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FORMULATION AND CLINICAL APPLICATION OF CARDIAC VECTOR HYPOTHESES IN ECG INTERPRETATION USING VECTOR PHYSICS PRINCIPLE

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ABSTRACT

Electrocardiography (ECG) is one of the most important diagnostic tool in medical field. A lot of advancements had come in the ECG machine, yet the basic physics principle of ECG is not clearly understood. The concept of Einthoven triangle and the cardiac vector describing the electrical activity of the heart was first described by Einthoven even before a century but he never published a complete detailed description of the same. The attempts by various other researchers in trying to solve the relationship between Heart and Lead vector was incomplete. In electrocardiographic and vector-cardio-graphic analysis, the ECG voltage is treated as a vector and these voltages are used as vector components until Burger emphasised that voltage is a scalar quantity. He attempted to solve this problem using scalar (dot) product but he derived the dimension of cardiac vector as an imaginary physical quantity. After many decades, the complete Heart-lead vector relationship explained using cardiac vector and the Einthoven's equilateral triangle hypotheses was published in the year 2012 but it is not widely known to the medical professionals probably due to the mathematics involved in it. The proposed Cardiac vector hypotheses derived using scalar product of two vectors states that cardiac vector is an electrical field vector of dimension volt/metre. The aim of the current research study is to discuss in detail the basic mathematics and physics involved in the formulation of cardiac vector theory and its clinical application in ECG interpretation.

KEYWORDS: Heart vector, Lead vector, Einthoven triangle.

INTRODUCTION

Coronary heart disease is the number one killer disease in the world. It is one of the major economic burden and poses a great challenge to the scientific community in the 21st century. **Electrocardiogram (ECG)** is one of the most important diagnostic tool for appropriate interpretation and diagnosis of coronary artery disease. ECG interpretation plays a vital role in the initial evaluation of patients presenting with cardiac complaints but it is often difficult and an arduous task especially for the junior medical healthcare professionals.[1] The understanding of the **Einthoven's triangle hypotheses** is central to the field of electrocardiography, but the concept of cardiac vectors is very difficult to understand.[2]

The concept of **cardiac vector** describing the electrical activity of the heart and the three cardinal bipolar limb lead vectors (lead I, lead II & lead III) forming an **equilateral triangle** with heart at the centre of the **homogeneous volume spherical conductor** was first described by **Einthoven**, the father of Electrocardiography even before a century.[3] But he **never published** a complete **detailed** description of the same.[4]

Many researchers have **disproved the einthoven's equilateral triangle model**, thinking the orientation of the three cardinal bipolar **limb lead vectors** as Einthoven's triangle, assuming **cardiac vector** as a **non-real vector** quantity and stating that human body is not an homogeneous but an **heterogeneous linear resistive electrical conducting** medium.[5,6,7,8] This added controversy among the clinicians to the already incompletely derived concepts.

In classical electrocardiographic analysis and teaching, the **ECG voltage** is treated as a **vector** and these voltages are used as "vector" components to calculate the resultant manifest potential difference to represent the cardiac vector. The vector-cardiographers utilized voltage as a vector component until **Burger** emphasized that **voltage** is a **scalar** quantity. Burger laid the **theoretical foundation** of vector-cardio-graphy and electrocardiography by proposing the "heart vector" ($\vec{H}$) and "lead vector" ($\vec{L}$) concepts.[9] He defined the voltage in a lead as the scalar (dot) product of the "heart vector" and "lead vector", but **derived** the **dimensions of heart vector** which do not apply to any known physical entity. Several investigators have tried to solve the heart-lead vector relationship but **no single attempt** was **able to solve** the basic theoretical flaws in ECG.[10] So, "**imaginary cardiac vector hypothesis**" was proposed by subsequent researchers stating that cardiac vector is a non-real vector.[10,11]

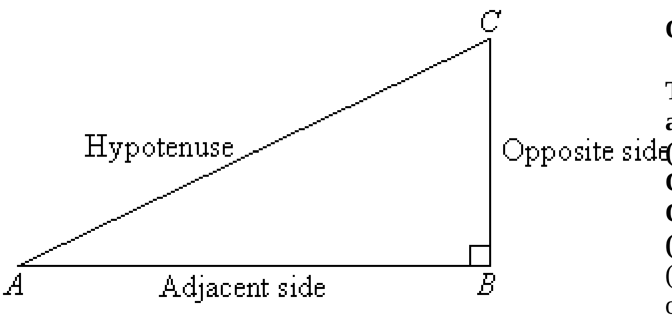
The **complete heart-lead vector relationship** described by using cardiac vector and the Einthoven's equilateral triangle hypotheses was proposed by **Rajini Samuel (Myself)** in the year **2012**.[12] But unfortunately, it is not widely known to the medical professionals probably due to the mathematics involved in it. **Cardiac vector hypotheses** states that cardiac vector is an **electrical field vector** of dimension **volt/metre** and the voltage recorded in a particular lead is the result of scalar (dot) product between cardiac and the lead vector.

The aim of the current research study is to discuss in detail the basic mathematics and physics involved in the formulation of cardiac vector theory and its clinical application in ECG interpretation which when properly utilized at the patient care will result in saving millions of lives.

MATERIALS AND METHODS

Right angled triangle

In a right angled triangle (one of the angle is 90^0), the side **opposite** to **90^0** is **hypotenuse**. The side adjacent to the angle A is called **adjacent side** and the side opposite to the **angle A** is called **opposite side**.



In trigonometry

Sin A = opposite side/ hypotenuse

Cos A =adjacent side/hypotenuse

Tan A = sin A/ cos A

= opposite side/adjacent side [where 0° < A < 90°]

Vector vs Scalar

Vector is a physical quantity that has **both magnitude** and **direction**. **Scalar** is a physical quantity that has **only magnitude** and **no direction**.

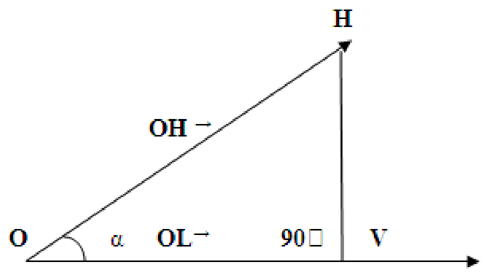
Unit vector

A unit vector is a vector quantity whose magnitude is one and has direction only. For example, if a **vector** is divided by its **own magnitude**, then its **magnitude** becomes **one(unity)** and so it has **only direction**.

Scalar or dot product

If **two vectors** are **multiplied** and the product is a **scalar** quantity, then it is scalar or dot product of vectors. It is equal to the **product** of the **magnitudes** of the **two vectors** and the **cosine** of the **smallest angle** between them.

Projection of Heart vector on Lead vector



OH $^{\rightarrow}$ or **h**$^{\rightarrow}$(Heart Vector) is projected onto the **OL**$^{\rightarrow}$ or **l**$^{\rightarrow}$ (Lead Vector)

In the right angled triangle OHV

A perpendicular line is drawn from the point H (tip of the **Heart vector OH** $^{\rightarrow}$) on to the **lead vector (O L**$^{\rightarrow}$**)** which meets at the **point V**.

