Electrophysiology and Biopotential Issues on Human Electrocardiogram: A Review

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Abstract: Problem statement: The heart is the first organ and most importantly to form in the body, where is found the most powerful generator of electromagnetic energy in the human body. Electrophysiology was the best method used to diagnose human heart problem. Knowledge of the electrical potentials in human heart was a quantum leap in the science of the human heart. Recently, there had been a growing interest in studying the human ECG. Unfortunately a very complicated issue which requires a relatively good understanding of everything that had been said about the heart. Focus on the review of physical, electromagnetic basis of human heart's biopotentials and understanding the basic equations of cardiac electrophysiology that represents the basis to all clinicians whether in postnatal (pediatric or adult) or prenatal (foetal) Medicine. **Approach:** Mathematical method used for derivation of the essential equations of human heart electrical potentials, this equation will develop the principle sciences of human heart, the equation also outlier finding of the electromagnetic base of human electrophysiology. **Results:** Heart is important electrical generator in human body. The voltage and current which was generated in human heart represent the basis of heart biosciences. The electromagnetic energy of the heart not only envelops every cell of the human body, but also extends out in all directions in the space around human body. **Conclusion:** The proposed technique for electrophysiology and potentials on human ECG is useful and the results may contribute to the references for later studies.

Key words: Electrophysiology, human electrocardiogram, surface potentials, electromagnetic basis of the electrocardiogram, signal to noise ratio, human heart, trigonometric identities, electromagnetic energy

INTRODUCTION

This review study deals with the genesis of human heart bioelectric signals that are recorded routinely in modern clinical practice. Given adequate monitoring equipment, the phenomena named the Electrocardiogram (ECG) consisting many forms of bioelectric phenomena can be recorded with relative ease for example Electroencephalogram (EEG), Electroneurogram (ENG), Electromyogram (EMG) and Electroretinogram (ERG).

Biomedical Engineers generally have a good physical insight into the nature of electromagnetic fields produced by bioelectric sources and because of their comprehensive understanding of the physical problem, they may contribute to the solution of biological problems (Afek *et al.*, 2011).

Bioelectric potentials are Method and system for recognizing and characterizing bioelectric potential or Electromyographic (EMG) signals associated with at least one of a coarse gesture and a fine gesture that is performed by a person and use of the bioelectric potentials to enter data and/or commands into an electrical and/or mechanical instrument.

Electrically they exhibit a resting potential and when appropriately stimulated, produces an action potential, as the following paragraphs explain.

In this review study the electrophysiological aspects of cardiac development and an ECG for monitoring are presented.

Electrophysiology of the human heart: An electrophysiology study or EP study is a diagnostic procedure to look closely at the electrical function of

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your heart. It is the most accurate and reliable method of evaluating your heart rhythms and helps your cardiologist determine the treatment option that is most appropriate for you (Scanziani and Hausser, 2009). It's involves a measurements of voltage change or electric current on a wide variety of scales from single ion channel proteins to whole organs like the heart. In neuroscience, it includes mea surements of the electrical activity of neurons and particularly action potential activity (Vigmond *et al*., 2003). Recordings of large-scale electric signals from the nervous system such as electroencephalography may also be referred to as electrophysiological recordings.

Human ECG: The electrocardiogram or ECG is a way of measuring the electrical activity of the heart (Jevon, 2010). However, is unfortunately a very complicated issue which requires a relatively good understanding of everything that has been said about the heart (Alfaouri and Daqrouq 2008), So far it is a very useful tool indeed for analyzing the activity of the heart-especially since many problems can be diagnosed by looking at the conducting system but it's also very hard to get your head round and not something to be taken lightly. More details Fig. 3 shows the Schematic representation of normal ECG, this schematic is best endector of a clinical masurment .

