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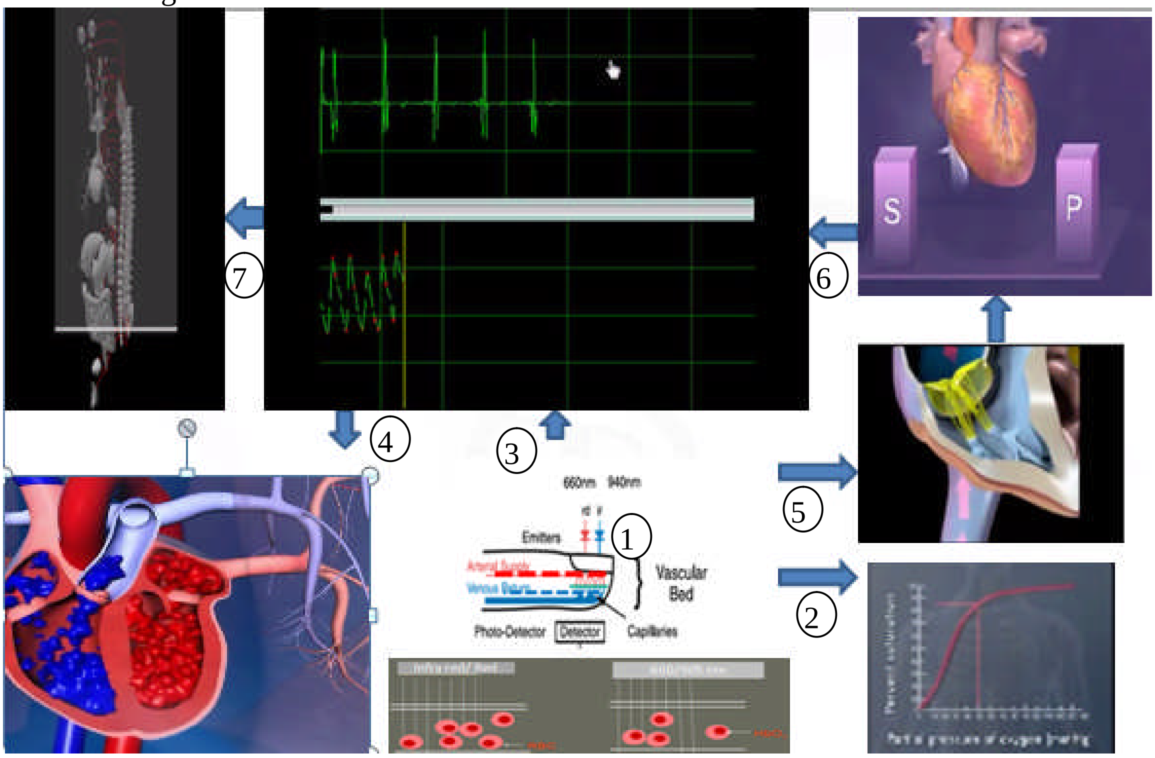
Writer: Albert MAAREK
Reviewer: Richard Clement

Features' diagram



The ES Teck PEMS system is using the spectrophotometry technology (oximeter (1)) with 3 features and signal processing analysis managed by software.

(2) The Pulse Oximeter (SpO2 sensor) displays SpO2%, pulse rate value and vertical bar graph pulse amplitude.
The Photoelectrical Plethysmography' feature is the signal processing analysis of the pulse waveform provided by the oximeter. (3)
The mathematical analyses provide indicators to estimate the hemodynamic parameters. (4)
The Heart Rate Variability feature, (5) analyzes both in the time domain (statistical methods) and in the frequency domain (spectral analysis). Each QRS complex is detected and the so-called normal-to-normal (NN) or Rate-to-Rate (RR) intervals between adjacent QRS complexes are the result of sinus node depolarization. (6)
The signal processing analysis of the measurement provides indicators to estimate the ANS (Autonomic Nervous System) activity. (7)

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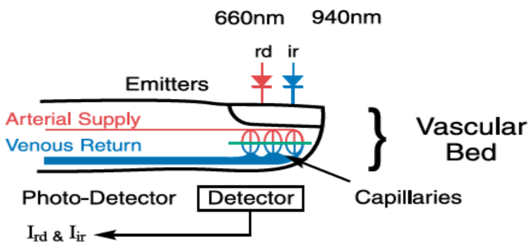
SpO2 % measurement:

Pulse Oximeter

The ES Teck pulse oximeter consists of a computerized monitor and a probe attached to the patient's finger. The monitoring unit displays digital percentage read out of a calculated estimate of the patient's hemoglobin (Hgb) that is saturated with oxygen (SpO2). A visual waveform indicator is displayed with a resolution of 50 ms and the heart rate..
The device measures two types of hemoglobin: oxygenated and deoxygenated. Since two different substances are being measured, two frequencies of light are necessary. This is called spectrophotometry. The red frequency measures desaturated hemoglobin and the infrared measures oxygenated hemoglobin. If the oximeter measures the greatest absorbance in the red band, it will indicate low saturation. If the greatest absorbance is in the infrared band, it will indicate a high saturation.
The pulse oximeter utilizes the two wavelengths of light to calculate the saturation of Oxyhemoglobin. As a light is shone through the finger, it is picked up by a receiver. Some of the light is absorbed by the tissues, including arterial blood. As the artery fills with blood, the absorption increases; and as the artery empties, the absorption decreases. Since the pulsating blood is the only substance that is changing, the stable substances (skin and tissue) are eliminated from the calculation.



Basis For Measurement:

$$\frac{I_{rd}}{I_{ir}} = \frac{S_{rd} + N_{rd}}{S_{ir} + N_{ir}} = \text{Ratio } (r) \rightarrow \% \ SpO_2$$

SpO2 % Normal range [(6) (7) (9)]
95% for adult
>= 96% for children

Oxyhemoglobin Dissociation curve [(11) (12) (13) (14)]
Oxygen can be measured in two forms:
Partial atmospheric pressure of oxygen (PaO2)
Oxygen saturation (SaO2)
Calculated estimate of oxygen saturation (SpO2): an indirect SaO2
There is a relationship between the amount of oxygen dissolved in the blood and the amount attached to the hemoglobin. This is called the normal oxyhemoglobin dissociation curve.

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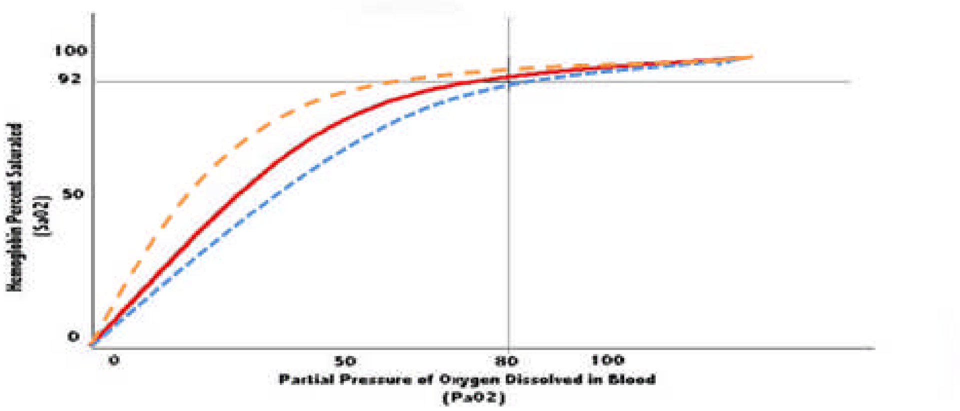
Normal Oxyhemoglobin Dissociation Curve



The chart above illustrates that when the PaO2 is 80, the hemoglobin is 92% saturated with oxygen. As the pressure of oxygen increases, the hemoglobin saturation increases. A pressure of 105 or above will completely saturate the hemoglobin. More oxygen can still be diffused into the blood but the hemoglobin is at its maximum capacity. By using the pulse oximeter we can indirectly assess the PaO2 by measuring the SpO2. For example:

97% saturation = 97 PaO2 (normal)
90% saturation = 60 PaO2 (danger)
80% saturation = 45 PaO2 (severe hypoxia)

Oxygen - hemoglobin Affinity Changes.
The functions of hemoglobin are oxygen pickup and delivery. The hemoglobin has an affinity (the strength of bond between oxygen and hemoglobin) that can be increased or decreased due to various situations. If hemoglobin has an increased affinity, it is highly saturated; but oxygen is less available for release to the tissues due to the strong bond. The reverse is also true.