The triangle OHV is a right angled triangle.

α: the **angle** between the cardiac and lead vector

OV: adjacent side ; **OH**: hypotenuse

Cos α = adjacent side/hypotenuse

= OV/OH

OV= OH COSα

The scalar or dot product between Heart (cardiac) and lead vectors

(OH $^{\rightarrow}$**). (O L**$^{\rightarrow}$**) = (OH) (OL) COSα**

OH: magnitude of the Heart Vector

OL: magnitude of the lead vector

(OL^) = (OL$^{\rightarrow}$**)/OL**

(OL^) is a unit vector of magnitude one and direction only.

If a **perpendicular line** is **drawn** from the tip of the **cardiac vector** into their respective **leads**, then the **corresponding segment in that leads** represents the **magnitude of the voltage** recorded in that **particular lead**.

OV: voltage recorded in that particular lead

(OH $^{\rightarrow}$**).(O L**$^{\rightarrow}$**) = (OH) (OL) COSα**

Lead vector is divided by its magnitude to form the unit lead vector and this is substituted.

(OH $^{\rightarrow}$**).(OL^) = (OH) COSα**

Since **OV= OH COSα**, Voltage recorded in a particular lead is the result of dot product between the lead vector (measured in metre) and the cardiac vector(measured in volt/metre). Hence voltage (measured in volt) is a scalar quantity. The dimension of cardiac vector is volt/metre which denotes the **electrical field vector** (measured in **volt/metre**).[12]

(OH →): Cardiac vector(axis) denotes the resultant vector.
(OL^): It denotes the orientation of the electrode (lead vector or lead axis).
(OH) COSα: voltage recorded in a particular lead is due to the projection of heart(cardiac) vector on a lead vector (orientation of the electrode).
(OH →). (OL^) = (OH) COSα or (h→). (l^)= (OH) COSα

From the above equation it is very clear that the voltage recorded in a particular lead depends on :

1. Both the **magnitude** and **direction** of the **cardiac vector**.
2. Only on the direction of the lead vector because here **lead vector (OL ^ or l^) is a unit vector** of **magnitude one** and has **only direction**.
3. If a cardiac vector is **parallel** to a particular lead (**α** angle is **zero**), then it will make the greatest impression on that lead and the ECG will record the maximum deflexion on that lead because **Cos 0** is **one**.
4. If a cardiac vector is directed at **right angles** (90°) or perpendicular to a particular lead axis, the net impression on that lead will be nil (either equiphasic or a null deflexion) because **Cos 90** is **zero**.
5. As the **angle α,** between the cardiac and the lead vector **increases,** the **voltage** recorded in that particular lead will **decrease** and vice versa**.**
6. If the two vectors are moving in the opposite direction, the voltage recorded in that particular lead will be negative because **cos value** for **obtuse** angle is **negative**.

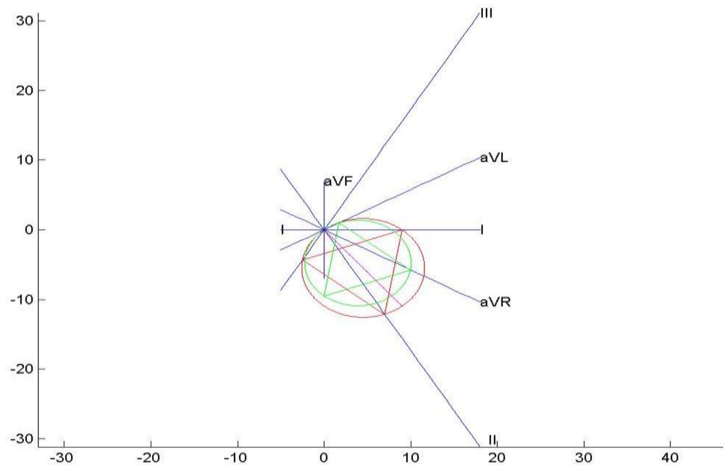
The values of cosine (cos) angles for the following angles is given below.

Cos angles	$\cos 0^0$	$\cos 30^0$	$\cos 45^0$	$\cos 60^0$	$\cos 90^0$	$90° < \theta < 180°$ (obtuse)
Values	1	0.866 or [$\sqrt{3}/2$]	0.707 or [$1/\sqrt{2}$]	0.5 or [1/2]	0	Negative

[$\sqrt{2}$ = 1.414; $\sqrt{3}$ = 1.732]

From the above values, it is very clear that as the **angle increases**, the **cos value will decrease**. The value is **zero** for **90^0** and **negative** for **obtuse angle**.

Relationship between various leads



The leads I, II, and III together with augmented limb leads aVR, aVL, and aVF form the basis of the hex-axial reference system, which is used to calculate the heart's electrical axis in the frontal plane. **Leads I, II** and **III** are called the **Bipolar limb leads**.[3] These electrodes are located on the limbs, one on each arm and one on the left leg.

Lead I is the voltage between the (positive) left arm (LA) electrode and right arm (RA) electrode. **Lead I** = **LA – RA.**

Lead II is the voltage between the (positive) left leg (LL) electrode and right arm (RA) electrode. **Lead II** = **LL – RA.**

Lead III is the voltage between the (positive) left leg (LL) electrode and left arm (LA) electrode. **Lead III** = **LL-LA.**

Leads aVR, aVL and **aVF** are the **augmented** limb leads. They are derived from the same three electrodes as leads I, II, and III, but they use **Goldberger's central**

terminal (GCT) as their negative pole. **Goldberger's central terminal** is a combination of inputs from two limb electrodes, with a **different combination** for **each augmented lead.**

The common virtual electrode, known as the **Wilson's central terminal (**WCT or **V_W)**, is produced by **averaging the potentials measured** from the electrodes **RA, LA,** and **LL** referred to the **reference electrode** on the **right leg** using three identical resistors (5kΩ or higher) connected to a single point to give an average potential of the body.[3,13,14]

V_w = 1/3 (RA + LA+ LL)

The **WCT** does **not** represent **a zero potential**, since it is approximately around 0.3 mV. Similarly **GCT** does **not** have a **zero potential**. Consequently aVR, aVL and aVF and V1-V6 leads are **not truly unipolar**, but bipolar leads, with the indifferent pole carrying a very low negative potential. The term "unipolar", popularized by Wilson, is a misnomer, since no leads can be truly "unipolar", all requiring positive and negative poles. Thus the term unipolar when first introduced by Wilson and Goldberger also realized that such leads were not truly unipolar.[13,14] Thus the GCT is **variable**, consisting of the mean of the potentials of the 2 (**different** for the **3 recordings**) limb leads, in contrast to the **WCT** which is **unvariable. (same** for the **3 recording)**

The standard ECG consists of 3 different sets of leads: the **bipolar leads I, II** and **III,** the **unipolar precordial V1-V6 leads** recorded via the **stable WCT**, and the **unipolar aVR, aVL** and **aVF** leads recorded through the **changing GCT.**[13] An electrode placed on the **right leg** acts as a **ground** for **all leads** which serves as a **reference electrode** for recording purposes.

