cardiopulmonary system Cardiovascular Research 58 (2003) 1–9



HF power decreases with # of vessels involved

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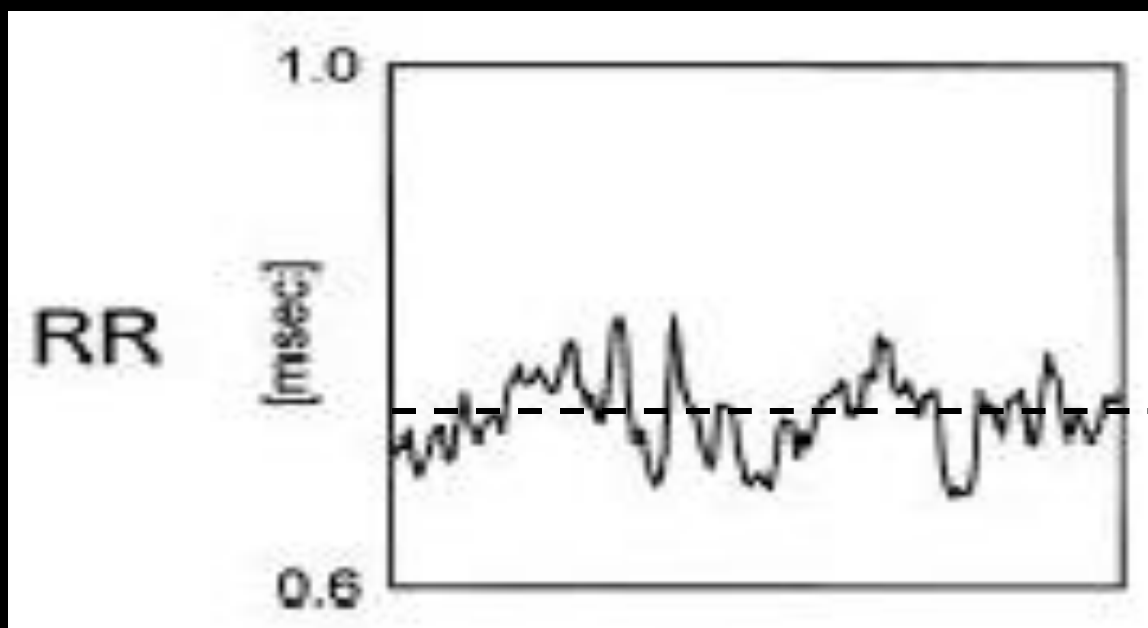
Time Analysis of HRV

uses standard deviation or variance of (normal) R-R intervals

Coefficient of variance = SD/mean
= SDNN/mean



mean

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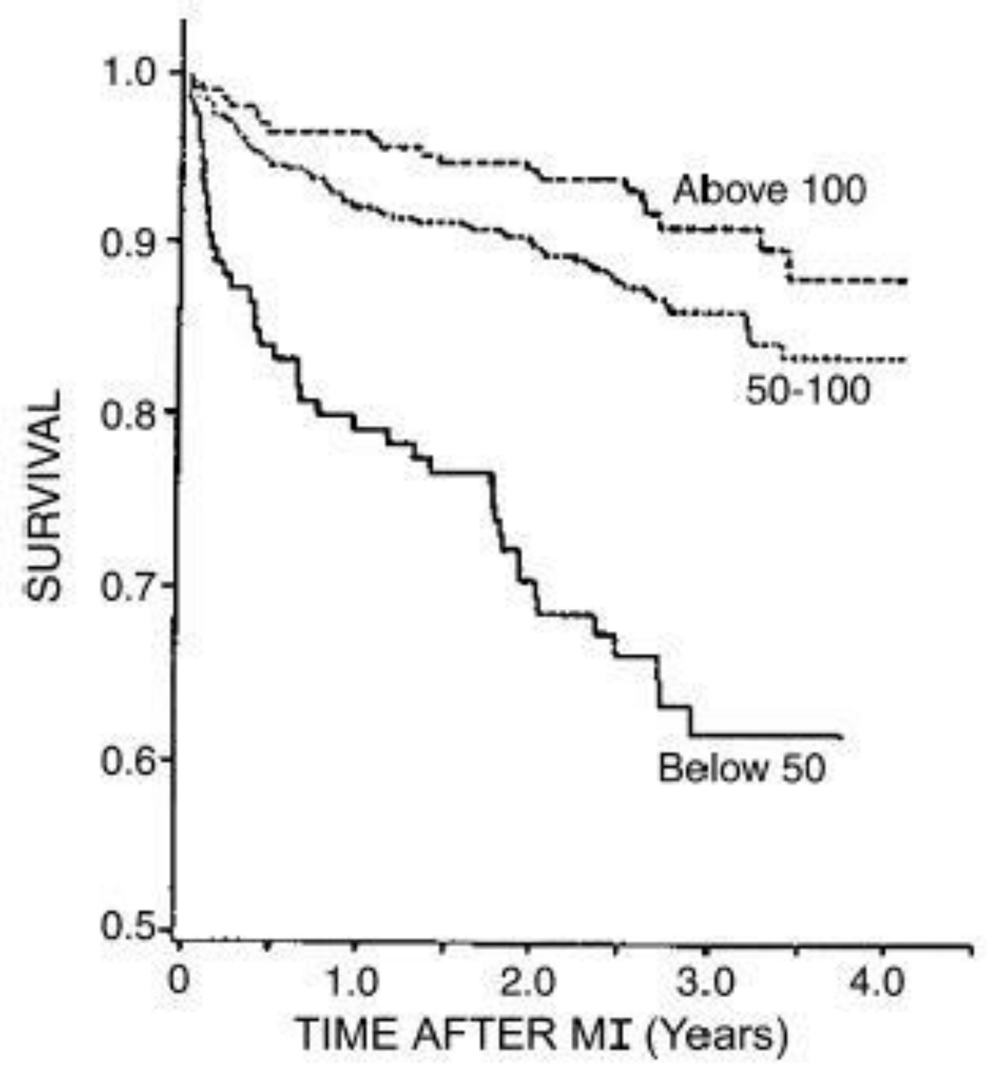
Kleiger RE, Miller JP, Bigger JT, Moss AJ. Decreased heart rate variability and its association with increased mortality after acute myocardial infarction. Am J Cardiol 1987;59:256–62.



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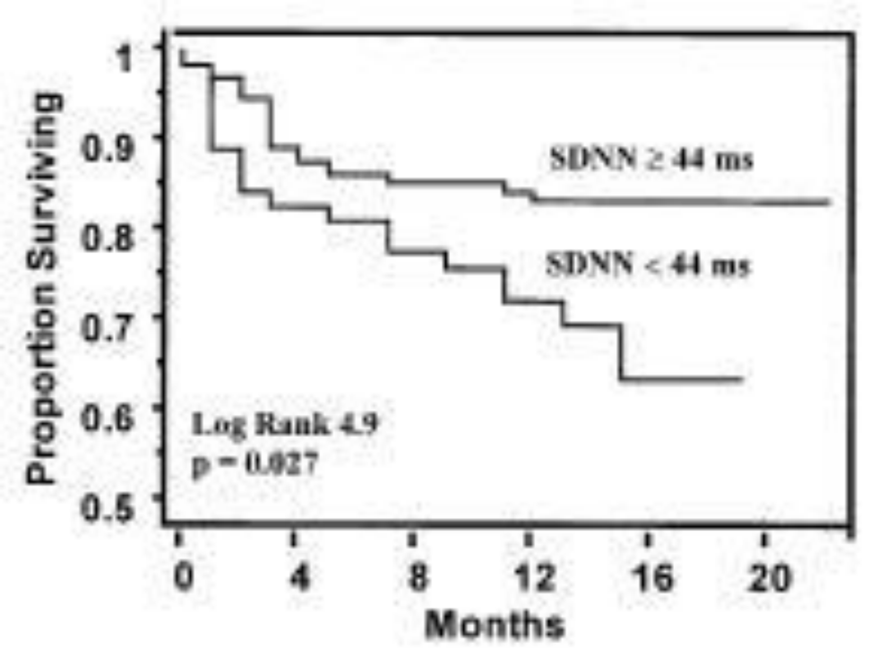
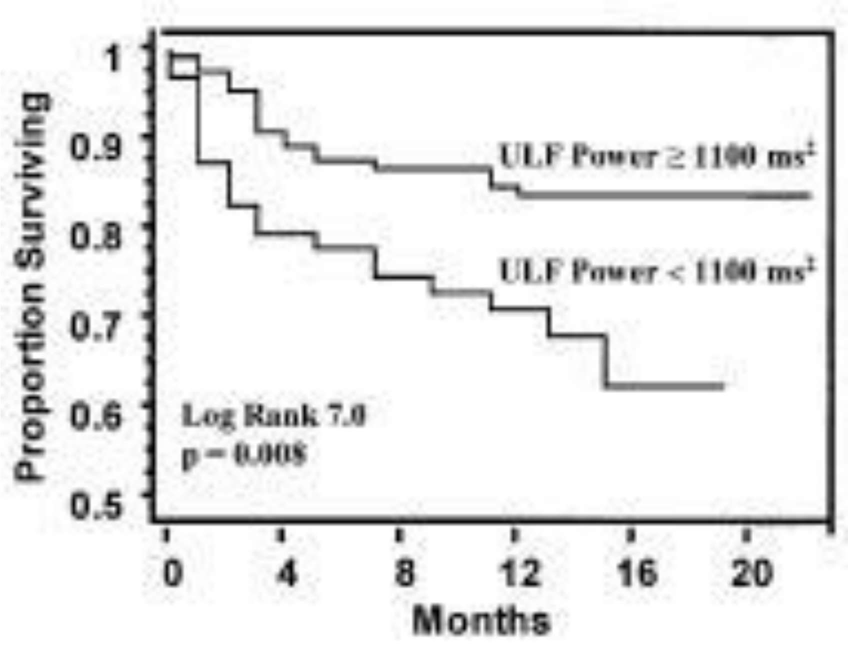
Measures of Heart Period Variability as Predictors of Mortality in Hospitalized Patients With Decompensated Congestive Heart Failure

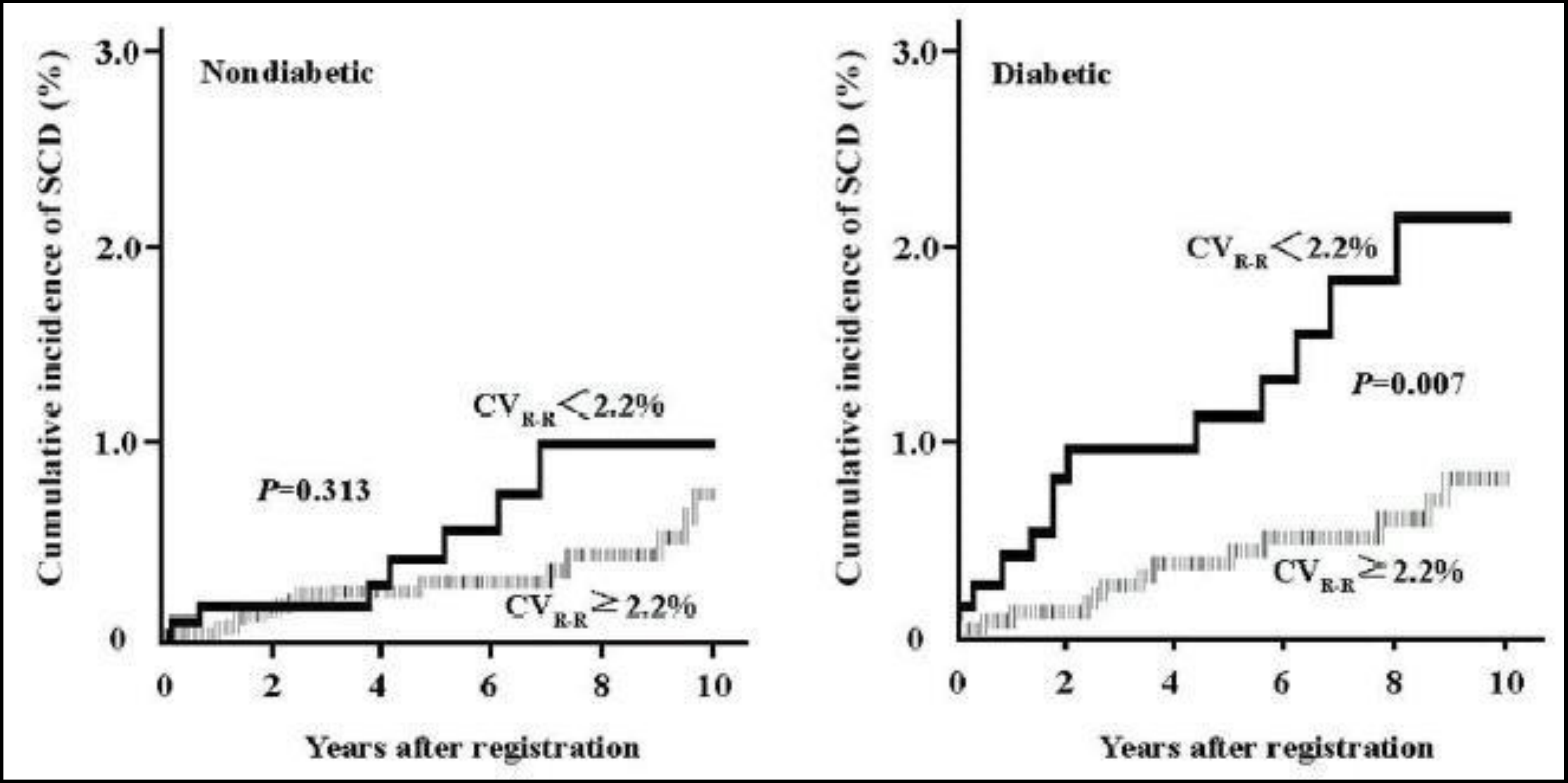
Doron Aronson, MD, Murray A. Mittleman, MD, DrPH, and Andrew J. Burger, MD