Hemoglobin % and tissue oxygen delivery
Also, the hemoglobin % in the blood is proportional to the blood viscosity.
Hemoglobin % increased will decrease the tissue oxygen delivery.

SpO2 % and acid base balance
A decrease in pH (acidosis) shifts the standard curve to the right (blue line), while an increase (alkalosis) shifts it to the left (orange line) . This is known as the Bohr Effect.

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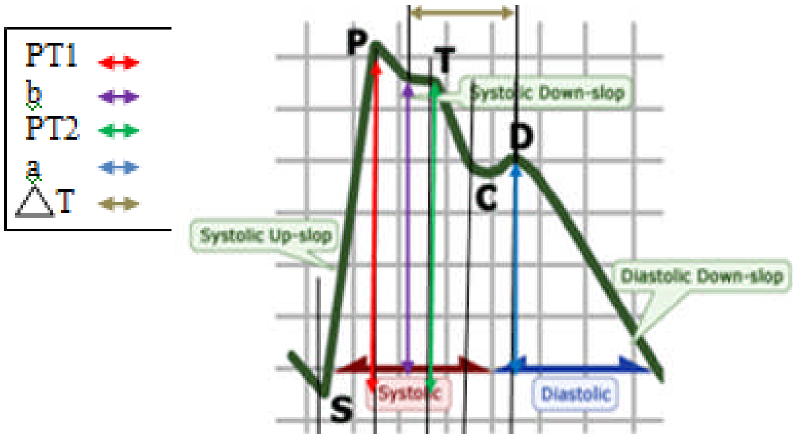
Photoelectrical Plethysmography

Non invasive pulse wave analysis is useful for evaluation of vascular load and vascular aging. [1] It is usually measured at the palpable artery, including carotid, femoral, and radial arteries. [2] These pulse wave tracings provide more precise information concerning blood pressure changes than systolic and diastolic pressures only. [3] The basic idea of the augmentation index was first described by Murgo et al [4] in 1980 in relation to the reflection return point in the ascending aorta. Kelly et al [2] first used the term "augmentation index" in their 1989 study evaluating age-related changes in AIs. They showed age-related increase in AIs at carotid and radial arteries. Ascending aortic pressure can be divided into 2 components at the anacrotic notch, where maximal flow velocity is observed. [2] The early systolic component is caused mainly by left ventricular ejection, and the second component is augmented by peripheral reflection wave. [5] PTG detects the changes in the amount of light absorbed by hemoglobin, which reflects changes in blood volume. Wiederhelm et al [6] showed pulsatile pressure changes in vessel down to metaarteriole size that corresponded to pulse tracing. PTG has been used to evaluate arterial compliance in relation to changes in the amplitude of wave, [7] but the wave contour itself is not usually used. The SDPTG has been developed to allow more accurate recognition of the inflection points on the original plethysmographic wave, ie, anacrotic or dicrotic notches. In 1972, Ozawa recorded the first and second derivative waves of PTG and reported that the first derivative wave had characteristic wave contours. In 1978, he further reported that the second derivative wave had characteristic contours that facilitated the interpretation of the original waves. The conventional PTG measurements came to be performed less frequently because of difficulties in analysis and reading, and most clinicians made recordings of the second derivative wave alone because of the simplicity of evaluating the heights of each wave and the ease of recognition of the changes in the waveforms.

Original wave: PTG (8)

Description of the wave

S (Starting point)
P (Percussion wave)
T (Tidal wave)
C (Incisura)
D (Dicrotic wave)



Estimated Indicators from PTG

1. AI = augmentation index = PT2/PT1 Normal range according with age in I.U (10). AI will be increased in case of hypercholesterolemia or reduced carotid elasticity. (10)
2. **S-P time: Etc** (Estimated Cardiac Ejection time): Normal range 260~380 ms
3. **PH (Pulse High):** Normal range from 2 to 8 in I.U .Indicator related to systolic blood pressure.