The difference in the potential of the GCT and WCT is reflected in the difference of the voltages recorded by these 2 systems. This modification of Goldberger leads to the **augmentation** of the recorded limb leads by **50%,** as can be shown mathematically.[3,13]

aVR = RA - ½ (LA + LL)
VR = RA - 1/3 (RA + LA+ LL)
Dividing aVR/VR
= {RA - ½ (LA + LL) } / RA - 1/3 (RA + LA+ LL)
= 3/2

So, the augmentation is 3/2 or 1.5 times higher or in terms of percentage it is 50% higher.
aVR/VR = 3/2 or VR/aVR =2/3

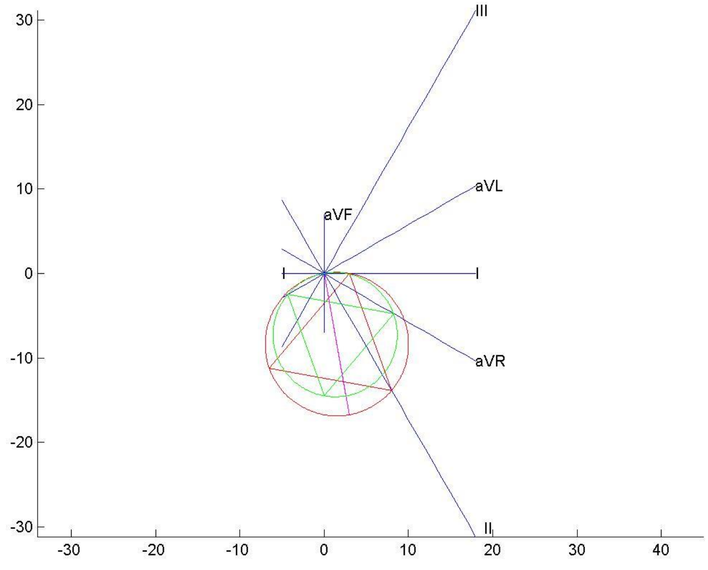
The values obtained for augmented leads (**aVR/aVL/aVF)** using **GCT** should be multiplied by **2/3** to get the values for **VR/VL/VF** obtained using **WCT.**[13]

Lead augmented vector right (aVR) has the positive electrode on the right arm. The negative pole is a combination of the left arm electrode and the left leg electrode.
aVR = RA - ½ (LA + LL) = 3/2 (RA – V_W)

Lead augmented vector left (aVL) has the positive electrode on the left arm. The negative pole is a combination of the right arm electrode and the left leg electrode.
aVL = LA – ½(RA+LL) = 3/2(LA-V_W)

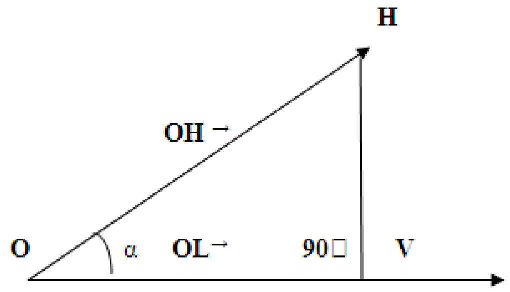
Lead augmented vector foot (aVF) has the positive electrode on the left leg. The negative pole is a combination of the right arm electrode and the left arm electrode.
aVF= LL – ½(RA+LA) = 3/2(LL – V_W)

Projection of Heart Vector onto the three Bipolar and three Unipolar Limb lead Vectors



The heart vector (represented by the **diameter of the circle**) is projected onto the various limb lead vectors (3 bipolar and 3 unipolar limb lead vectors).[12] The voltage recorded in a particular lead is determined by the Heart-Lead Vector relationship which was already discussed.

Heart - Lead vector relationship



The **perpendicular line** drawn from the tip of the cardiac vector to the lead vector meets at the **point V** which denotes the **voltage** recorded in that particular lead. Similarly, the **perpendicular lines** are drawn from the tip of the heart vector to the various **6 lead vectors** (Lead I, Lead II, Lead III, aVR, aVL and aVF lead vectors) meeting at their respective points which denote the voltage recorded in that particular leads.

We already know the following relationship between the bipolar and unipolar limb lead voltages.[3,12,13,14]

aVR= -(lead 1+ lead 2)/2
aVL= lead1 - (lead2) /2
aVF= lead 2- (lead 1) /2

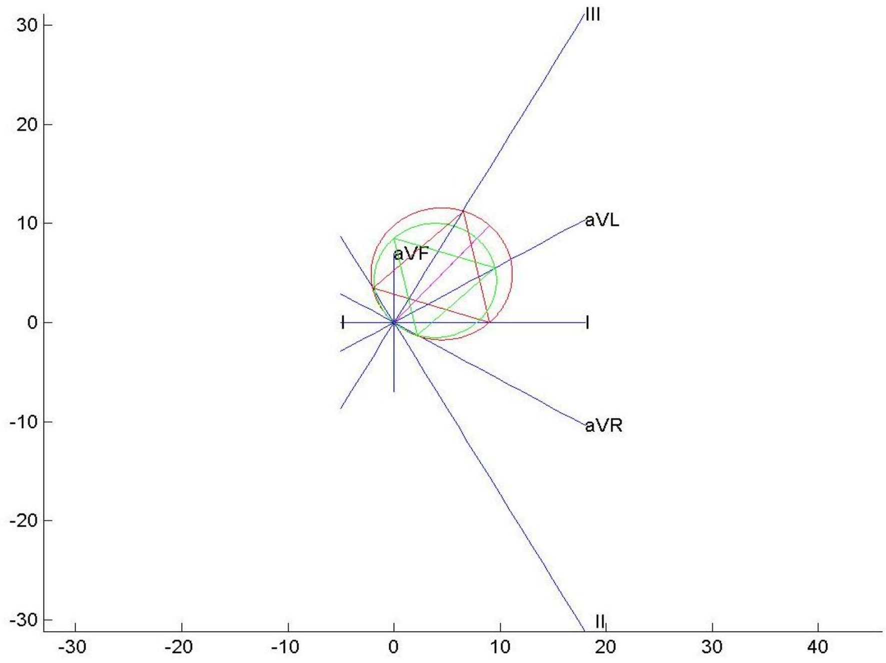
We also know the following.