(Am J Cardiol 2004;93:59–63)



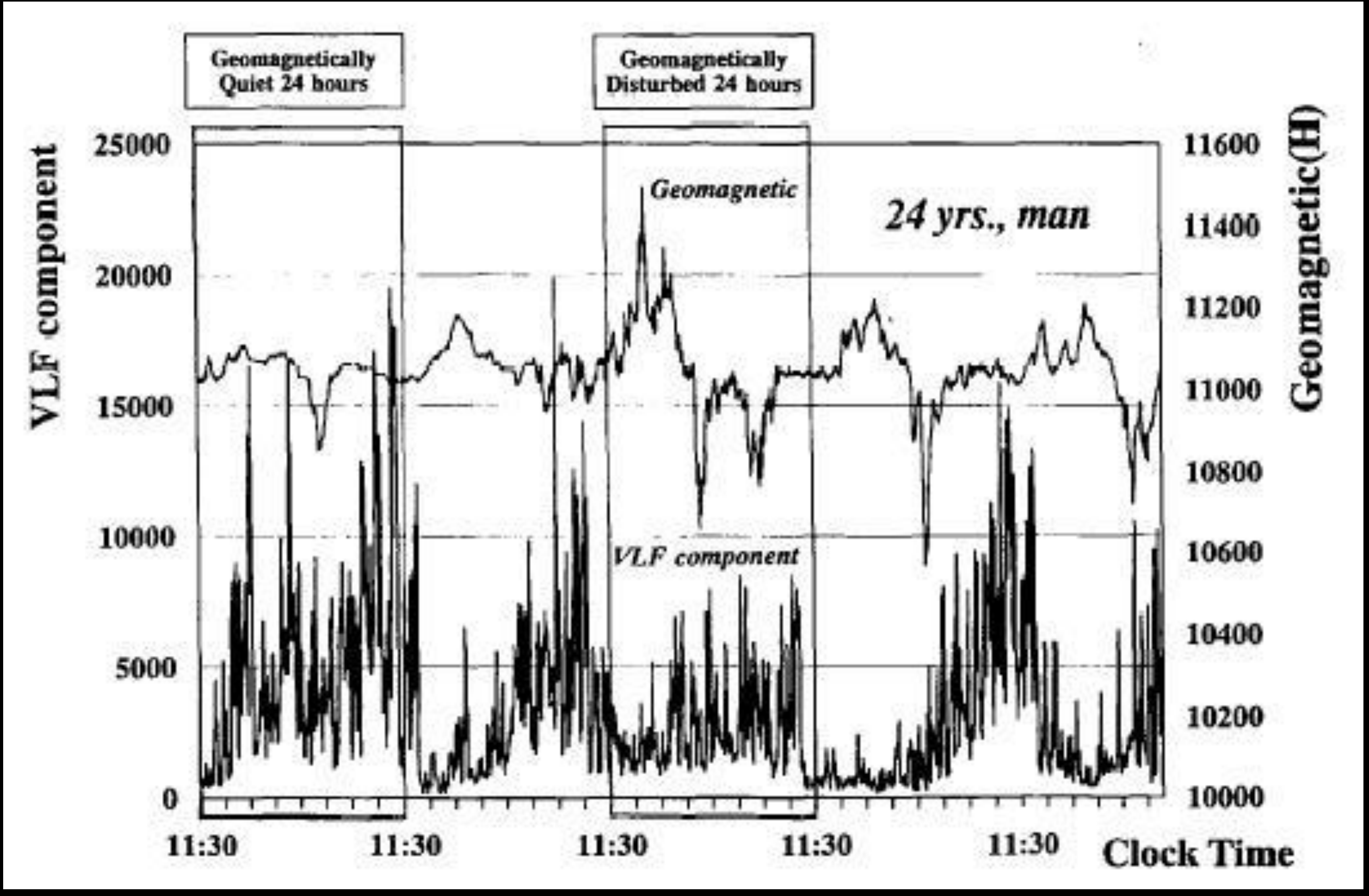


Prognostic Marker of Suden Coronary Death in DM



Geomagnetic disturbance associated with decrease in heart rate variability in a subarctic area Biomed Pharmacother 2001 ; 55 : 51-6

K. Otsuka[1]*, G. Cornélissen[2], A. Weydahl[3], B. Holmeslet[4], T.L. Hansen[4], M. Shinagawa[1], Y. Kubo[1], Y. Nishimura[1], K. Omori[1], S. Yano[5], F. Halberg[2]



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Modulatory effects of respiration

Luciano Bernardi[a,*], Cesare Porta[a], Alessandra Gabutti[a], Lucia Spicuzza[b], Peter Sleight[c]

Autonomic Neuroscience: Basic and Clinical 90 (2001) 47–56

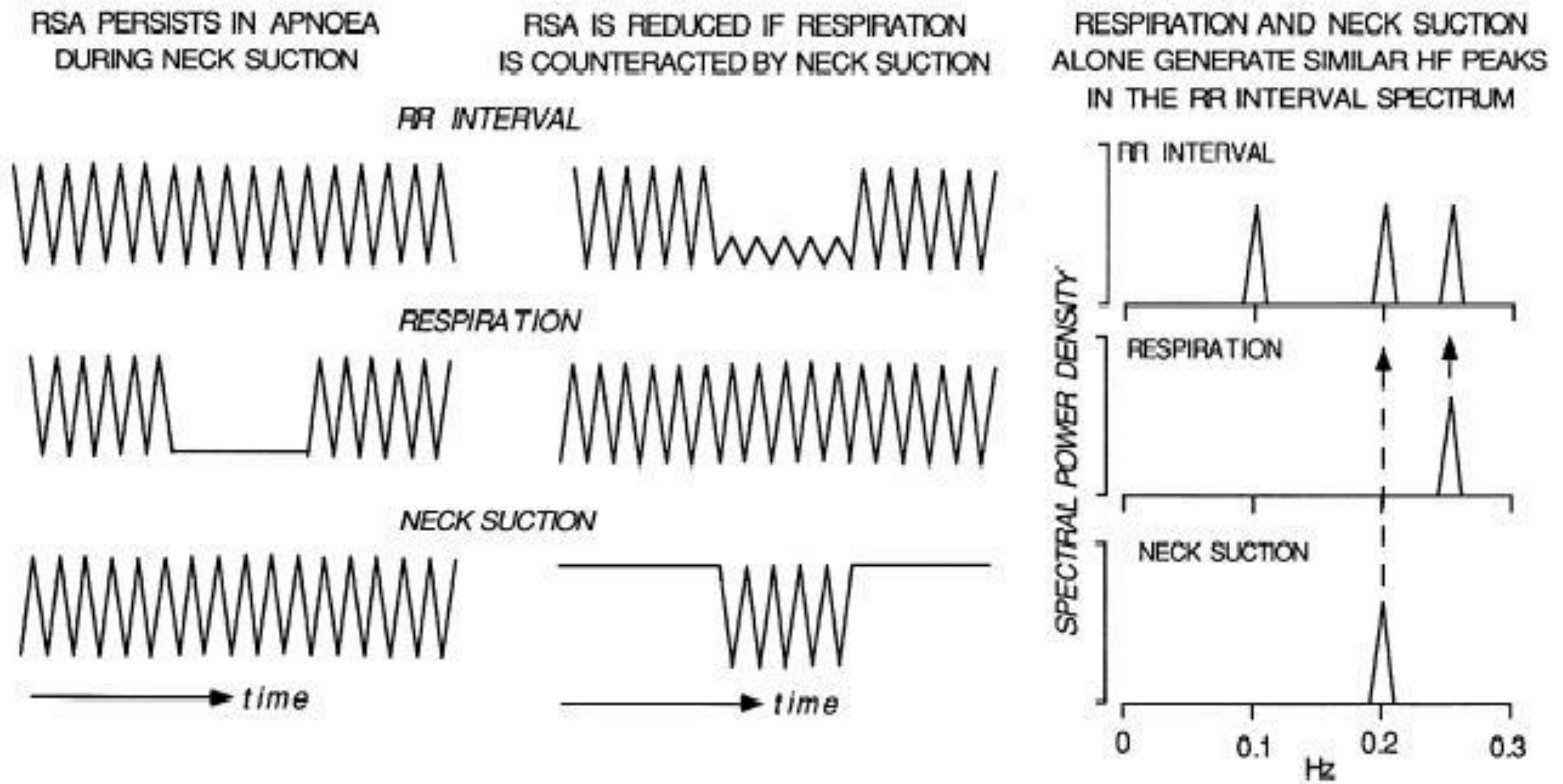


Fig. 1. Effect of arterial (carotid) baroreceptors on respiratory sinus arrhythmia (RSA). Left panel: Despite apnoea, RSA persists if carotid baroreceptors are stimulated at (by neck suction) the same frequency of breathing. Middle panel: If carotid baroreceptors are stimulated at the same frequency of respiration but with appropriate phase, RSA can be reduced by the counteracting effect of neck suction on respiratory changes in arterial pressure. Right panel: Stimulation of carotid baroreceptors at a frequency close but distinct to that of respiration (0.20 and 0.25 Hz, respectively) produces an RSA of similar amplitude (as could be seen in the power spectra) of that simultaneously generated by the respiration.

Phase delay of baroreceptor response to inspiration induced increase in BP may account for LF component of HRV

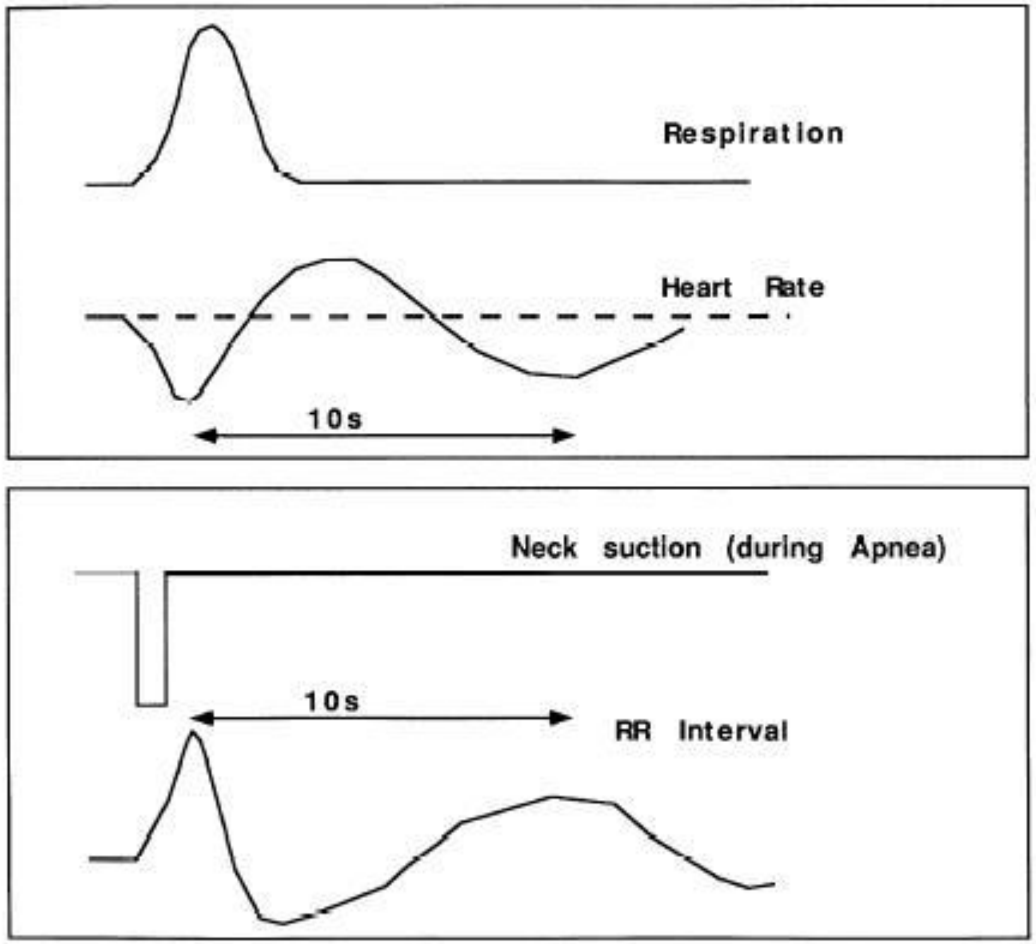


Fig. 3. A single deep breath elicits a damped oscillation in the RR interval (and in blood pressure) whose period is similar to that of spontaneous low-frequency oscillation (i.e., 10-s period, or 0.1 Hz or 6 cycles/min); a very similar effect can be obtained by a sudden and transient stimulation of carotid baroreceptors (by neck suction).