The activity on the body surface is known to reflect the activity of the heart muscle underneath and in its proximity. A clinically accepted lead system (Fig. 4) has been devised and is called the 12-lead system. It comprises a combination of electrodes taking measurements from different regions designated limb leads, the pericardial leads and the chest leads. Limb leads derive signals from electrodes on the limbs and are designated as leads I, II and III. Pericardial leads are designated aVR, aVL and aVF and are derived by combining signals from the limb leads. The remaining six leads, V1, V2,…V6, are chest leads. Together, ECGs from these various leads help define the nature of the activity on a specific part of the heart muscle: for example, ischemia (impaired oxygen supply to the muscle) or infarction (damage to the muscle) on the left side of the chest may be noticeable in lead III. The ECG signals (Fig. 3) at the surface of the body are small in amplitude for adult of human the mean value Approximately about 150 µv (Ali and Zeng, 2010), which make the measurements susceptible to

artifacts generated by the relative motion of the electrode and the skin as well as by the activity of the nearby muscles. An important consideration in good ECG signal acquisition is the use of high-quality electrodes. Since ECG instruments are often used in critical-care environments; they must be electrically isolated for safety and protected from the high voltages generated by defibrillators. ECG biopotential amplifiers find use in many monitoring instruments, pacemakers and defibrillators. The ECG today is used to monitor the electrical workings of the heart. Physicians use this information to discover such things as heart rate, arrhythmias, myocardial infarctions, atrial enlargements, ventricular hypertrophies and bundle branch blocks.

The physical basis of electrocardiography: As a result of the electrical activity of the cells, current flows within the body and potential differences are established on the surface of the skin, which can be measured using suitable equipment (electrodes) (Clifford *et al*., 2006). The graphical recording of these body surface potentials as a function of time produces the electrocardiogram. The simplest mathematical model for relating the cardiac generator to the body surface potentials is the single dipole model. This simple model is extremely useful in providing a framework for the study of clinical electrocardiography and vectorcardiography (Niederer *et al*., 2011), though of course much more complex treatments have been developed. The dipole model has two components, a representation of the electrical activity of the heart (the dipole itself) and the geometry and electrical properties of the surrounding body. First, consider the representation of the electrical activity of the heart (Hobbie, 1973) as an action potential propagates through a cell (i.e., in the myocardium), there is an associated intracellular current generated in the direction of propagation, at the interface of resting and depolarizing tissue. This is the elementary electrical source of the surface ECG, referred to as the current dipole. There is also an equal extracellular current flowing against the direction of propagation and so charge is conserved. All current loops in the conductive media close upon themselves, forming a dipole field (Fig. 1). The heart's total electrical activity at any instance of time may be represented by a distribution of active current dipoles where the Fig. 2 shows the the direction of this current.
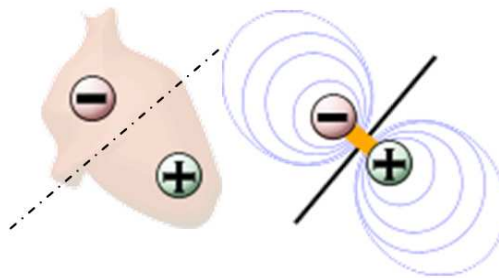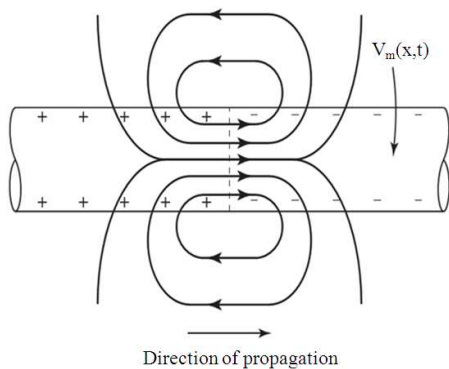
Fig. 1: heart view as electrical potential

Fig. 2: The dipole field due to current flow in a myocardial cell at the advancing front of depolarization. where V_m is the Tranmembrane potential (Clifford *et al*., 2006)
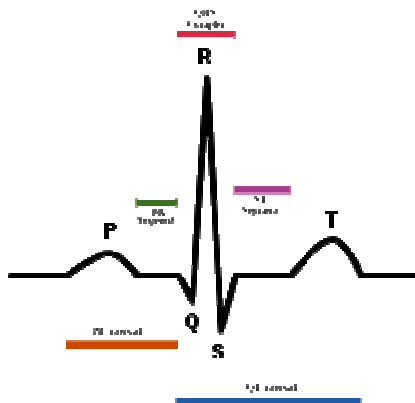