Lead 1+ lead 3 = lead 2 (Einthoven equation)
aVR + aVL + aVF = 0

The above two equations are based on **kirchoff's law** which is widely accepted.[3,12]

In the hexaxial reference system, if the points denoting the voltages of the bipolar limb leads (Lead I, Lead II and Lead III) are connected, they form an equilateral triangle. Similarly, if the points denoting the voltages of the unipolar limb leads (aVR, aVL and aVF) are connected, they form an equilateral triangle.[12] Convert the equilateral triangles into circles. The two circles have same origin, same orientation but with different radii (or diameter).[12]

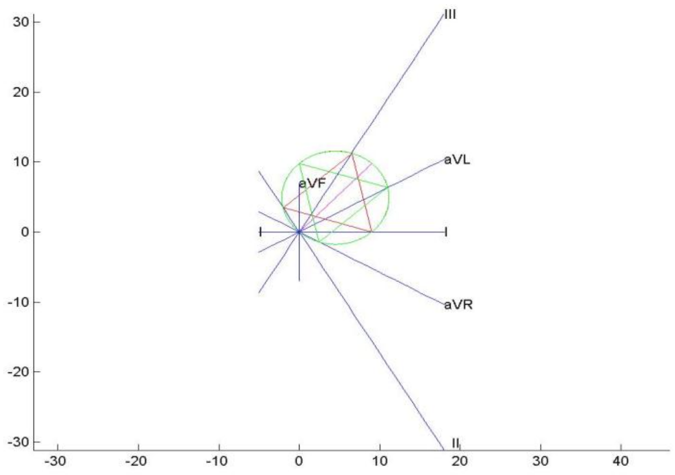
Two circles (2 equilateral triangles) with same origin.



Each circle has same origin, same orientation, but different radii because the bipolar and unipolar limb leads have **different resistance**.[12,15] The **diameter** of the circle denotes the **cardiac vector** (resultant vector). The perimeter (**circumference**) of the circle denotes the **electrical field** of the **heart** with heart at the **centre** of the circle. This principle is similar to the physics principle of **homogeneous volume spherical conductor**. The centre of the hex-axial reference system is the **zero point** which denotes the **origin**. (This centre point **does not denote the Wilsons central terminal**.)

Since the **Right arm, left arm** and **left leg** (Voltages represented by the electrodes or lead vectors, Lead I, lead II, Lead III, aVR, aVL and aVF) are the **vertices** of an **equilateral triangle**, the **limb lead vectors also form** an equilateral triangle with heart at the centre.

Two equilateral triangles lie on the same circle (correction factor 1.154 is applied)

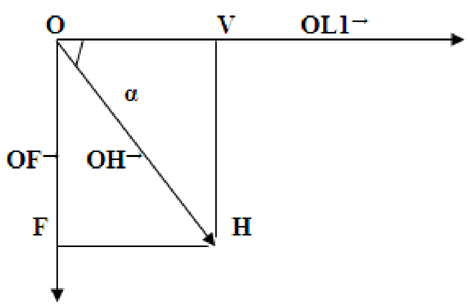


The **orientation** of the **circle** is the **same** for both the bipolar and unipolar limb leads because the **electrode position** is **same** (right arm, left arm and left leg) for both of them and they **record the same electrical field** of the heart in a different view (angle). But the **magnification** is **different** (higher for Bipolar limb leads) because the bipolar and unipolar limb leads have different resistance and the **ratio** of their resistance is **4/3**.[12] According to ohms law(**V=IR)**, if the resistance(R) is increased, the voltage(V) is also increased for the same current(I) flowing.

Here the ratio of the area of the two circles is always constant and equal to 4/3. The square root of 4/3 is 1.154.[12,15] The ratio of their radii is 1.154. Multiply each unipolar limb lead voltages by **1.154** and then plot. Now the **two equilateral triangles** are on the **same circle**.

One circle denotes that **heart** is always situated in the **centre of the electrical field** which it generates. The right arm, left arm and left leg are the extensions of its electrical field.

Angle determination in ECG



O: point of **origin** (**zero** at the centre of the hexaxial reference system)
OL1→: lead I Vector (Unit vector in metre)
OV: Voltage recorded in lead I
OF→: aVF lead Vector (Unit vector in metre)
OF: Voltage recorded in aVF lead
OH→: Heart Vector (Volt/metre)

From the tip of the cardiac vector, two **perpendicular lines** are drawn which meet the **lead I** at **point V** and **aVF lead** at **point F**.

In the right angled triangle OVH
Tan α = opposite side/adjacent side
= VH/OV
= OF/OV (from the diagram it is very clear that OF = VH)
Tan α = aVF/lead I

It is already discussed that the unipolar and bipolar limb leads have different resistance. So, the correction factor of 1.154 is to be applied.[12,15] The formulae to calculate the angle determination in ECG is
Tan α= (1.154*aVF)/ Lead 1

The values of tangent (tan) angles for the following angles is given below.

Tan angles	tan0^0	tan30^0	tan45^0	tan60^0	tan90^0
Values	0	1/√3 (0.577)	1	√3 (1.732)	Infinity (undefined)

Suppose if the value of **aVF** is **zero**, the corresponding **angle** for that tan value is **zero degree**. So, the **cardiac vector** is **perpendicular** to **aVF** or **parallel** to **Lead I**. If the value of the **Lead I** is **zero**, the corresponding **angle** for that tan value (**1/0 =infinity**) is $\mathbf{90^0}$. So, the **cardiac vector** is **perpendicular** to **Lead I** or **parallel** to **lead aVF**. The tan value is negative in both the 2^{nd} and 4^{th} quadrant. For $\mathbf{2^{nd}}$ **quadrant** in the hex-axial reference system (**lead I negative** & **aVF positive**), angle should be subtracted from 180 degree. For the $\mathbf{4^{th}}$ **quadrant** (**lead I positive & aVF negative**) angle should be subtracted from 360 or zero degree.

RESULTS

The cardiac circles were constructed using the voltages recorded in the bipolar and unipolar limb leads citing with 4 ECG graphs.(for the QRS,ST and T wave vectors) First the **two triangles** formed by the **bipolar** and **unipolar** limb lead voltages were constructed using the **net voltages** (measured in **mm**). The **mathematical relationship** between the **bipolar** and **unipolar limb leads** is applied. Then the **equilateral triangle** is **converted** into a **circle**. Now the 2 circles have the **same origin**, **same orientation** but with different radii (diameter) because of the difference in their resistance which was already clearly discussed. The **orientation** of the **diameter** of the circle denotes the **resultant cardiac vector**. The **angle** subtended by the cardiac vector with the Lead I vector (axis) denotes the cardiac axis which was **calculated** by the derived formulae. Then the **vector principle** was applied for the **constructed cardiac circles** (QRS, ST& T) to assess in the **ECG interpretation**.

From the **figure 1** (ECG graph with **normal QRS/T angle**) **QRS circle** and **T circle** are constructed and shown in **figure 2** and **3** respectively. Their QRS and T voltage values are shown in the **table1**. From the **figure 4** (ECG graph with **T wave inversion in inferior** leads Lead **III & aVF**) QRS circle and T circle are constructed and shown in **figure 5** and **6** respectively. The QRS and T voltage values are shown in the **table 2**. From the **figure 7** (ECG graph with **ST elevation** in **inferior** wall leads) QRS circle and ST circle are constructed and shown in **figure 8** and **9** respectively. The QRS and ST voltage values are shown in the **table3**. From the **figure 10** (ECG graph of intraventricular conduction defect with **wide abnormal QRS/T angle**) QRS circle and T circle are constructed and shown in **figure 11** and **12** respectively. The QRS and T voltage values are shown in the **table 4**.