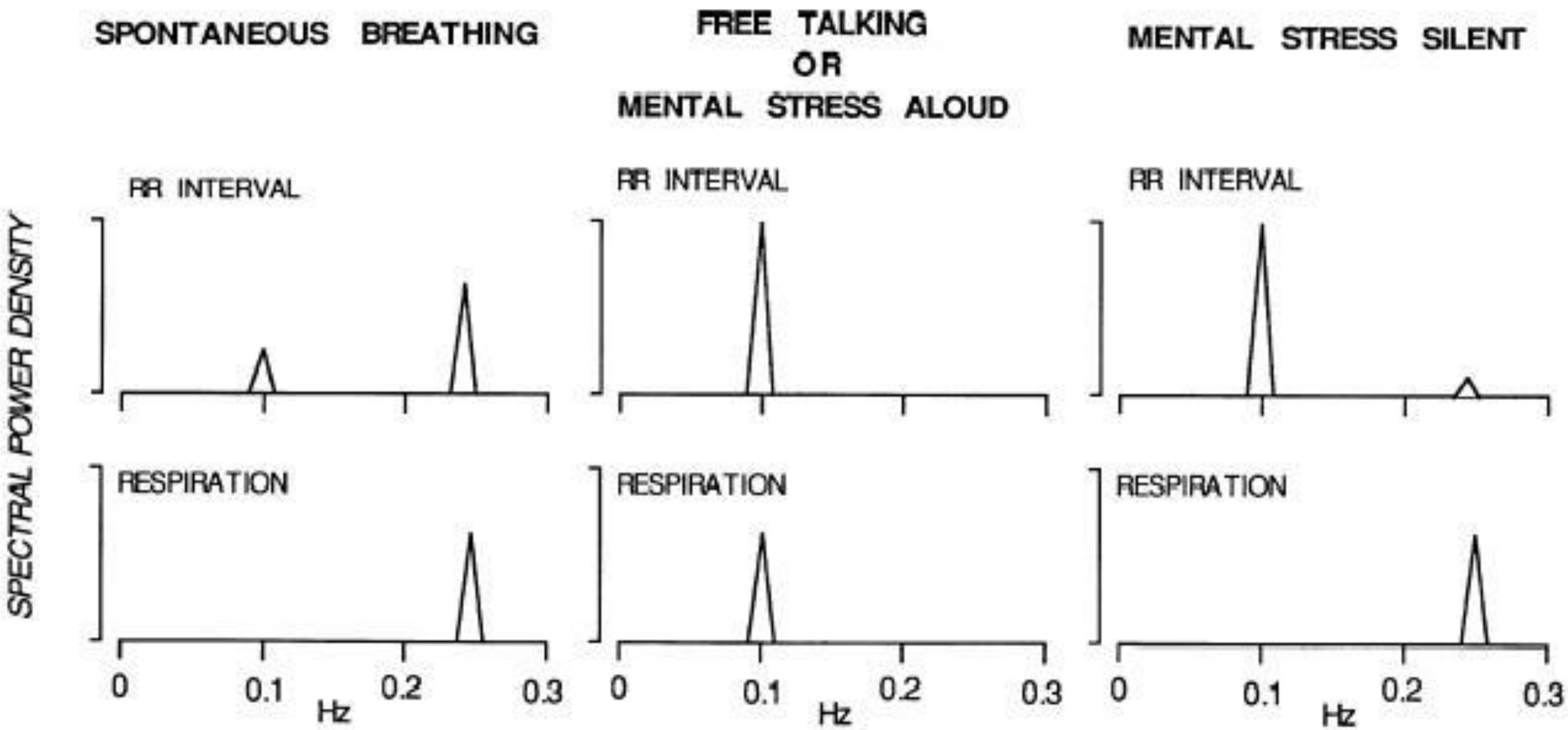
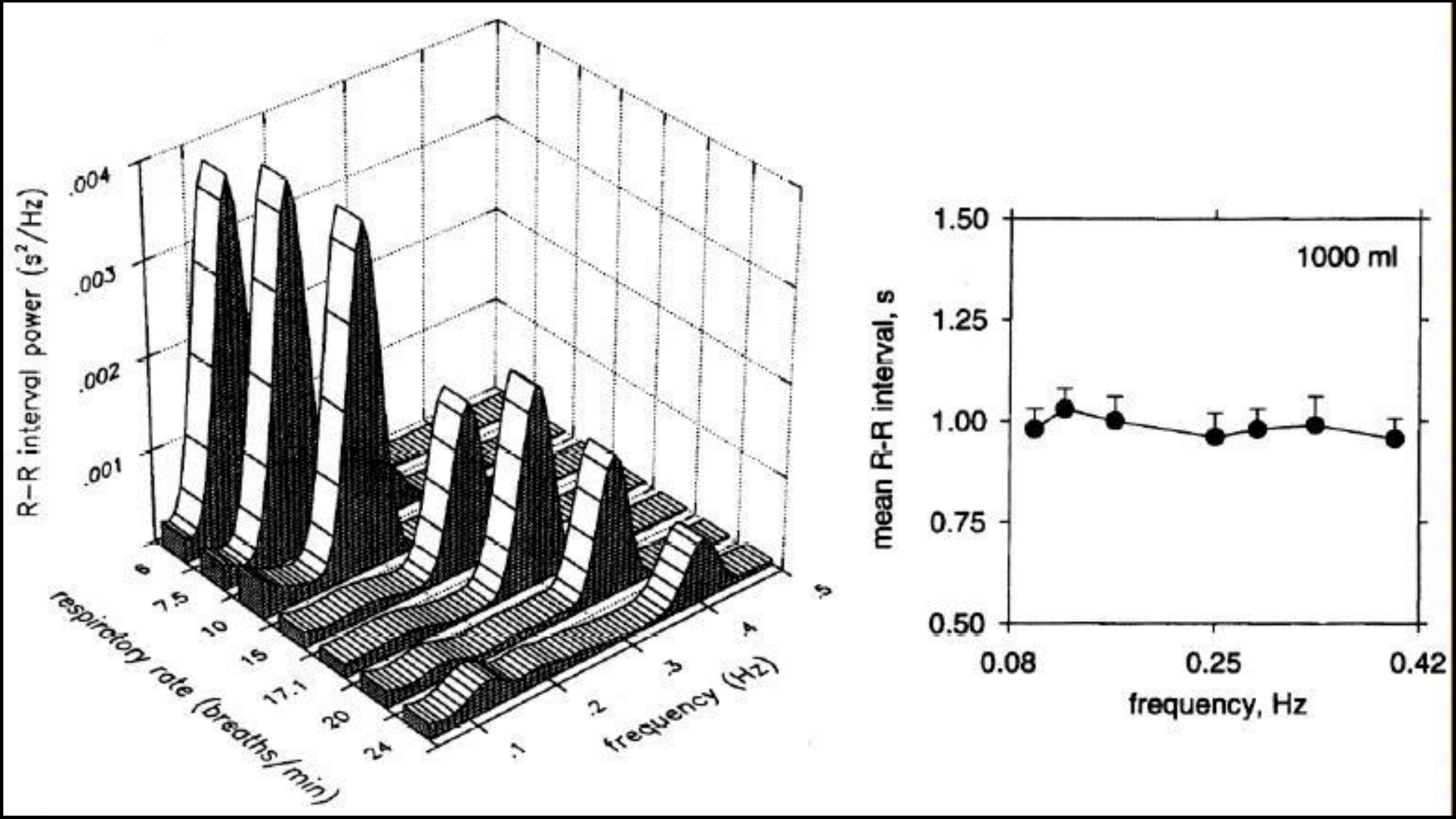


Fig. 4. Effect of talking and stress on respiration and RR interval power spectra: during spontaneous breathing (subject silent) the RR spectrum has predominant HF respiratory power; during free talking, due to the slowing of breathing, the RR spectrum shows a marked increase of low-frequency power due to the slowing of respiration; during mental stress aloud, the LF increases both because of the sympathetic activation and because of the slow breathing; when the subject undergoes a mental stress silent, the increase in LF is due only to sympathetic activity and not to the modulatory effect of breathing.

10 subjects breathing at different rates (TV = 1000 ml)

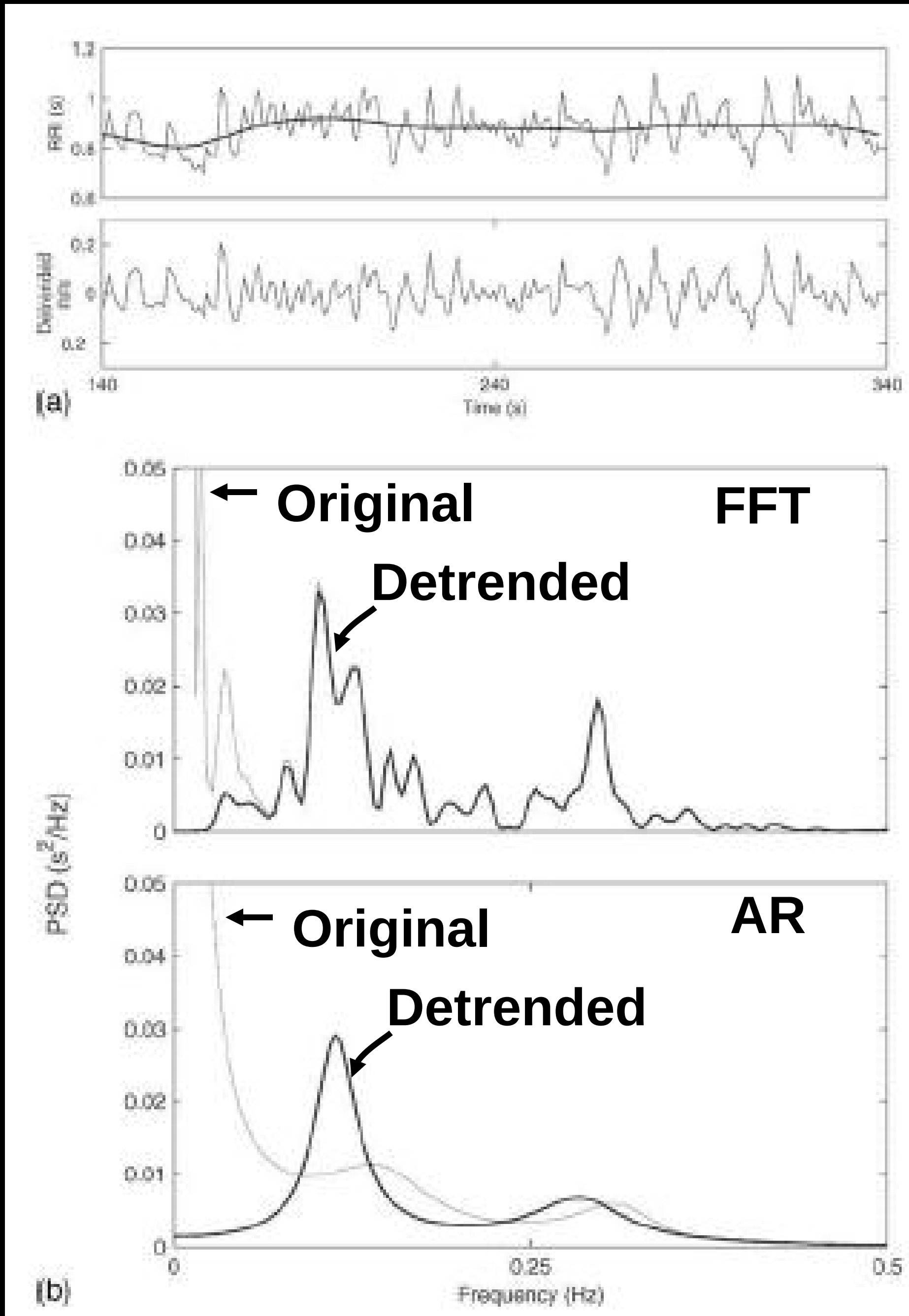


Breathing at different rates effects spectral power but not HR
Thus is not a measure of autonomic tone (absolute nerve traffic)
but is a measure change (modulation) of nerve traffic.