Fig. 3: Schematic representation of normal ECG

In general, they will lie on an irregular surface corresponding to the boundary between depolarized and polarized tissue. If the heart were suspended in a homogeneous isotropic conducting medium and were observed from a distance sufficiently large compared to its size, then all of these individual current dipoles

may be assumed to originate at a single point in space and the total electrical activity of the heart may be represented as a single equivalent dipole whose magnitude and direction is the vector summation of all the minute dipoles. The net equivalent dipole moment is commonly referred to as the (time-dependent) heart vector M (t). As each wave of depolarization spreads through the heart, the heart vector changes in magnitude and direction as a function of time. The resulting surface distribution of currents and potentials depends on the electrical properties of the torso.

As a reasonable approximation, the dipole model ignores the known anisotropy and in homogeneity with the torso treats the body as a linear, isotropic, homogeneous, spherical conductor of radius, R and conductivity, σ. The source is represented as a slowly time-varying single current dipole located at the center of the sphere. The static electric field, current density and electric potential everywhere within the torso (and on its surface) are no dynamically related to the heart vector at any given time (i.e., the model is quasi-static).The reactive terms due to the tissue impedance can be neglected. Laplace's equation (which holds within the idealized homogenous isotropic conducting spherical torso) may then be solved to give the potential distribution (Φ) on the torso as Eq. 1:

$$\Phi(t) = \cos\theta(t)3|M(t)| / 4\pi\sigma R^2 \qquad (1)$$

where, θ(t) is the angle between the direction of the heart vector M(t) and OA the lead vector joining the center of the sphere, O, to the point of observation, A. $|M|$ is therefore the magnitude of the heart vector (Fig. 6). More generally, the Potential difference between the two points on the surface of the torso would be Eq. 2:

$$V_{AB}(t) = M(t).L_{AB}(t) \qquad (2)$$

where, L_{AB} is known as the lead vector connecting points A and B on the torso. It is useful to define a reference Central Terminal (CT) (Fig. 5) by averaging the potentials from the three limb leads Eq. 3:

$$\Phi_{CT}(t) = \Phi_{RA}(t) + \Phi_{LA}(t) + \Phi_{LL}(t) \qquad (3)$$

where, RA indicates right arm, LA indicates left arm and LL indicates left leg. Note that ϕ_{CT} should be zero at all times.

Einthoven lead system: Historically the first one who designed the measuring system for human cardiac is Willem Einthoven 1901. This system named Einthoven lead system is illustrated in Fig. 5 is a system that describes a triangle vector around the human body.
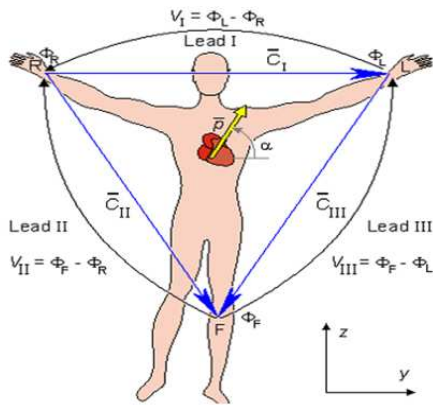
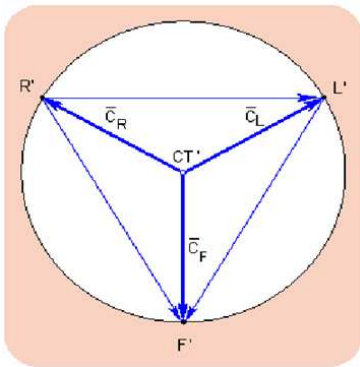Fig. 4: A triangle vector around human body; adopted with permission from (Malmivuo and Plonsey, 1995)