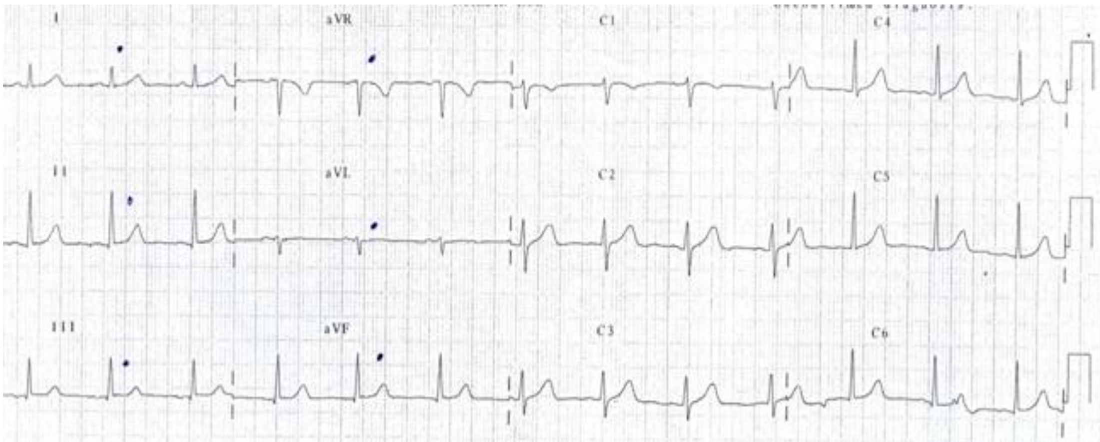


Figure 1: ECG graph with normal QRS/T angle.

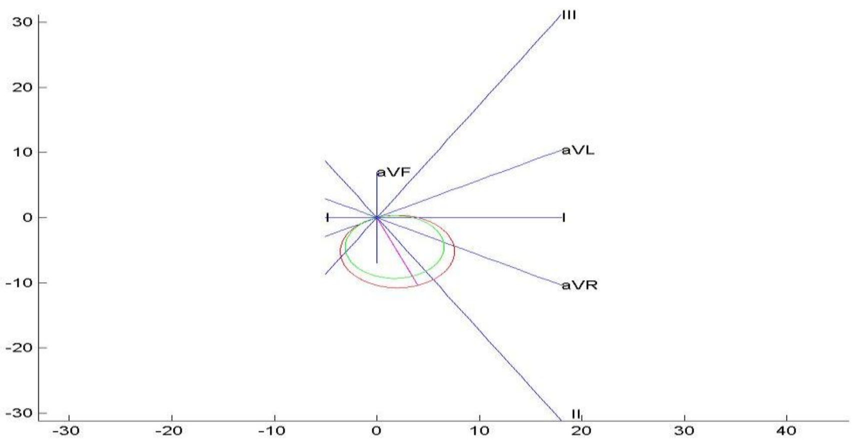


Figure 2: 2 circles (without triangles) of the ‘QRS’ voltages of the patient ECG with normal QRS/T angle.

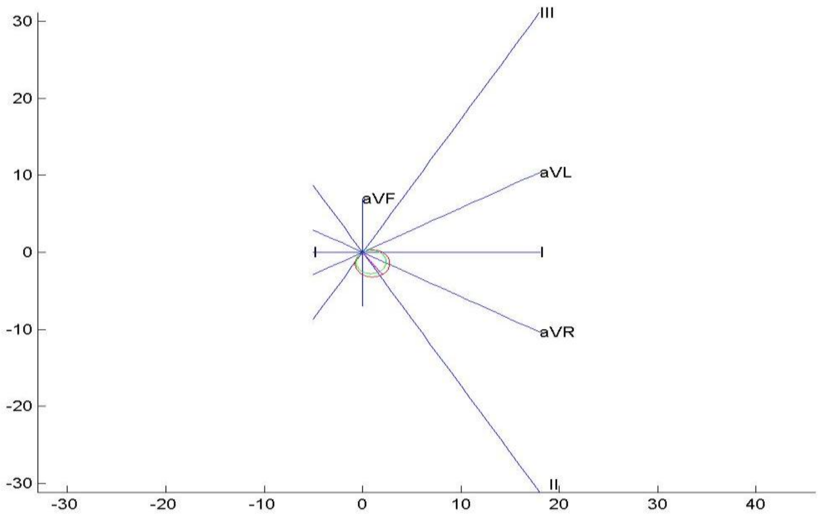


Figure 3: 2 circles (without triangles) of the 'T' voltages of the patient ECG with normal QRS/T angle.

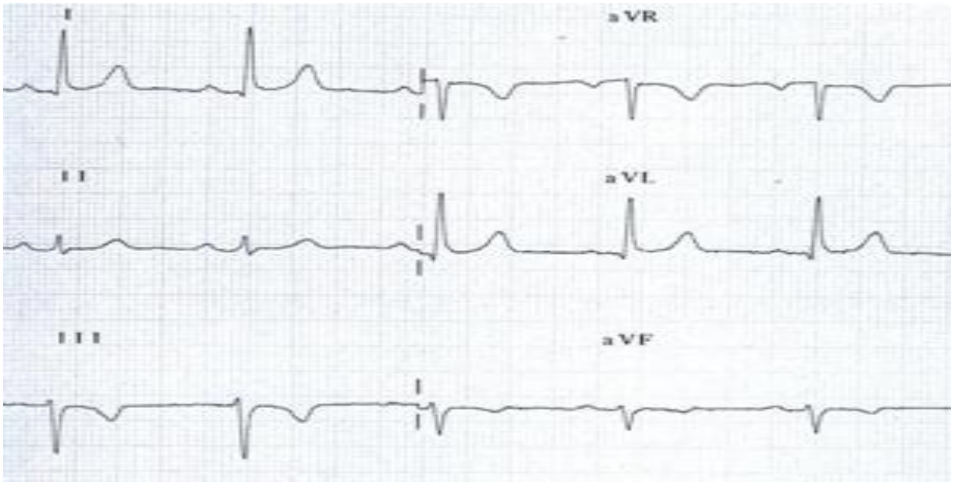


Figure 4: ECG with abnormal T angle (T- wave inversion in Lead III & Lead aVF denoting Inferior wall ischemic changes).