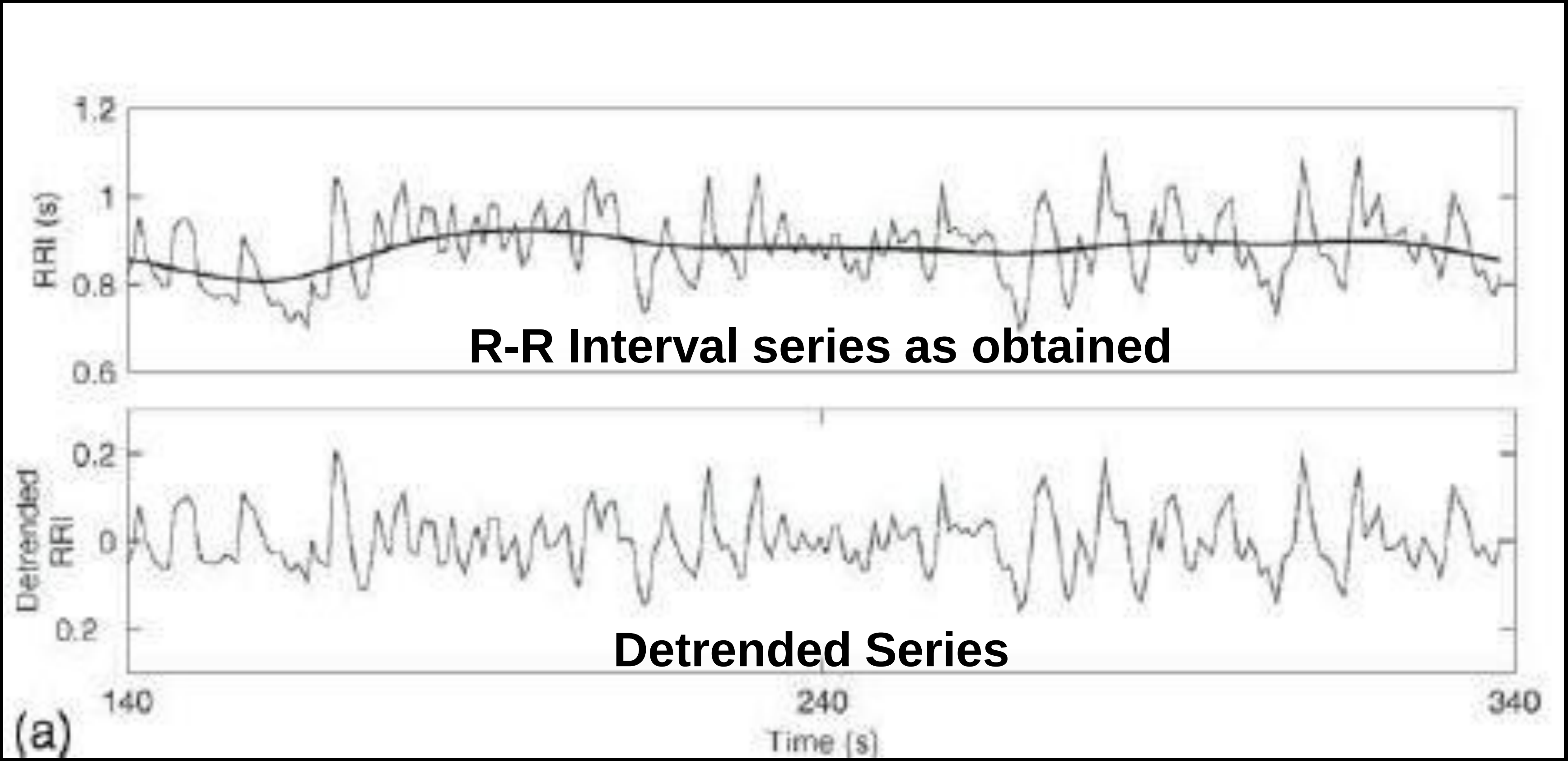
R-R Interval series as obtained

Detrended Series

Power Spectral Density (PSD) of R-R Series



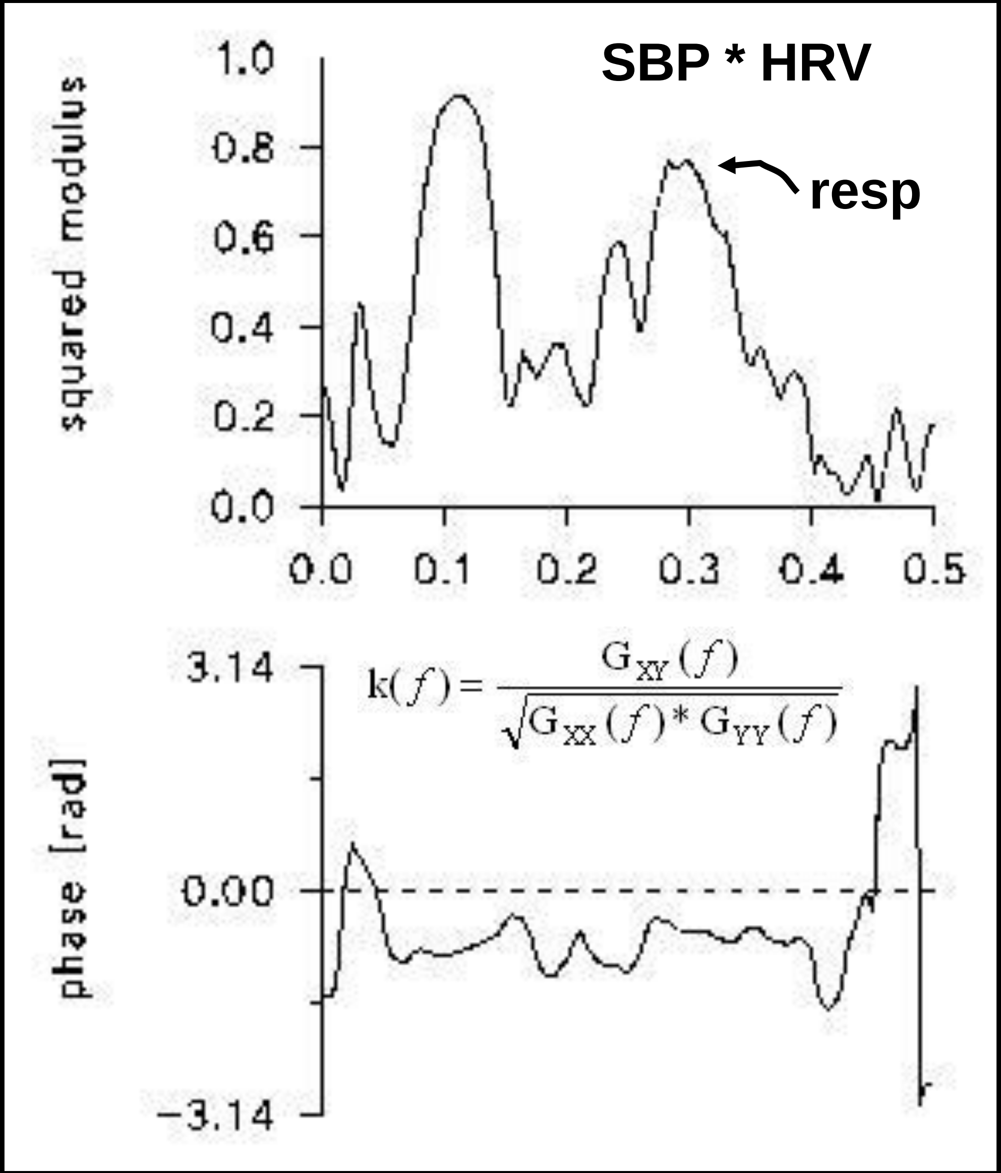
Effect of Detrending



Coherence Function - Degree of linear correlation as fn of frequency

Gxx, Gyy and Gxy are spectra of x(t), y(t) and crosspectrum of x and y

$[K(f)]^2$

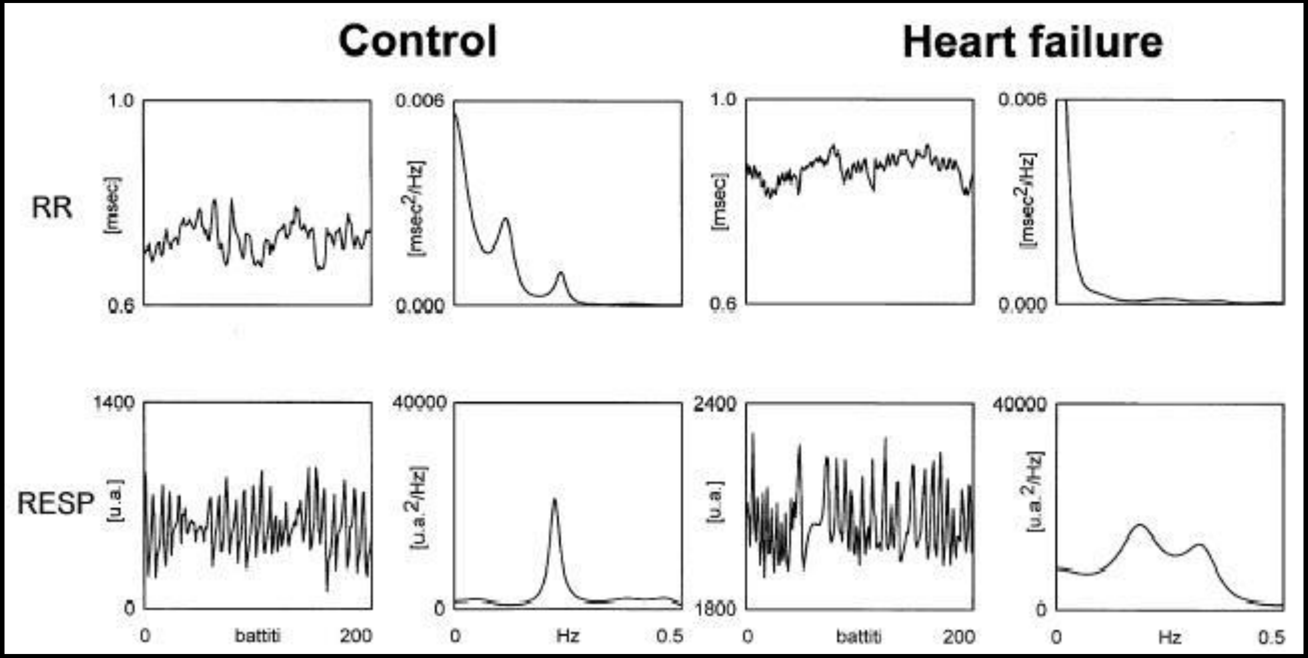


Some Basic Definitions

Heart rate variability in chronic heart failure

Stefano Guzzetti *, Renata Magatelli, Ester Borroni, Silvia Mezzetti

Autonomic Neuroscience: Basic and Clinical 90 (2001) 102–105



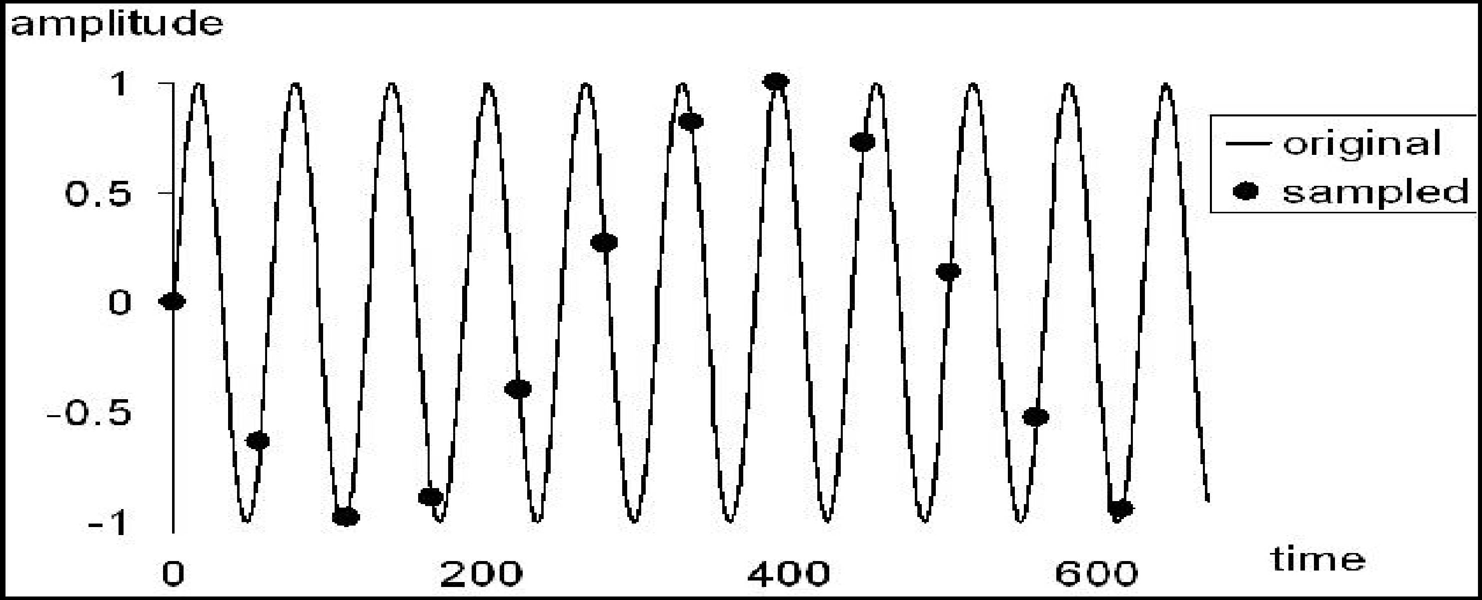
If $x(k)$ is the k-th value of a time series of N samples with sampling period Δt , its energy E is defined as:

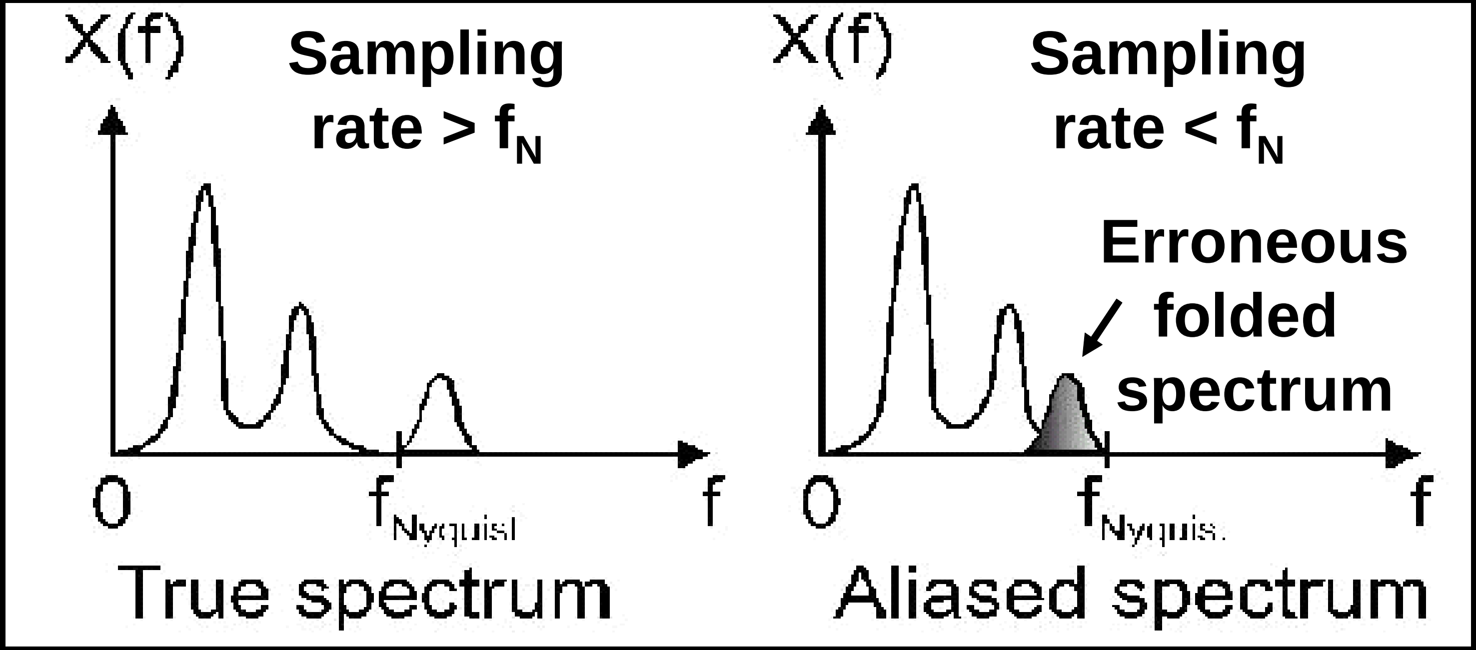
$$E = \sum_{k=0}^{N-1} \left| x(k) \right|^2 \Delta t$$

$$P = \frac{E}{N\Delta t} = \frac{1}{N} \sum_{k=0}^{N-1} \left| x(k) \right|^2$$

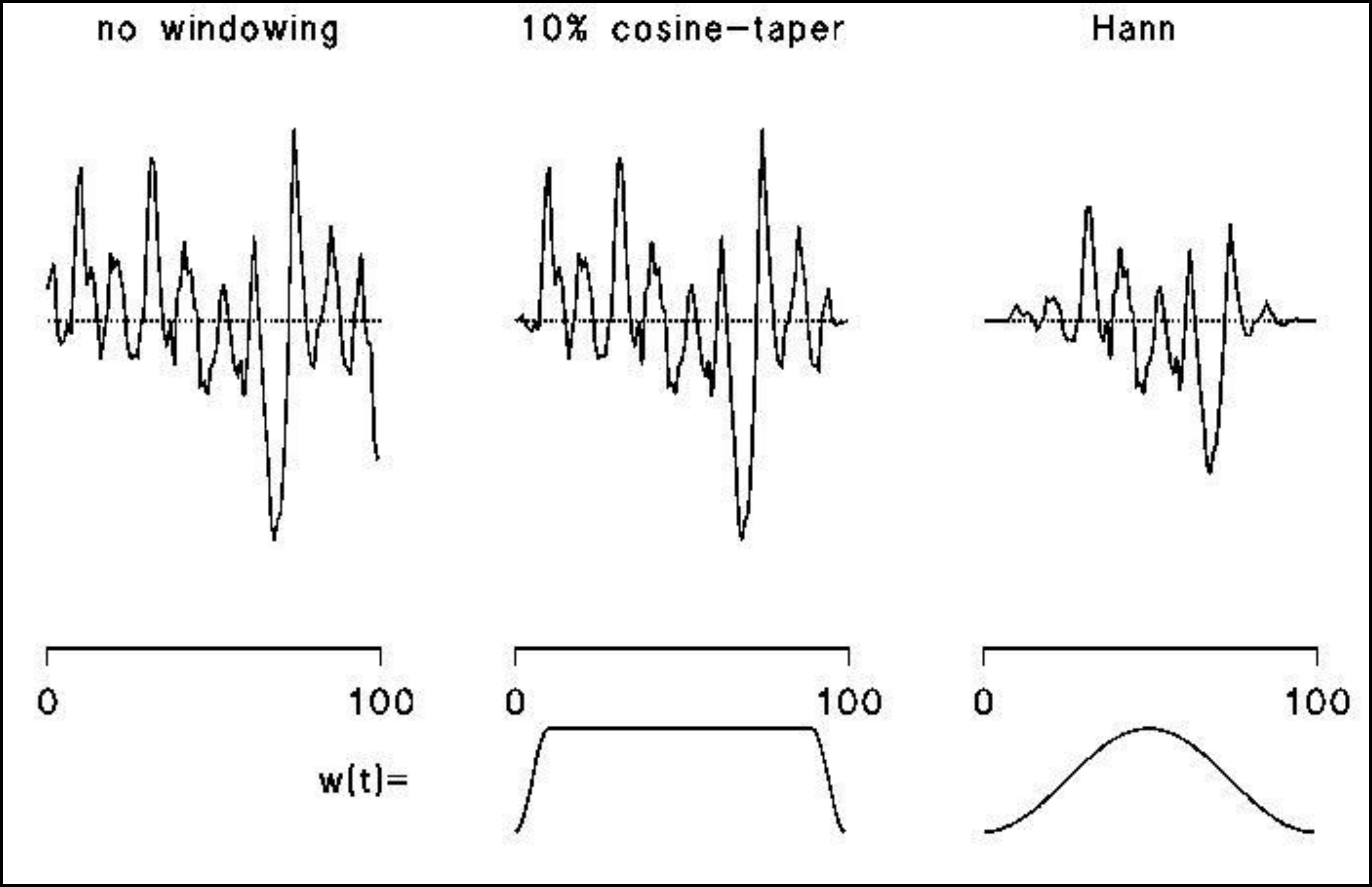
For zero-mean time series, the power is equal to the variance of the sample of the N values $x(k)$.

Aliasing Artifacts





Windowing



Autocorrelation Function

Measure of the dependence of time series values at one time on the values at another time.

Given the time series x(*n*), *n*=1, 2, ...N, the autocorrelation function at lag *k* is defined as:

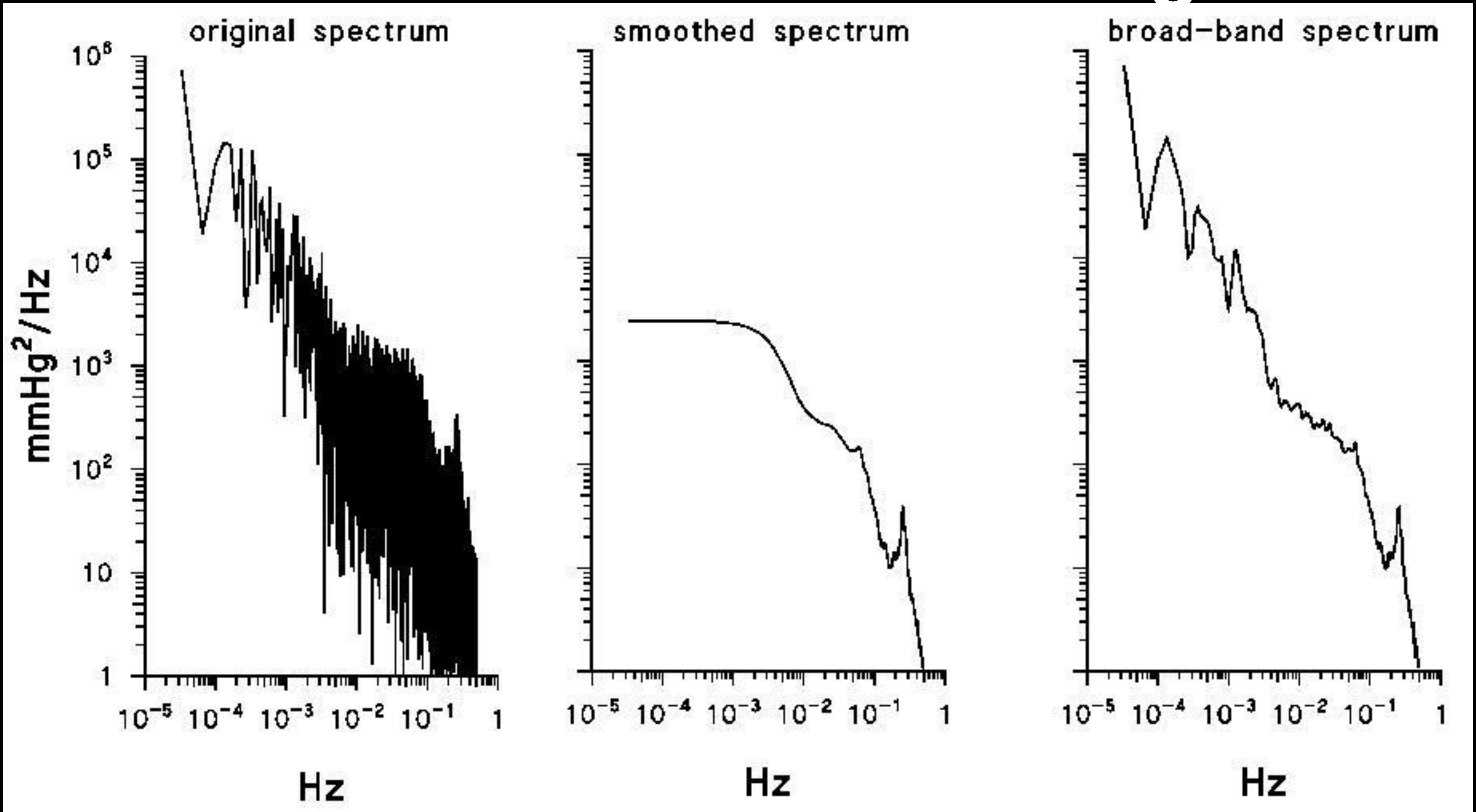
$$R_{xx}(k) = \frac{1}{N-k}\sum_{n=1}^{N-k} x(n)x(n+k)$$