Fig. 5: Wilson central terminals; adopted with permission from (Malmivuo and Plonsey, 1995)
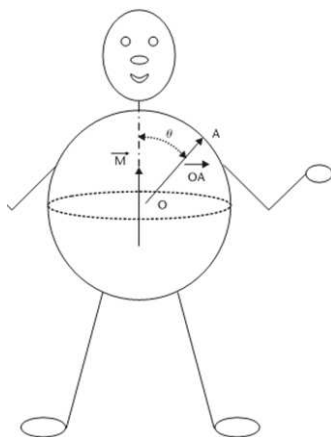

Fig. 6: The idealized spherical torso with the centrally located cardiac source (Clifford *et al.*, 2006)

The Einthoven limb leads (standard leads) as defined in Fig. 4 above by (Malmivuo and Plonsey, 1995), it is possible to measure the leads Eq. 4

$$\text{leadI}: V_I = \Phi_L - \Phi_R$$
$$\text{LeadII}: V_{II} = \Phi_F - \Phi_R \qquad (4)$$
$$\text{LeadIII}: V_{III} = \Phi_F - \Phi_L$$

Where:
V_I = The voltage of lead I
V_{II} = The voltage of lead II
V_{III} = The voltage of lead III
Φ_L = Potential at left arm
Φ_R = Potential at the right arm
Φ_F = Potential at the left foot

The left arm, right arm and left leg (foot) are also represented with symbols L_A, R_A and L_L, respectively.

According to Kirchhoff's law these lead voltages have the following relationship Eq. 5:

$$VI + VIII = VII \qquad (5)$$

To prove this idea simply Treat ECG as a Vector with magnitude V and an angle θ, then Eq. 6:

$$\text{LeadI} = V\cos(\theta)$$
$$\text{LeadII} = V\cos(60 - \theta) \qquad (6)$$
$$\text{leadIII} = -V\cos(60 + \theta)$$

By using the following trigonometric identities:

$$\text{LeadIII} = -V\cos(60 + \theta) =$$
$$-V\{\cos(60) * \cos(\theta) - \sin(60) * \sin(\theta)\} \qquad (7)$$

$$\text{LeadII} = V\cos(60 - \theta) =$$
$$V\{\cos(60) * \cos(\theta) + \sin(60) * \sin(\theta)\} \qquad (8)$$

By using subtraction Eq. 8 from Eq. 7 can get Eq. 9:

$$\text{LeadII} - \text{LeadIII} = 2 * V * \cos(60) * \cos(\theta)$$
$$= 2 * V * 0.5 * \cos(\theta) = V\cos(\theta) = \text{LeadI} \qquad (9)$$

Therefore Eq. 10:

$$\text{LeadIII} = \text{LeadII} - \text{LeadI} \qquad (10)$$

Hence only two of these three leads are independent. The lead vectors associated with Einthoven's lead system are conventionally found based on the assumption that the heart is located in an infinite, homogeneous volume conductor. One can show that if

the position of the right arm, left arm and left leg are at the vertices of an equilateral triangle, having the heart located at its center, then the lead vectors also form an equilateral triangle.

Wilson central terminal in human heart: Frank Norman Wilson (1890-1952) where mentioned in (Malmivuo and Plonsey, 1995) investigated how electrocardiographic unipolar potentials could be defined. Ideally, those are measured with respect to a remote reference (infinity). But how is one to achieve this in the volume conductor of the size of the human body with electrodes already placed at the extremities? This was formed by connecting a 5 KΩ resistor from each terminal of the limb leads to a common point called the central terminal, as shown in Fig. 5 Wilson suggested that unipolar potentials should be measured with respect to this terminal which approximates the potential at infinity. Actually, the Wilson central terminal is not independent but, rather is the average of the limb potentials. This is easily demonstrated by noting that in an ideal voltmeter there is no lead current. Consequently, the total current into the central terminal from the limb leads must add to zero to satisfy the conservation of current (Fig. 3). Accordingly, we require that Eq. 11:

$$I_R + I_L + I_F = \frac{\Phi_{CT} - \Phi_R}{5000} + \frac{\Phi_{CT} - \Phi_L}{5000} + \frac{\Phi_{CT} - \Phi_F}{5000} \quad (11)$$

where, the I_R, I_L, I_F is current and Φ is electrical potential.