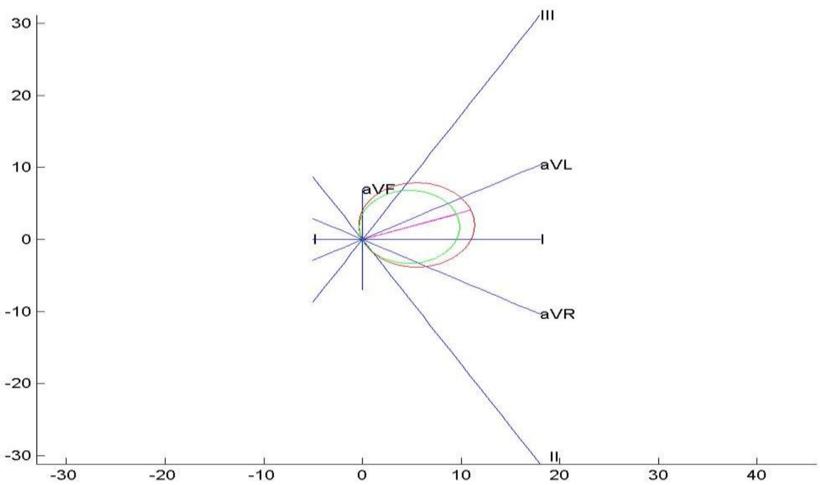


Figure 5: 2 circles (without triangles) of the 'QRS' voltages of the patient ECG with abnormal T angle (T- wave inversion in Lead III & Lead aVF denoting Inferior wall ischemic changes).

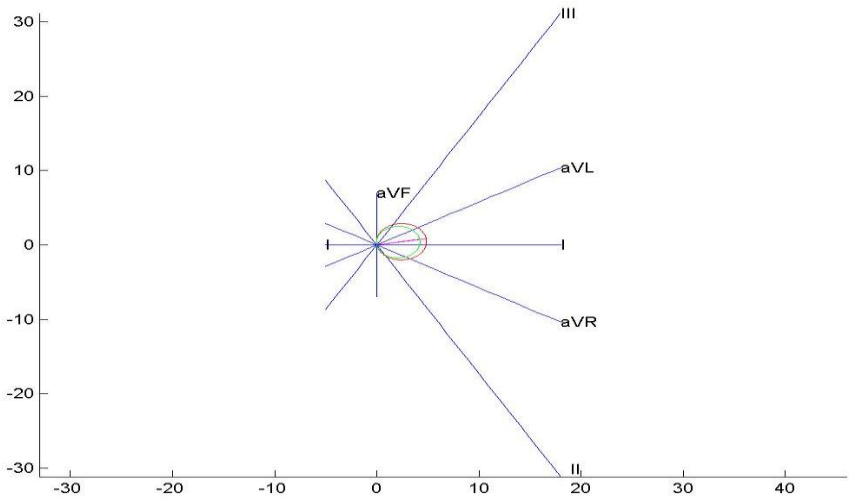


Figure 6: 2 circles (without triangles) of the 'T' voltages of the patient ECG with abnormal T angle (T- wave inversion in Lead III & Lead aVF denoting Inferior wall ischemic changes).

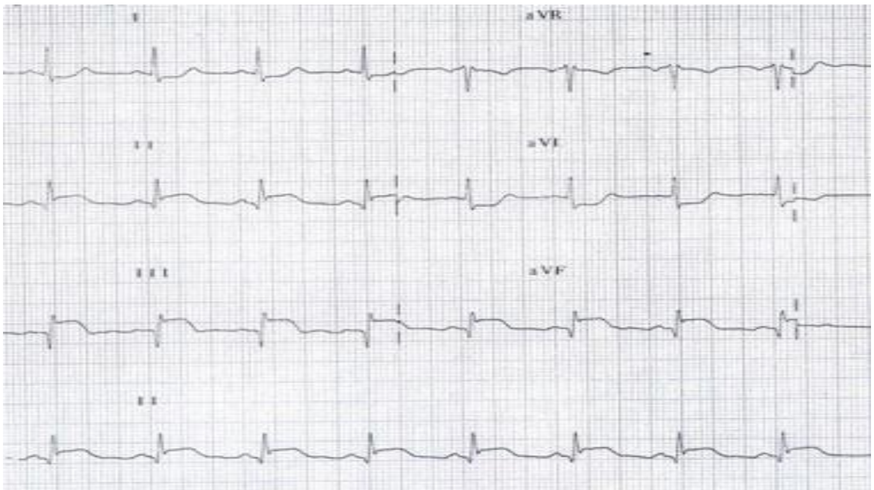


Figure 7: ECG with ST elevation in Leads II, III & aVF(denoting Inferior wall myocardial infarction changes).

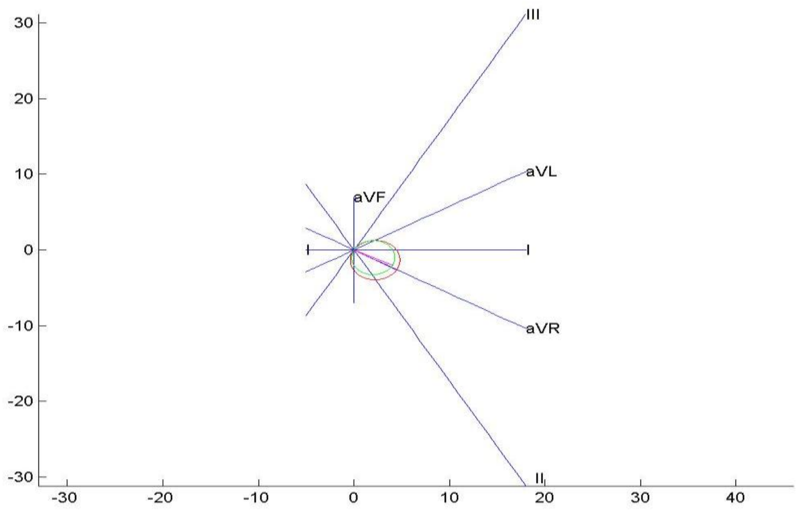


Figure 8: 2 circles (without triangles) of the 'QRS' voltages of the patient ECG with ST elevation in Leads II, III & aVF(denoting Inferior wall myocardial infarction changes).

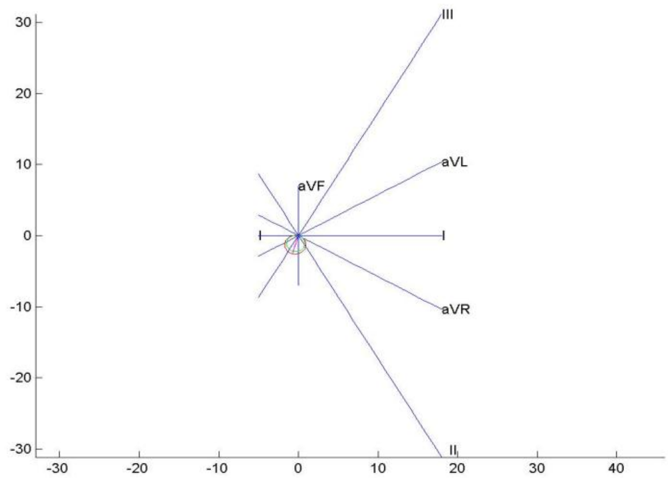


Figure 9: 2 circles (without triangles) of the 'ST' voltages of the patient ECG with ST elevation in Leads II, III & aVF (denoting Inferior wall myocardial infarction changes).