The value of the autocorrelation function at lag 0 is the power of x(*n*), or its variance if the mean value of x(*n*) is zero:

$$R_{xx}(0) = \frac{1}{N-k}\sum_{n=1}^{N-k} x(n)^2$$

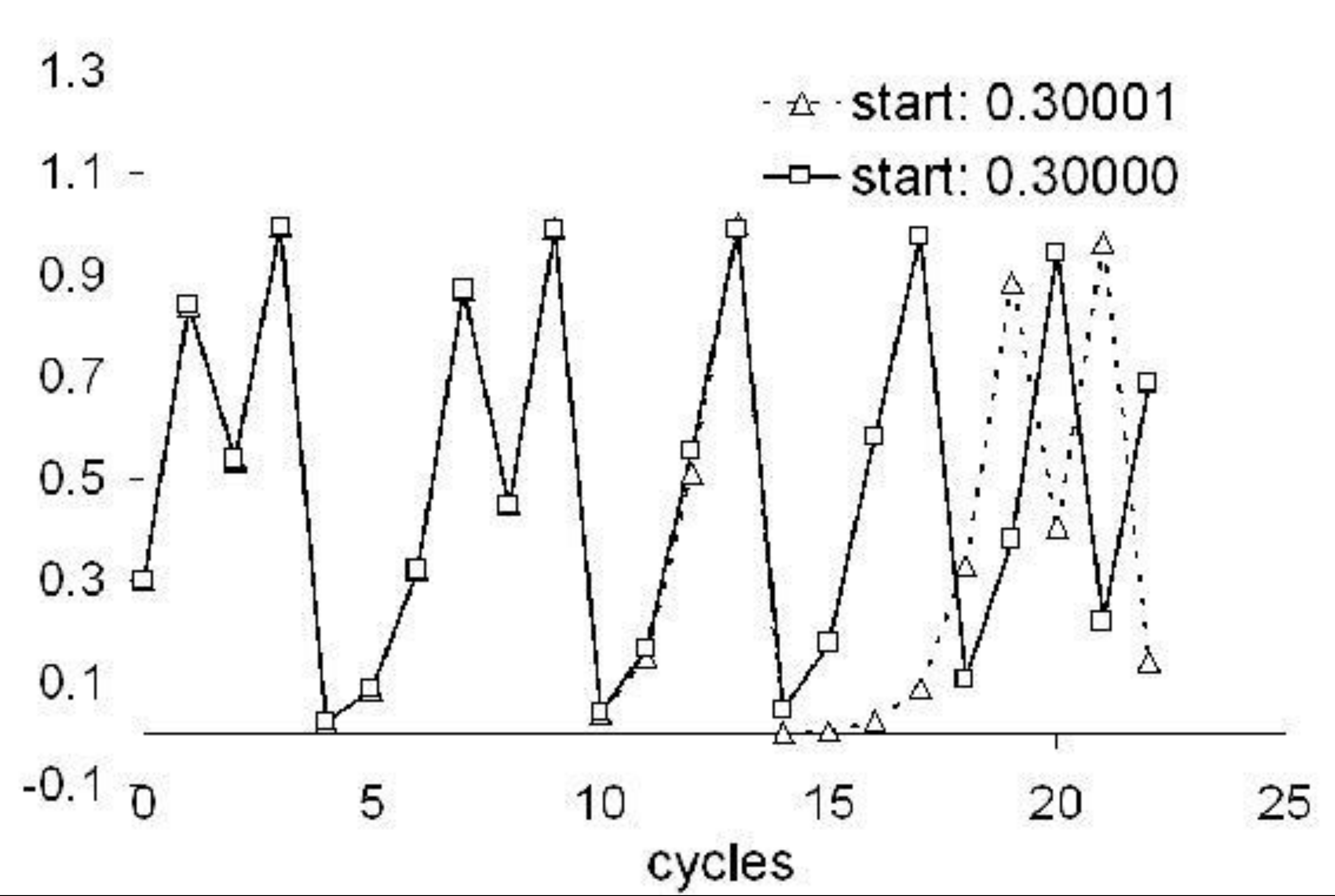
Moreover, $\sqrt{R_{xx}(\infty)}$ is the mean value for random processes.

Broad Band Smoothing



Left: unsmoothed FFT spectrum of blood pressure from a 8-h recording: this spectrum is characterized by a very high frequency resolution, but also by a very high estimation variance. Centre: the same spectrum smoothed by a moving average filter of order 250 (i.e., average over 250 adjacent spectral lines). Estimation variance is largely reduced, but the frequency resolution dramatically worsens and important spectral details may be lost at the lower frequencies. Right: broad-band spectrum obtained from the raw FFT spectrum by averaging adjacent spectral lines: in this case the number of lines to average increases with the frequency from 1 to 250. The desired reduction of the estimation variance is obtained at the highest frequencies preserving the original frequency resolution at the lowest frequencies.

Chaos

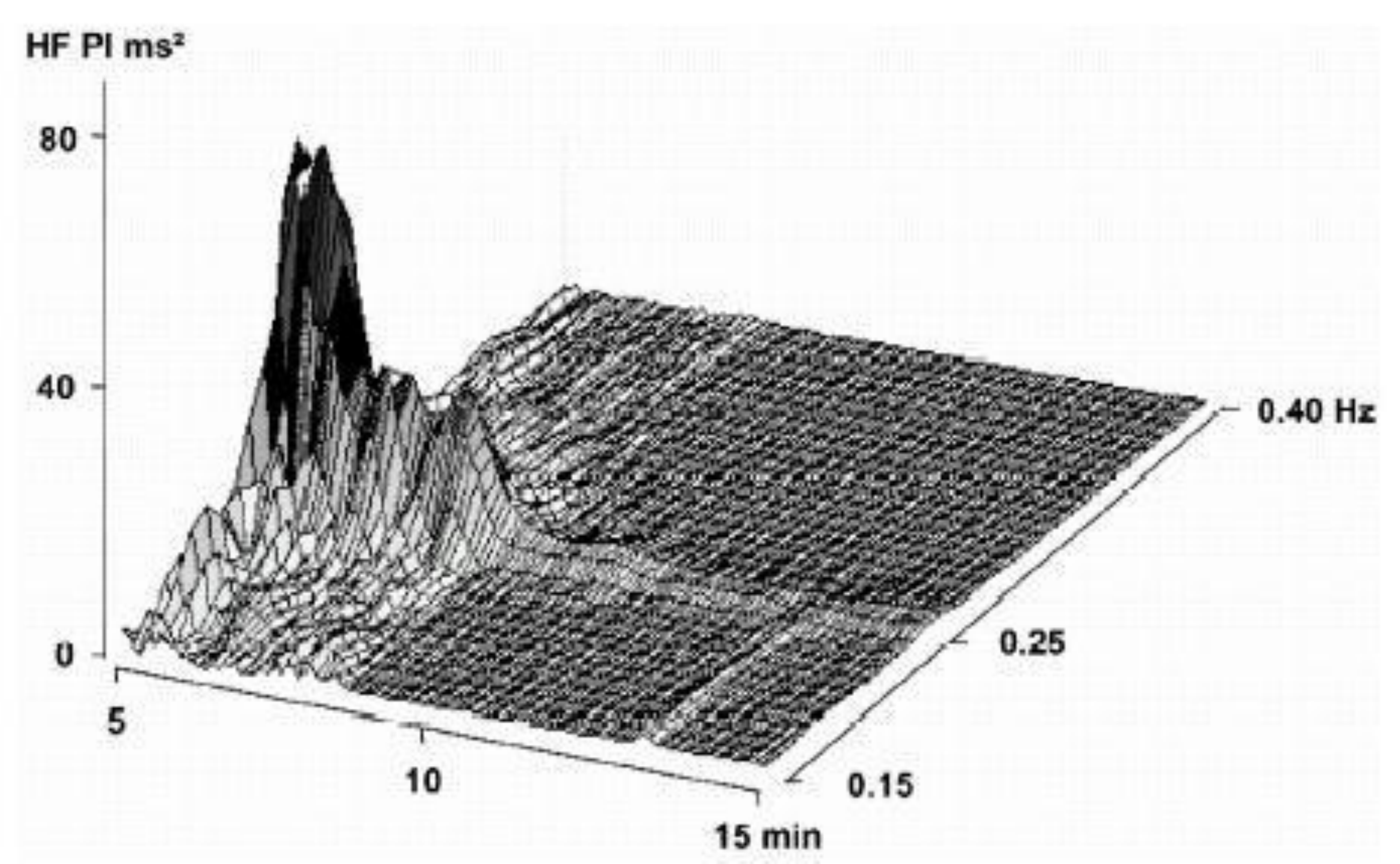


Sensitivity to initial conditions. Small changes in initial conditions lead to totally different behaviour patterns after a certain time (here 14 cycles). This sensitivity to initial conditions may be quantified by means of the largest Lyapunov exponent.

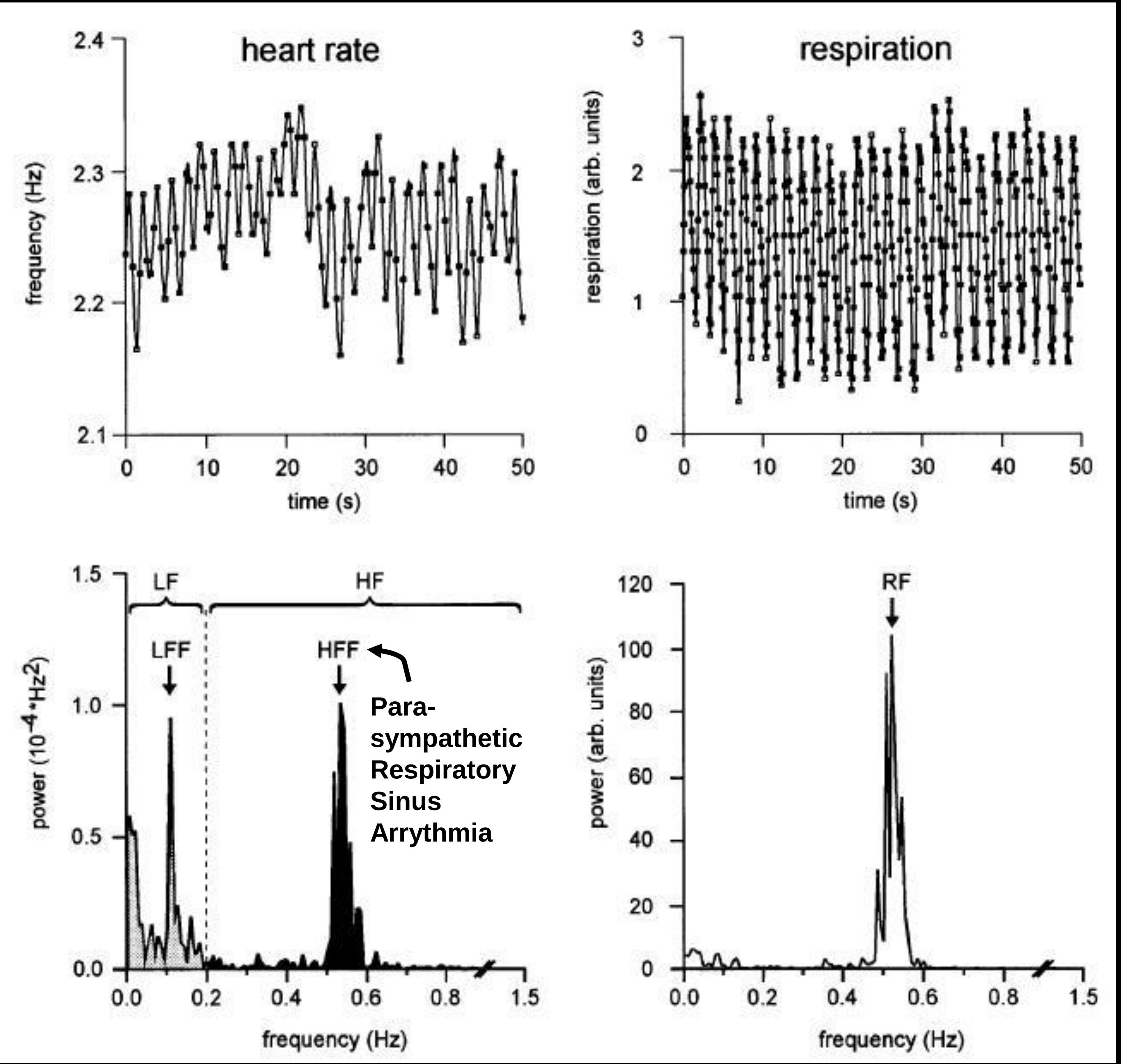
Effects of drugs on the autonomic control of short-term heart rate variability