It is found that the CT is the common point. The Wilson central terminal represents the average of the limb potentials. Because no current flows through a high-impedance voltmeter, Kirchhoff's law requires that Eq. 12:

$$I_R + I_L + I_F = 0 \quad (12)$$

Then Eq. 13:

$$\Phi_{CT} = \frac{\Phi_R + \Phi_L + \Phi_F}{3} \quad (13)$$

Since the central terminal potential is the average of the extremity potentials it can be argued that it is then somewhat independent of any one in particular and is therefore a satisfactory reference. In clinical practice good reproducibility of the measurement system is vital. Results appear to be quite consistent in clinical applications.

The location of the Wilson central terminal is typically in the center of the Einthoven triangle (Malmivuo and Plonsey, 1995).

It is possible to measure the voltage signal between the Wilson Central Terminal and an electrode location on the human body. This voltage is called the monopolar ECG and the voltage between any two electrode locations is called the bipolar ECG.

Electromagnetic basis of the electrocardiogram: The electrical currents and potentials generated in the heart are the result of opening and closure of ionic channels at a cellular level. The coherent activation of numerous cellular reactions of this sort results in electrical fields that propagate in the so called body volume conductor, resulting in measurable potentials at the body surface. Neglecting the underlying chemical reactions, from an electromagnetic point of view, the biological volume conduction problem is somewhat unusual in the sense that the current sources are within the conductor rather than being due to induction. Through the study of electrical and magnetic properties of body tissues, it is found that the cardiac volume conductor problem has the following important features (Sameni, 2008):

- The electric displacement current is negligible. Therefore, the electromagnetic problem is quasi static, which means that the electric and magnetic fields are decoupled, the electric field is proportional to the gradient of the electric scalar potential and the divergence of the current density is zero
- The problem is linear, meaning that superposition holds for the potentials due to several sources
- For frequencies below several kilohertz, the capacitive component of the electrical impedance of body tissues is negligible, which means that the tissues are within a very good approximation, resistive

Electrical potential in human heart: A human heart can be described as an electrical dipole, electrical voltage equation represent importation knowledge. Till now no finding information on the exact voltage value coming from the heart and may any human body has a unique voltage value (Bera *et al*., 2005). Finding Approaches of calculating the equation of electrical voltage of human heart in that research assumed heart to be as cylindrical volume, the coordinate of any point tangent to the cylindrical volume is (ρ, Φ, Z) at any point, the heart vector E_H may be assumed to have three components $E_{H\rho}$ along the radius vector, $E_{H\Phi}$ along the direction perpendicular to the radius vector and E_{HZ}

along the direction z . Any monopolar harmonic ECG voltage at any point in the frontal plane with respect to Wilson's Central Terminal (WCT) may be assumed to be due to the electric field component E_{HZ} of the heart vector. Let the Z-component of the sinusoidal nth harmonic ECG heart electric field vector at the origin coordinate of cylindrical volume (O) be E_{ZOn} sin $(n\omega_0 t)$ which will propagate, in all-possible directions. Let the average nth harmonic propagation constant along Z direction be γ_{zn} so that at a distance Z from the reference plane it may be measured as Eq. 14:

$$E_{zn} = E_{zon} e^{-\gamma_{zn}} .Z \qquad (14)$$

where, $\gamma_{zn}=(\alpha+j\beta)\alpha$ being the attenuation constant and β being the phase shift constant.

The voltage in a particular electrode location on a particular human body may be assumed to be as the following Eq. 15-16:

$$V_{zn}(t) = J_m(\rho k n) \qquad (15)$$

$$V_z(t) = \sum_{n=0}^{n} .J_m(\rho k n)\cos(n\omega_0 t - \theta) \qquad (16)$$

where, $\theta=\beta Z$, J_m Bessel functions of the first kind and k is a constant.