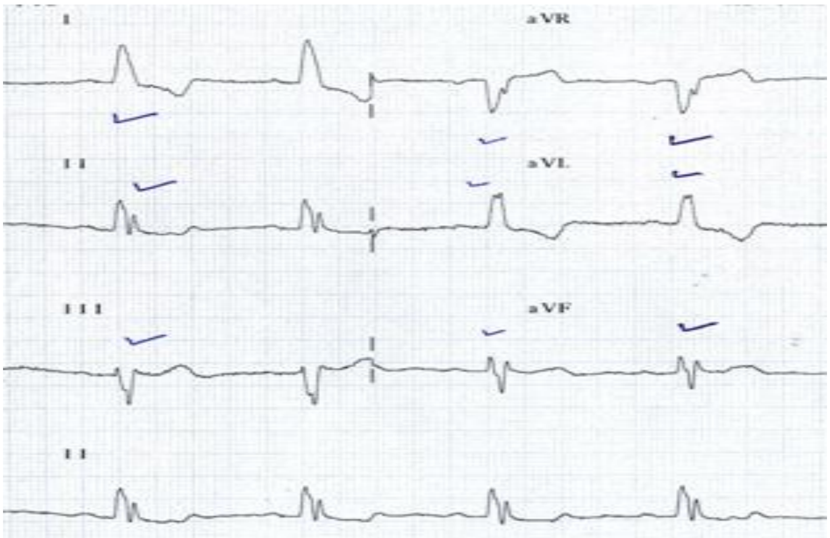


Figure 10: ECG graph of intraventricular conduction defect with wide abnormal QRS/T angle

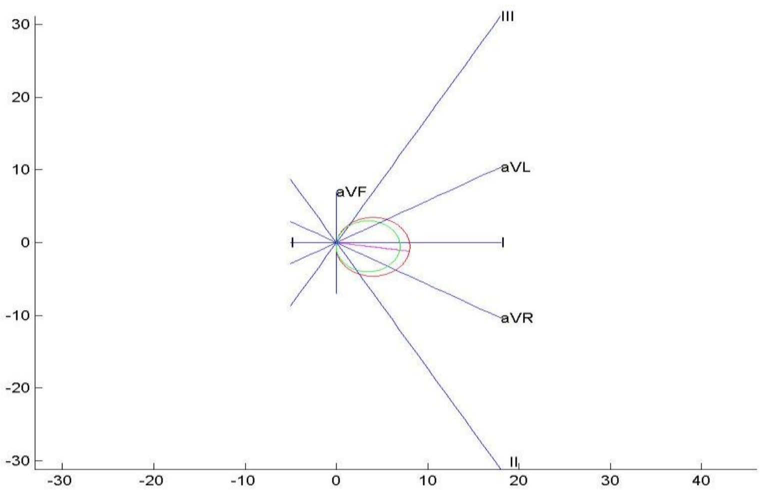


Figure 11: 2 circles (without triangles) of the 'QRS' voltages of the patient ECG with Intraventricular conduction defect with wide abnormal QRS/T angle.

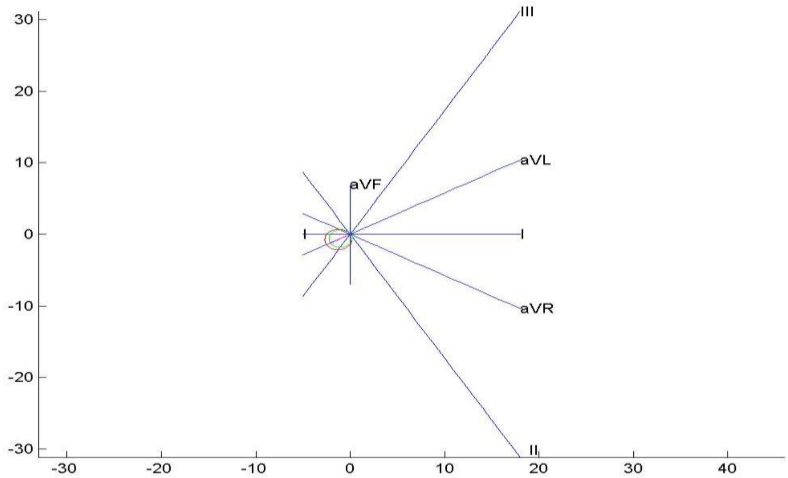


Figure 12: 2 circles (without triangles) of the 'T' voltages of the patient ECG with Intraventricular conduction defect with wide abnormal QRS/T angle

Table 1: QRS and T voltage values from the figure 1 ECG with normal QRS/T angle.

Leads	**QRS wave net voltage measured in mm**	**T wave net voltage measured in mm**
Lead 1	4.0	2.0
lead 2	11.0	3.5
lead 3	7.0	1.5
aVR	-7.5	-2.75
aVL	-1.5	0.25
aVF	9.0	2.5
Calculated Angle using the formulae: **Tan α= (1.154*aVF)/ Lead 1**	68.93	55.26
Comment	Normal QRS/T angle (both the QRS and T axis is normal)	

Table 2: QRS and T voltage values from the figure 4 ECG with abnormal T angle (T- wave inversion in Lead III & Lead aVF denoting Inferior wall ischemic changes).

Leads	**QRS wave net voltage measured in mm**	**T wave net voltage measured in mm**
Lead 1	11.0	4.83
lead 2	2.0	1.67
lead 3	-9.0	-3.16
aVR	-6.5	-3.25
aVL	10	4.0
aVF	-3.5	-0.75
Calculated Angle using the formulae: **Tan α= (1.154*aVF)/ Lead 1**	-20.16	-10.15
Comment	QRS axis is within normal but T-wave axis is abnormal (QRS axis is normal because it is **not infarcted**, only ischemia is present) (**T-vector deviating away** from the **inferior wall**, so T- wave is negative in Lead III & Lead aVF) In ischemia, **T vector** will move **away from the affected** wall or region.(**Primary change**)	

Table 3: QRS and ST voltage values from the figure 7 ECG with ST elevation in Leads II, III & aVF(denoting Inferior wall myocardial infarction changes).

Leads	QRS wave net voltage measured in mm	ST wave net voltage measured in mm
Lead 1	4.66	-0.8
lead 2	4.34	1.8
lead 3	-0.32	2.6
aVR	-4.5	-0.5
aVL	2.5	-1.7
aVF	2.0	2.2
Calculated Angle using the formulae: **Tan α= (1.154*aVF)/ Lead 1**	26.34	107.50
Comment	**ST (current of injury) vector** is towards the inferior wall leads Leads II,III& aVF) Reciprocal ST –depression is seen in leads oriented away from the current of injury. **QRS vector** is **not deviated** because the inferior wall is **not infarcted**.	

Table 4: QRS and T voltage values from the figure 10 ECG graph with Intraventricular conduction defect with wide abnormal QRS/T angle.