Jean-Luc Elghozi*, Arlette Girard, Dominique Laude

Autonomic Neuroscience: Basic and Clinical 90 (2001) 116–121



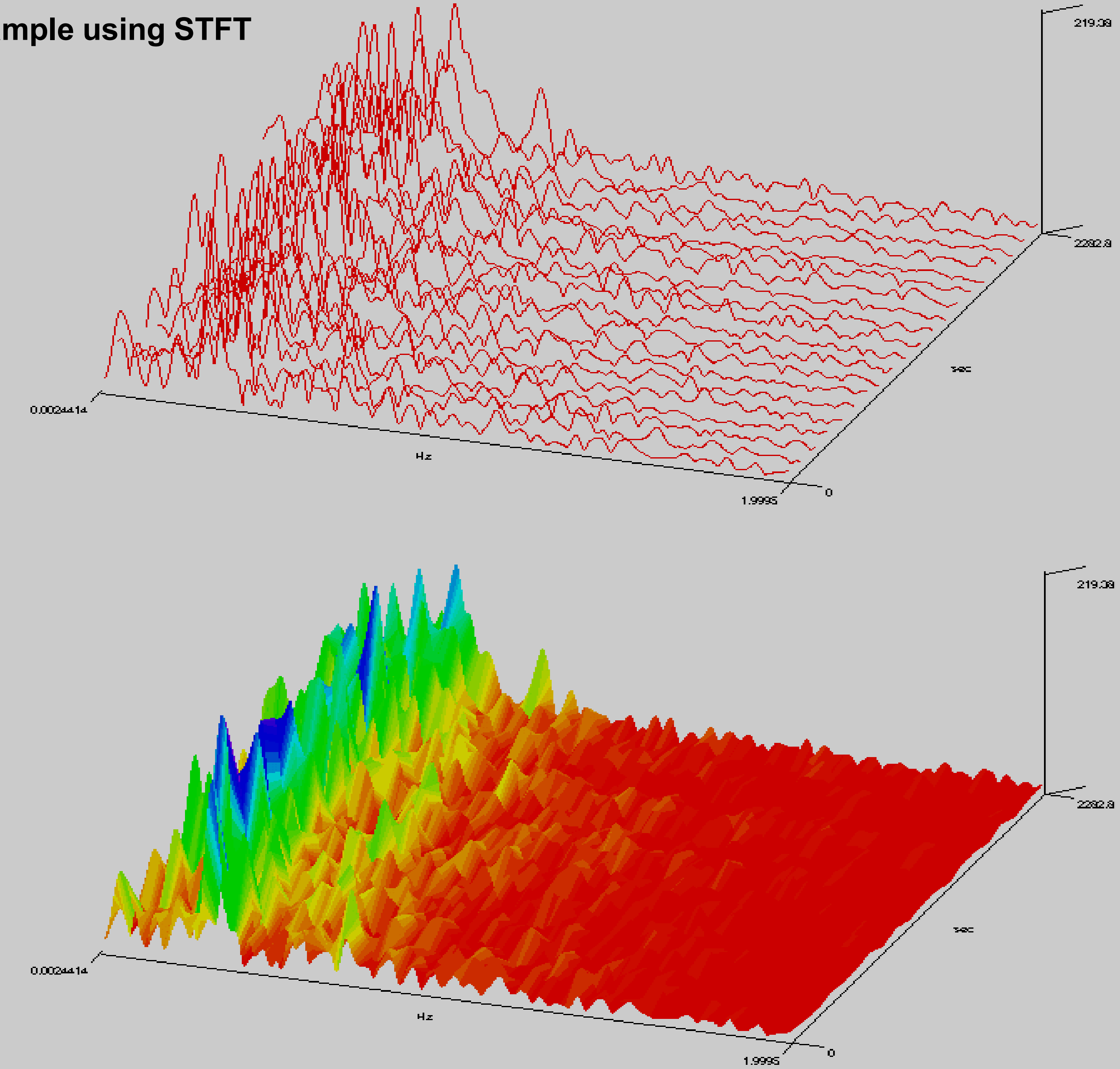
Note reduction in power by 15 minutes due to atropine



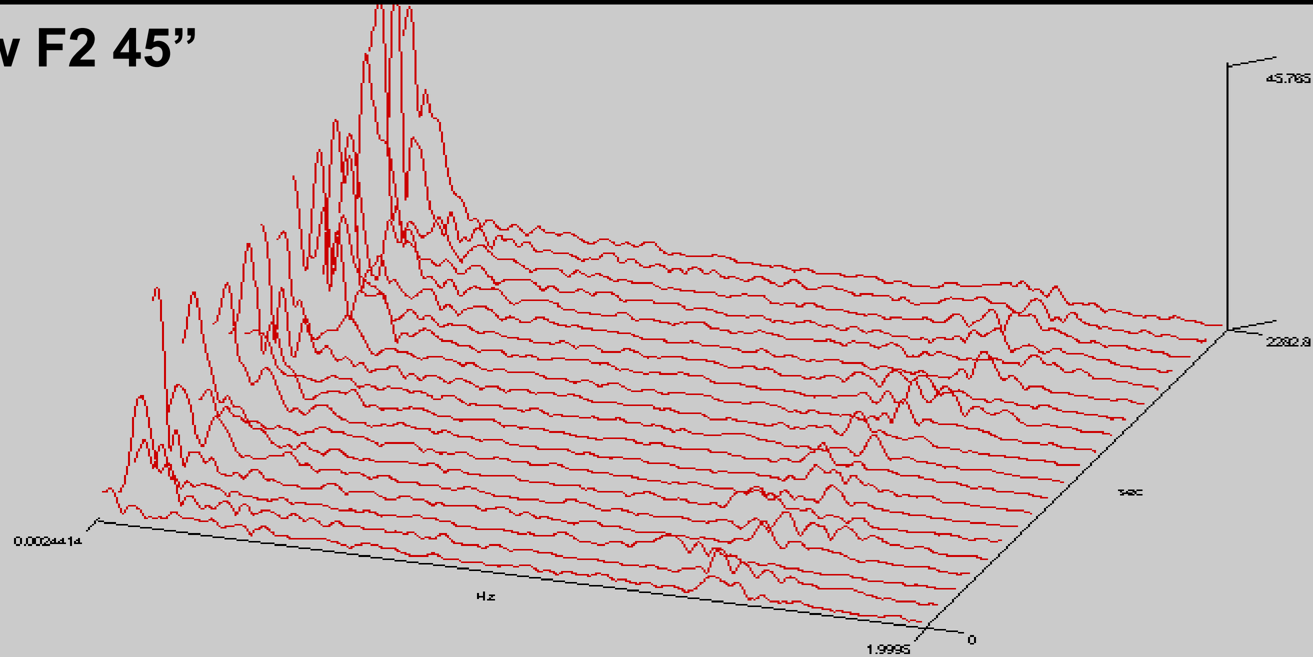
Patzak et al. AJP 1996;271:R1025-1032

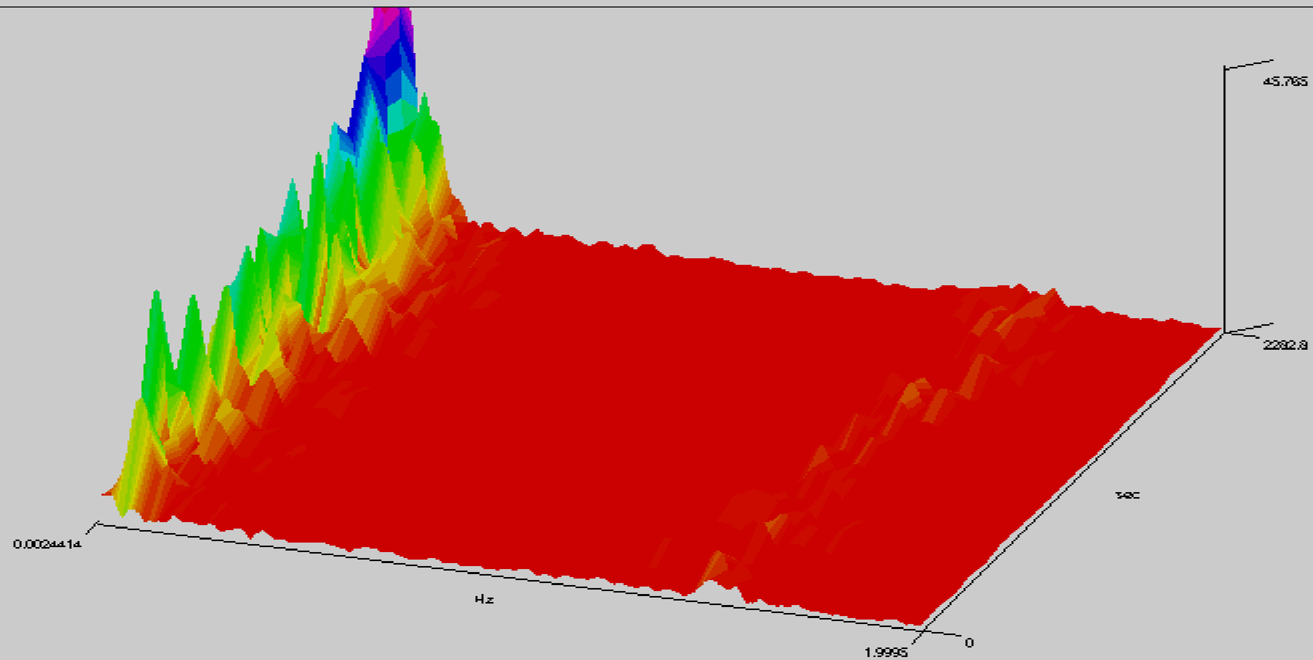
RESP

45” sample using STFT

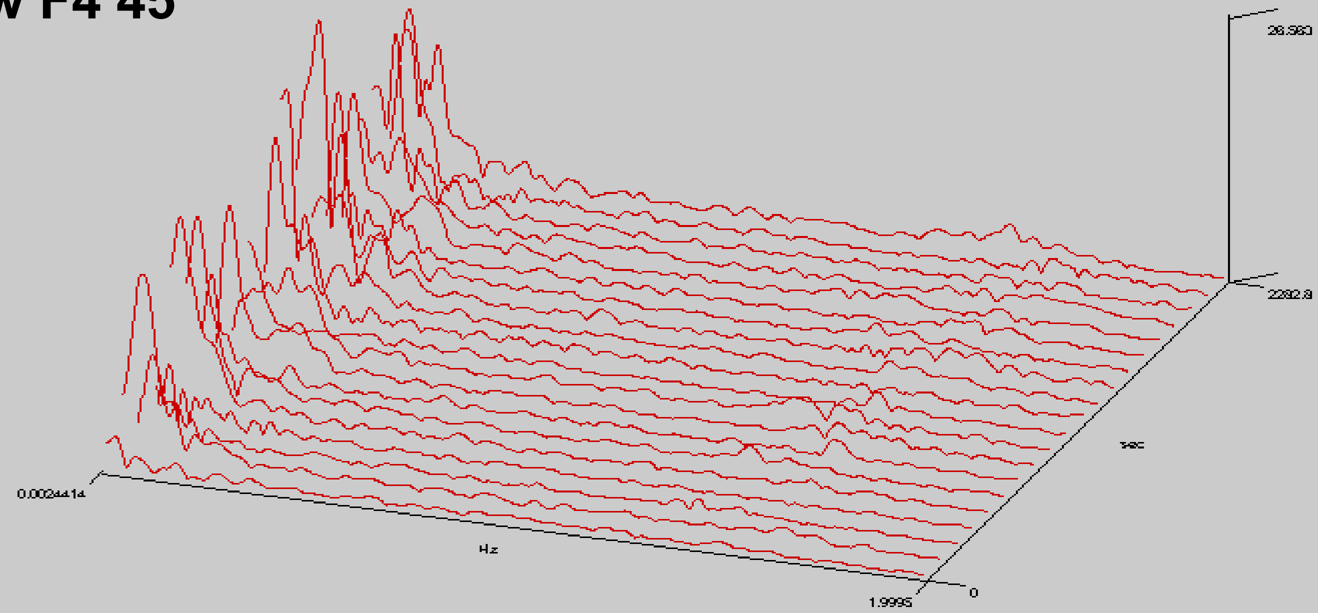


Flow F2 45”