Conductivity of human cardiac: The electrical potential ϕ, recorded at the body surface satisfies the well-known Poisson Eq. 17:

$$\nabla^2\varphi = \frac{1}{\sigma}\nabla \cdot J \qquad (17)$$

Where:

J   = The cardiac impressed current dipole moment density

σ = The conductivity at the measurement point of the potential ϕ

To solve this deferential equation, we require a model for the conduction media. For our problem of interest, we consider the volume conductor, or the propagation media, to be formed of M (a finite number of) homogeneous regions separated from one another by closed surfaces s_j having the conductivities σ'_j and σ''_j on its interior and exterior. Equation 17 may be transformed into a more useful representation for calculating the body surface potentials:

$$4\pi\sigma\phi = \int_u J.\nabla(\frac{1}{r})du + \sum_{j=1}^{M}(\sigma''_j - \sigma'_j)\int_{s_j} \phi_j \nabla(\frac{1}{rj})ds_j \qquad (18)$$

On the left-hand-side of equation, ϕ is the potential defference between a fixed point outside the charge distribution and the reference of potentials. It corresponds to the potentials recorded on the body surface. The volume v is an arbitrary volume containing the current dipole distribution (i.e. the heart).r is the radial distance of the element of volume or area from the point from which the potential ϕ is recorded. The potentials ϕ_j, inside the integral on the right-hand-side of equation are the potentials of surface elements of the integral. $\nabla.J$ is the divergence of J, $\nabla(1/r)$ is the gradient of 1/r and the dot sign (.) represents vectorial inner-product. Finally, dv, is the volume element and ds_j, is a vectorial surface element, normal to the j-th surface element. An equivalent equation that is more appropriate for the later presented models is as follows Eq. 19:

$$4\pi\sigma\phi = -\int_u (\frac{1}{r})\nabla.Jdu - \sum_{j=1}^{M}\frac{\sigma''_j - \sigma'_j}{\sigma''_j + \sigma'_j}\int_{s_j}\frac{2E_j}{r_j}.ds_j \qquad (19)$$

where, $E_j=(E' + E'')/2$ and E' and E'' are the electric fields on either sides of the surfaces with conductivity discontinuity.

From Eq. 18 and 19, we can see that the body surface potentials consist of two parts: a term corresponding to the divergence of the cardiac impressed current dipole moments and a term corresponding to the 'reflections' of the cardiac sources onto the surfaces of conductivity mismatch.

Calculation of Signal to noise ratio in ECG: Generally the calculation of signal to noise ratio defined as Eq. 20:

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{V^2_{rms,signal}}{V^2_{rms,noise}} \qquad (20)$$

For ECG recordings, it is not representative to use the power in the complete signal (Peters *et al*., 2006). Instead, an estimate of the average power in the QRS complexes in the recording is used. For this estimate, the peak-to-peak amplitude of all QRS complexes in the signal is determined. Assuming a sinusoid shape of the QRS complex. $V_{rms,signal}$ Becomes Eq. 21 :

$$V_{rms,signal} \approx \frac{1}{2}\sqrt{2} \cdot \frac{1}{2} \cdot V_{PP,QRS} \qquad (21)$$

This results in a signal to noise ratio of Eq. 22:

$$SNR = \frac{\frac{1}{8}V^2_{PP,QRS}}{V^2_{rms,noise}} \tag{22}$$

where, $V_{PP,QRS}$ is the mean peak-to-peak amplitude of the QRS complexes in the ECG signal and $V_{rms,noise}$ is the rms amplitude of the noise that was added to this signal.

The results show various methods for calculation electrical potential in human heart. In the revise of Physical Basis of Electrocardiography the potential distribution in human body was discussed. The Einthoven lead system and Wilson central terminal in human heart represent the bases of electrophysiology which was explained in this study. The derivation of the equation of Electrical potential in human heart and the conductivity of human cardiac muscles shows the Electromagnetic Basis of the Electrocardiogram .more benefits the calculation of signal to noise ratio, where it is easier to account for the value of SNR for QRS complexes.

CONCLUSION

The electrophysiology and biopotentails of human ECG are approximately the concept of electrical potential in human heart. From the findings, one observed the derivations of human heart electrical equation from the bases of electromagnetic or physics of the human heart. However, the idea to contribute to solve the human ECG problem. More work is well under way concerning the application of the human ECG version for the future research in this field. As much as the ideas are concerned, the current findings will contribute to the references for later studies.

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