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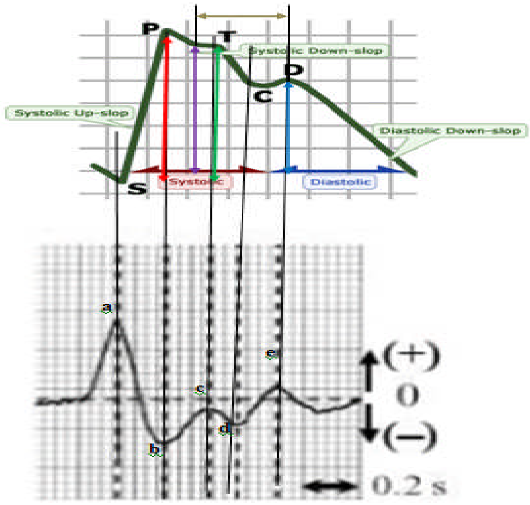
Representative waveforms of PTG (top) and SDPTG (bottom)

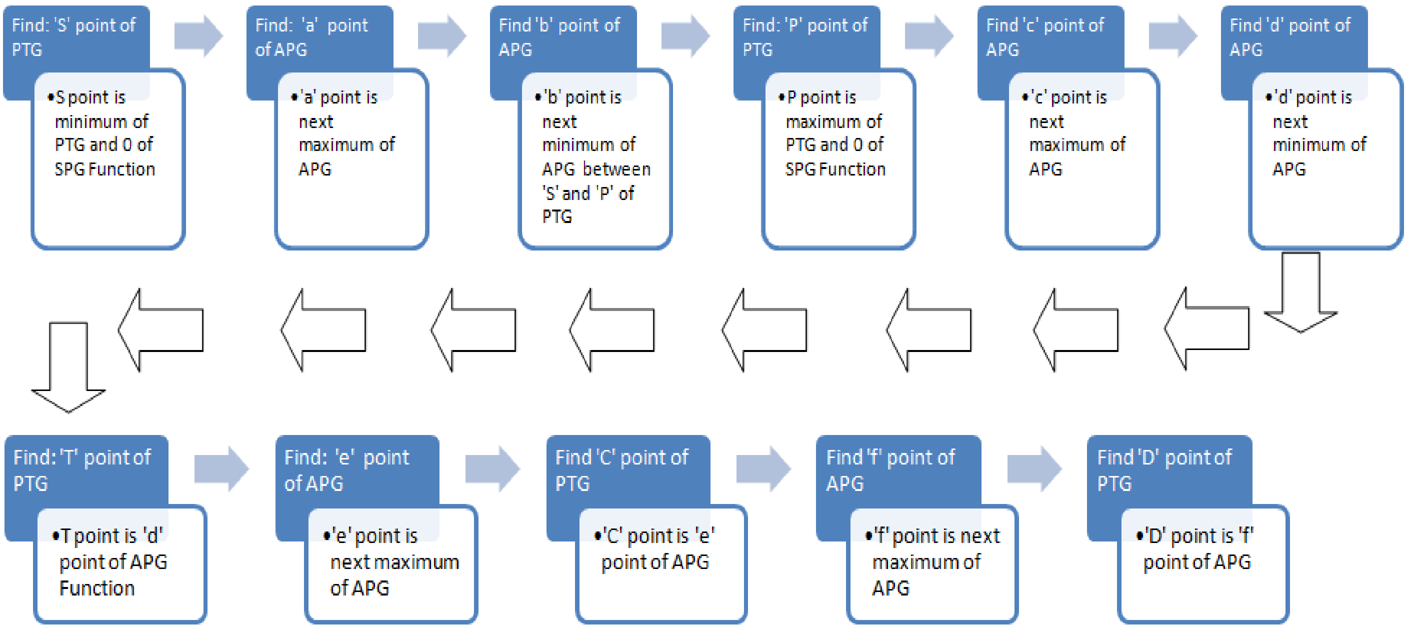
The SDPTG results of a process of mathematical acceleration of the original wave PTG (i.e. below the process)

Description of the SDPTG wave

The previous points of the PTG have a projection in the SDPTG : Point S => a, Point P => b, Point T => c, Point C => d, and Point => e . f will be the end point of the SDPTG .