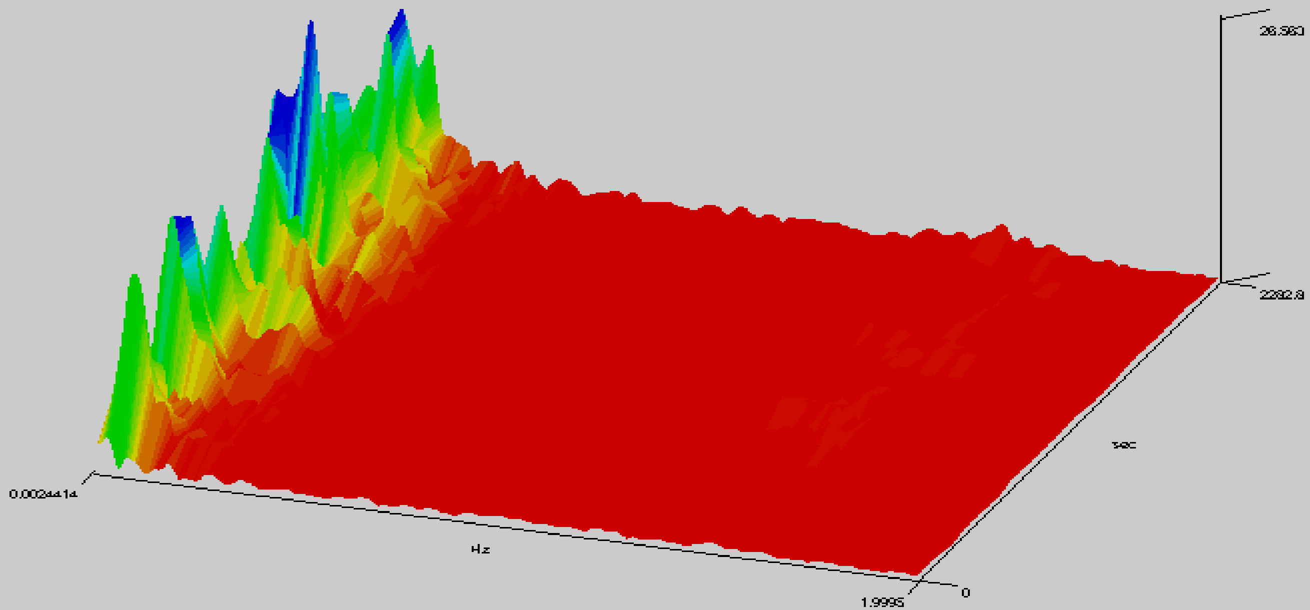

45.765
2282.8
sec
0.0024414
Hz
1.9995
0


45.765
2282.8
sec
0.0024414
Hz
1.9995
0

Flow F4 45”

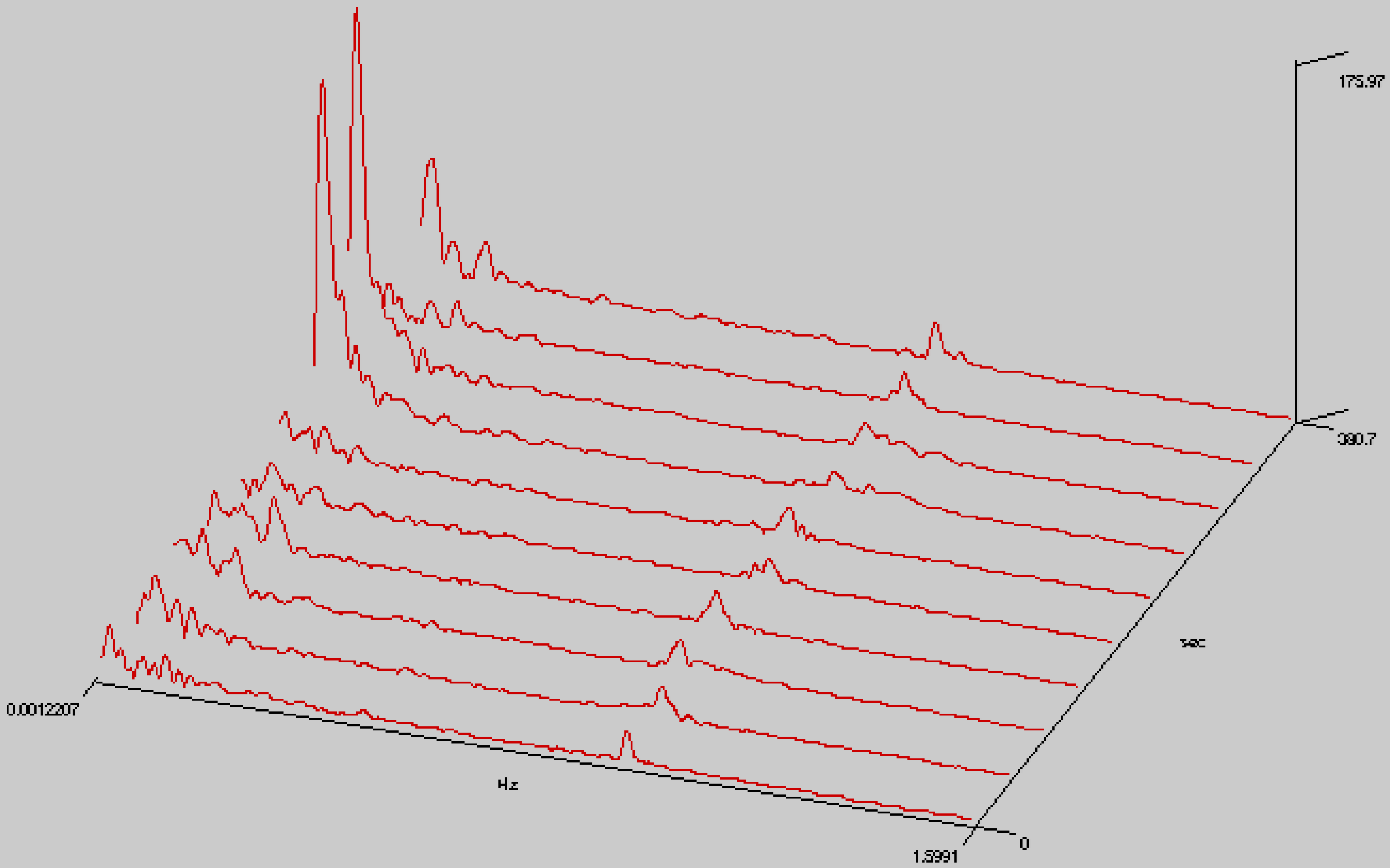


28.583
2282.8
sec
0.0024414
Hz
1.9995
0



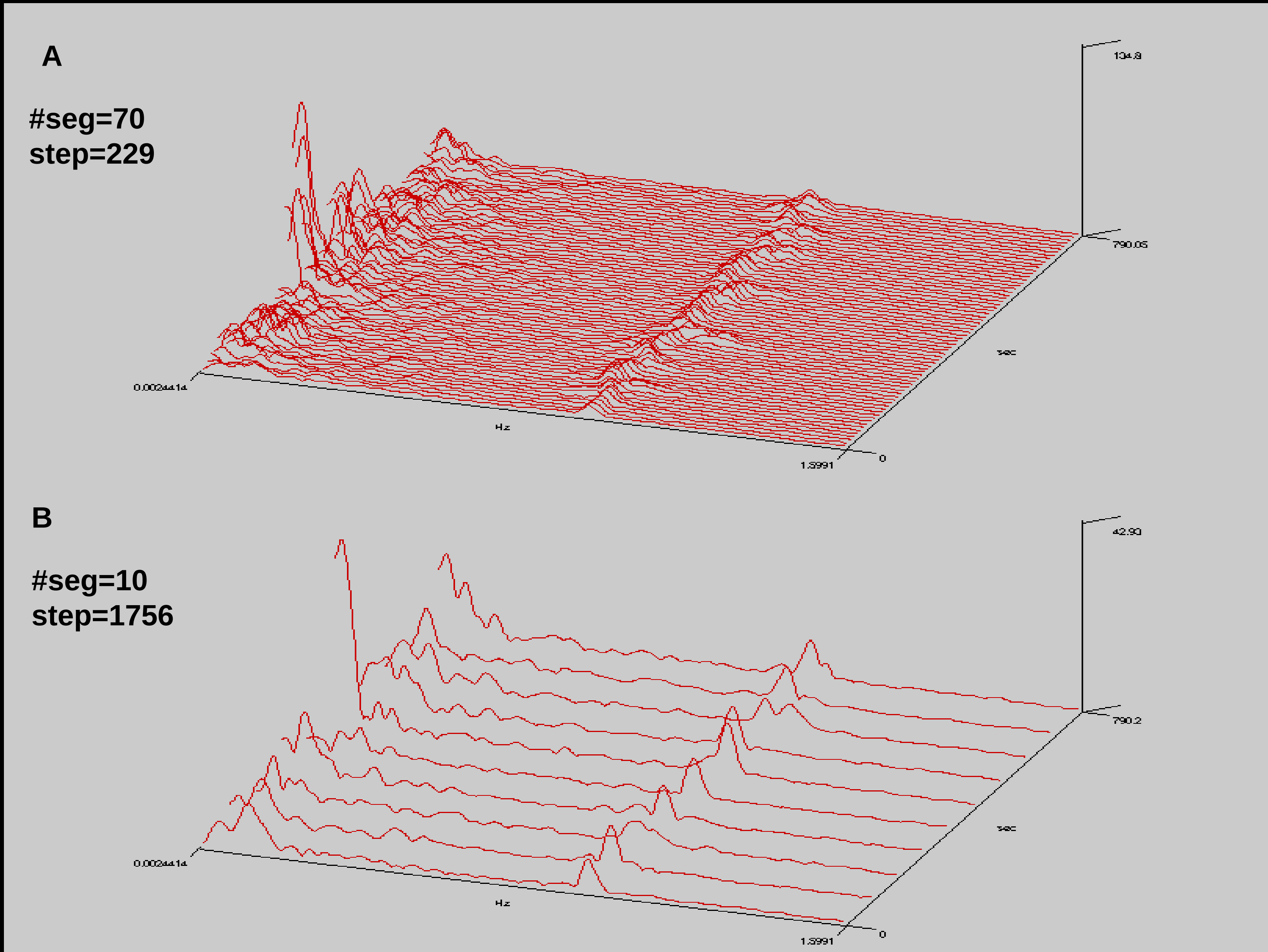
28.583
2282.8
sec
0.0024414
Hz
1.9995
0

HNM: 20” moor signal at 20 s/sec = 24000 pts on left hand =24000/20=1200 sec
precision=16384, #seg=10 therefore step =1756
precision ~ 16384/20 = 819.2 sec; step ~ 846/20 = 42.3 sec



Precision=number of points per spectrum
Step = S = number of points from start of one spectrum to start of the next

HNM: 20” moor signal at 20 s/s = 24000 pts on LH, both with precision = 8192, Fs = 20



Thank you for your attention

May your HRV be great!