Mathematical acceleration of the original wave PTG: Chart Flow



After 'D' PTG point -> Find 'S' PTG point again (do untill end of PTG / SDPTG signal)

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Mathematical formula

Acceleration is the second derivative of position with respect to time: d^2x / dt^2, which makes it the first derivative of velocity: dv / dt. Therefore, the acceleration is the slope of the curve on the velocity-versus-time graph.
Thus:
$a = dv / dt = d^2x / dt^2$
Acceleration is a quaternion with real and vector parts:
a= (V^2/R - cDel.v)) + (dcv/dR + cDelxv + V^2/R r)

a= (V^2/R - cV/R cos(v)) + (dv/dt + cv/R sin(v) + V^2/R r)
where R=ct and dR=cdt.
cv/Rcos(v) is the Centrifugal Acceleration a part of the real accelerations in the first parenthesis. The second parenthesis contains the vector accelerations.

Signal processing analysis.

1. The time of measurement from the pulse oximeter is 2 minutes and during this time we will have in average between 120 to 180 wave forms records. The PTG will be convert automatically in SDPTG fig 1

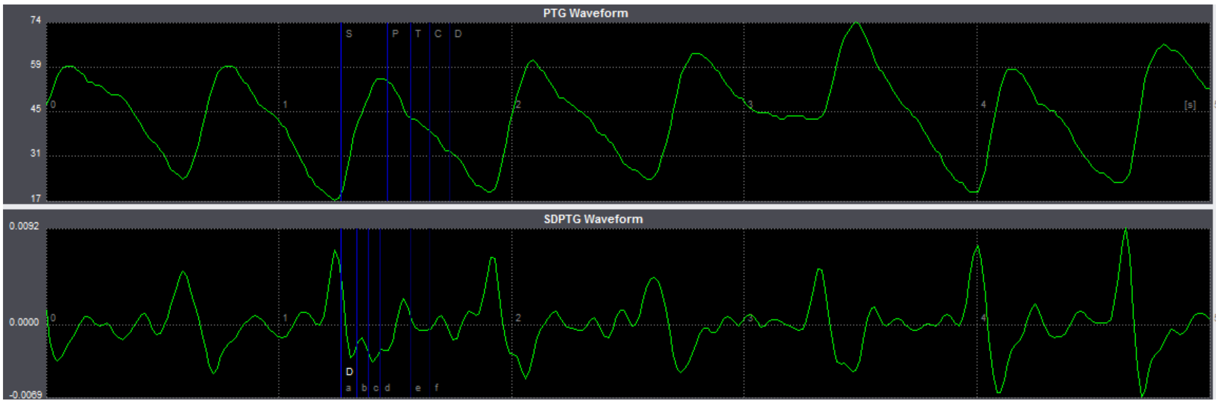

Fig 1

2. Application of the Discrete Fourier Transform (DFT) in the entire record and determination of the spectral analysis of the points a, b, c, d and e. (Fig .2)

DFT
The sequence of N complex numbers x0, ..., xN−1 is transformed into the sequence of N complex numbers X0, ..., XN−1 by the DFT according to the formula:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N} kn} \qquad k = 0, \dots, N-1$$

where i is the imaginary unit and is a primitive N'th root of unity. (This expression can also be written in terms of a DFT matrix; when scaled appropriately it becomes a unitary matrix and the Xk can thus be viewed as coefficients of x in an orthonormal basis.)
The transform is sometimes denoted by the symbol, as Signal Analysis .

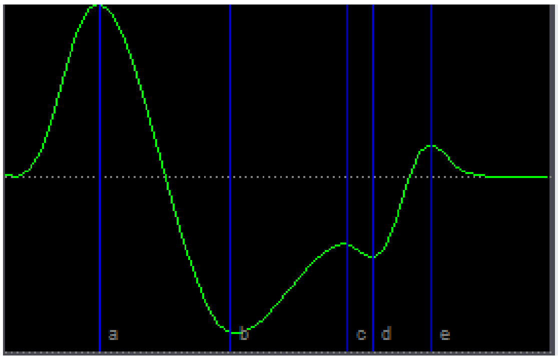

Fig.2. Reconstructive Wave STPTG (RWSDPTG) obtains from the spectral analysis of the point a, b, c, d and e.

Analysis of the Reconstructive Wave STPTG (RWSDPTG)

b/a: Related to the ejection power of the cardiac left ventricle related to the Aorta compliance
c/a: Related to the ESV (End Systolic Volume). Afterload. Decreased with inotropy and increased in heart failure.
-d/a: Related to the small artery (coronaries) compliance
e/a : Related to the EDV (End Diastolic Volume).Preload. EDV Increased with the increased venous return and blood volume.

Estimated SVR (Systemic Vascular Resistance)
Calculation:
Depend b/a and d/a

SV = Stroke Volume
Calculation
Depend e/a and d/a
SV = (value e/a – value d/a)

Q = Cardiac Output
Calculation
Depend e/a and d/a and HR
Q = (value e/a – value d/a) X HR

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BV= Blood Volume
Calculation
Formula and Normal range: BV = 0.06 X BW+ 0.77. In which blood volume = BV in mL and BW = body weight in grams.
Normal range e/a: 014 to 0.20

CI = Cardiac Index
Cardiac Index (CI) = Q / Body Surface Area (BSA)
BSA (m^2) = ([Height (cm) x Weight (kg)]/ 3600 $)^{½}$

EF= Ejection Fraction (EF)
EF = (SV / EDV) × 100%
Depend SV and value e/a (EDV)

MAP = MEANS Arterial Pressure
MAP = Q.SVR

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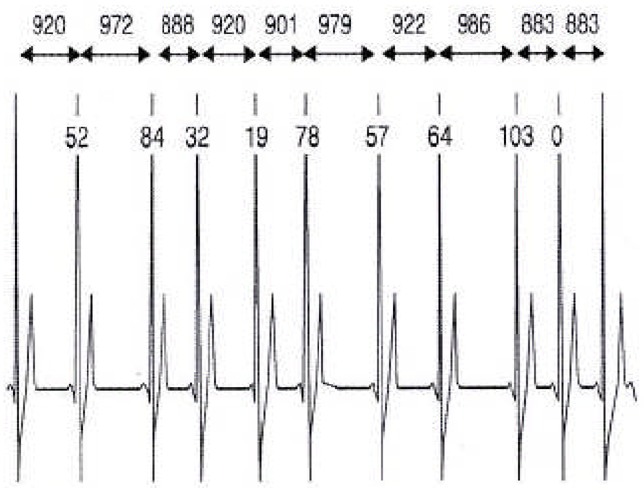
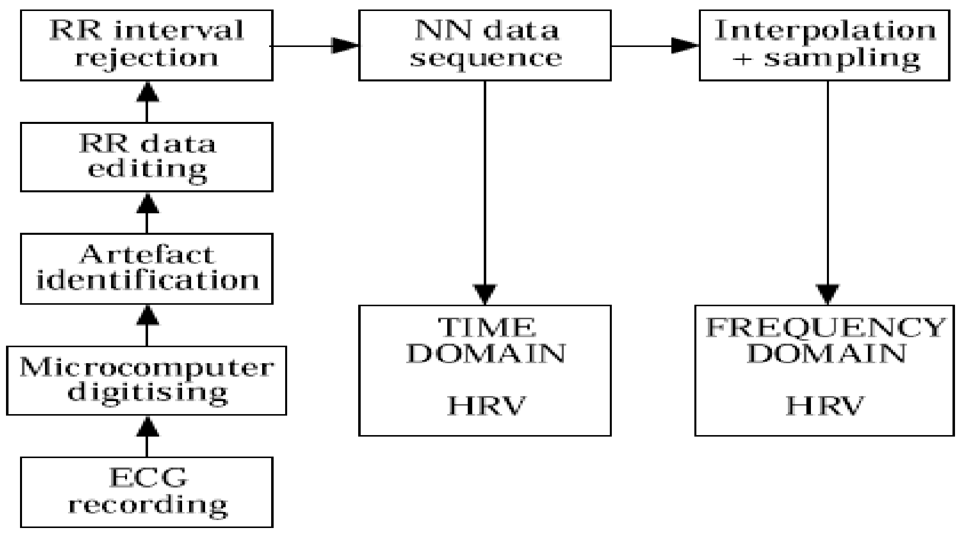
Heart Rate Variability (HRV) [1]
The HRV is a mathematical analysis of the Heart rate time. HRV evaluates the variation of the heart rate, both in the time domain (statistical methods) and in the frequency domain (spectral analysis). Each QRS complex is detected and the so-called normal-to-normal (NN) or Rate-to-Rate (RR) intervals between adjacent QRS complexes are resulting from sinus node depolarization



Example of an ECG output over 11 beats, R-R interval times and difference between adjacent R-R intervals are displayed.

Process of analysis



Means of the HRV Results

Time domain results		
Items	**Units**	**Description**
Heart Rate (HR)	bpm	Mean heart rate per minute
Mean values of RR intervals	ms	Mean of RR intervals
Maximum values (Mx)	ms	longest NN interval
Minimum values (Mn)	ms	shortest NN interval
MxDMn HIB	ms	The difference between the longest and shortest NN interval
MxDMn (HIB)	ms	Irregular heart beat (IHB) indicator. Displays when the device detects large variation in RR Interval during measurement.
SDNN	ms	Standard deviation of all NN intervals.
RMSSD	ms	The square root of the mean of the sum of the squares of differences between adjacent NN intervals.
NN50 count		Count Number of pairs of adjacent NN intervals differing by more than 50 ms in the entire recording. Three variants are possible counting all such NN intervals pairs or only pairs in which the first o the second interval is longer.
pNN50 %	%	NN50 count divided by the total number of all NN intervals.

frequency domain results			
Items	**Units**	**Description**	**Frequency range**
5 min total power	ms2	The variance of NN intervals over the recording segment	≤ 0·4 Hz
VLF	ms2	Power in very low frequency range	≤ 0·04 Hz
LF	ms2	Power in low frequency	range 0·04–0·15 Hz
HF	ms2	Power in high frequency range	0·15–0·4 Hz
LF/HF	%	Ratio LF [ms2]/HF [ms2]	

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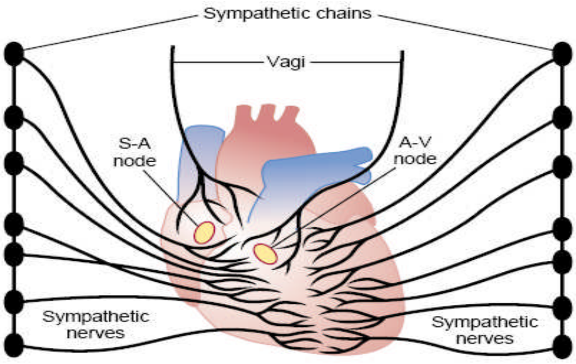
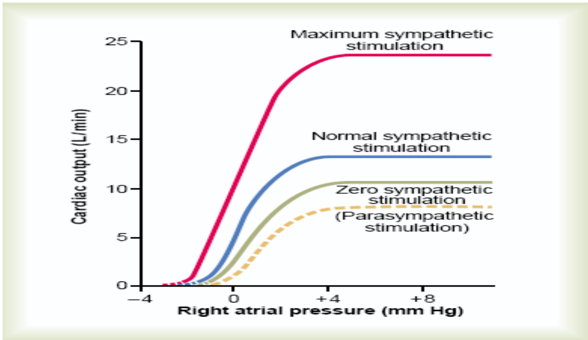
HRV and autonomic nervous system links
The autonomic nervous system is related to heart rate and heart rate variability (time between each beat) via the heart ANS innervations and the effect on the cardiac output curve of different degrees of sympathetic or parasympathetic stimulation. The Baroreceptor regulation will be carried out via the sympathetic system stimulation.





A.C. Guyton and J.E. Hall: Textbook of Medical Physiology Eleventh Edition. September 2005.

Indicators HRV [1]
Heart rate: Fast pulse may signal the presence of an infection or dehydration
Normal Range
For resting heart rate:

- newborn infants; 100 to 160 beats per minute
- children 1 to 10 years; 70 to 120 beats per minute
- children over 10 and adults (including seniors); 60 to 100 beats per minute
- well-trained athletes; 40 to 60 beats per minute

RMSSD: Indicator of Parasympathetic activity
HF: Indicator of Parasympathetic activity
LF: Indicator of Sympathetic system or both sympathetic and parasympathetic activity.
LF/HF: ratio considered by some investigators to mirror sympathetic/parasympathetic balance or to reflect sympathetic modulations.

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