Leads	QRS wave net voltage measured in mm	T wave net voltage measured in mm
Lead 1	8.0	-2.5
lead 2	5.0	0
lead 3	-3.0	2.5
aVR	-6.5	1.125
aVL	5.5	-2.5
aVF	1.0	1.125
Calculated Angle using the formulae: **Tan α= (1.154*aVF)/ Lead 1**	8.2	152.56
Comment	QRS axis is normal. But T axis is abnormal. The **T vector** is **moving away** from the **QRS vector** due to **secondary** changes.(QRS duration is prolonged)	

DISCUSSION

In some of the previous research articles it was mentioned that cardiac vector is not a real vector and it has properties **not exhibited by vectors** in the **vector algebra**.[10,11] Also it was stated that the Einthoven's triangle is a non-equilateral triangle and the heart does not lie in the centre of the triangle.[5,6,7,8] But it is clearly shown that cardiac vector is an electrical field vector of dimension volt/metre which has both magnitude and direction. The concept of **dot (scalar) product** between the two vectors in **vector algebra** is clearly applied to formulate the cardiac vector theory. In some of the research articles, they **tried to prove the shape of the triangle** formed by the cardinal bipolar **limb lead vectors**.[6,7,8] They calculated the inner angles formed by the sides of the lead vectors.[8] But **this is nothing to do** with the **Einthoven's equilateral triangle model** with heart at the centre of the electric field it generates and the right arm, left arm and left leg are the extensions of its electrical field. The limb lead **vector triangle concept** is simply explained that the **triangle gets shifted**.[12]

The heart (in zero potential) is at the origin in the centre of the hex-axial reference system. When the heart acquires certain potential (during depolarization and repolarisation) the triangle gets shifted but the **equilateral shape** of the triangle **remains** the **same** in **any of the 4 quadrants** of the hex-axial reference system.[12] The right arm, left arm and left leg are the vertices of an **electrical equilateral triangle** and not an anatomical triangle. Einthoven's statement about the human body to be an **homogeneous volume spherical conductor** with **heart** at the **centre** of the **sphere** (in **2 dimension** it is **circle**) is similar to the comparison of the **central nervous system** of our human body to a **computer**.

The application of the **cardiac vector hypotheses** is to be discussed in the following **already well known concepts in ECG**. The normal **QRS (Vector)** axis is **-30°** to **90°**. The normal **t wave axis** is between **0°** and **90°**. The frontal plane T wave axis is similarly directed to the frontal plane QRS axis. Therefore the T wave axis cannot be assessed in isolation but must be considered in its relationship to the QRS axis. The normal **QRS-T angle** does **not** normally **exceed 60°.**[16]

The standard leads **II, III** and lead **aVF** are oriented to the **inferior surface** of the heart.The **leads I** and **lead aVL** tend to be oriented to the high or superior **left lateral wall**. The lead aVR is oriented towards the cavity of the heart. The leads **V1 to V 6** are oriented towards the **anterior wall** of the heart. The leads **V1 to V 4** represent the **anteroseptal leads** and the leads **V5 and V6** denote the apical or **lateral leads**. The standard **lead I, lead aVL, V5 and V6** are collectively referred to as the **left-oriented leads**.[16]

There is **no lead directly oriented** to the **posterior wall** of the heart but inverse or mirror image changes may be reflected by the right precordial leads V1 to V3 especially lead V2. The **leads** oriented to the **right ventricle** reflect **rS complexes**, whereas leads oriented to the **left ventricle** reflect **qR complexes**. The initial r wave of the right oriented leads is larger in amplitude but the initial q wave of the left oriented leads recorded is usually small and not infrequently extremely small. The **transition** from an **rS complex** to a **qR complex** is most commonly manifest in **lead V3**. The amplitude of the **R wave** in the normal precordial ECG is invariably **taller** in **lead V5** than in **lead V6**. The normal **T wave** is **always upright** in the **left oriented leads** and is **usually upright** in **right oriented leads** in the adult. The **T wave** in **lead V6** is usually of **greater amplitude** than the T wave in **lead V1**.[16]

During ischemia, the heart muscle does not die because blood flow is sufficient to maintain life of the myocardium but not sufficient to cause repolarisation of the muscle. More blood is needed to repolarise than to depolarize. Because **T-wave** is produced by **repolarisation** of the ventricles, **ischemia** (decreased blood flow) causes T-wave axis to be deviated. This T-wave axis deviation causes the **T-wave** to be **inverted** (**negative deflexion**). Thus the **electrical field vector** of the heart during repolarisation of the ventricles (T- wave) will **not** be in the left lower quadrant (**normal axis quadrant**) and it will be located in other quadrant.

ST segment is an **iso-electric period** in the ECG. When the myocardium of the heart is injured, the current flows between pathologically depolarized and normally polarized areas resulting in leakage of current. This is called the **current of injury**. If the leads are **oriented towards** the current of injury vector (direction of the **vector** is from **endocardium to epicardium**) it results in **positive deflection** in that particular leads (**ST – elevation**). **Reciprocal ST-depression** (**negative** deflection) will be seen in the **leads oriented away** from the current of injury vector. In **sub-endocardial infarction**, ST segment and T wave changes will be **negative** which is **opposite (mirror image)** to those associated with transmural or subepicardial infarction. ST-depression is present, because the **direction** of the current of injury **vector** is from **epicardial to endocardium**.[16]

QRS-vector denotes the ventricular depolarisation. In myocardial infarction, the tissue is necrosed, so it is **electrically inert** and does not get depolarized. This is called **electrical hole**. The electrodes oriented towards this will **record** the activation of the **opposite ventricular** wall. QRS deflection will be **negative** (pathological q waves) oriented towards the wall of the heart having myocardial infarction.[16]

It is a well known fact in ECG, that **T vector** move **away** from the **affected** region. The **QRS** vector move **away** from the **infarcted** or **necrosed** region. The **ST** vector (current of injury vector) move **towards** the **injured** surface. In intra-ventricular conduction defect (duration of the QRS complex is prolonged), the **T vector** move **away** from the **QRS vector** due to the secondary phenomena and do not indicate primary abnormality.[16]

Following the fully evolved phase of acute myocardial infarction, there is a gradual resolution of the abnormalities. This is the **chronic stabilized phase**. Here, the **elevated ST** segment gradually **returns** to the **baseline**, becoming predominantly iso-electric once again. The **inverted T wave** gradually **regains** its **positivity**. Even the **QRS** complex **may regain some** of its previous **positivity**.[16]

From the cardiac vector hypotheses (**($\vec{H}$). (L^)= (OH) COSα),** it is very clear that the voltage recorded will be **positive** if both the vectors are in the **same direction(towards)** and **negative** if both the **vectors** are **moving away** in opposite direction. (Cos value is negative for obtuse angle). If the magnitude of the vector (P,QRS,T, & ST vector) is high, then the voltage recorded will also be high.

The **reversal** of the **leads** and the **misplacement** of the leads is a common but underreported technical error which can hinder proper ECG interpretation.[17,18] The same cardiac vector hypotheses **(Heart-Lead Vector Relationship)** can be applied to explain these errors. For example if the lead is **reversed**, the direction of the **vector is opposite,** so the voltage will be **wrongly recorded** as negative due to the technical error. Similarly, if the **precordial leads** are **not placed** in **correct** position, **magnitude** of the **heart vector** will be different and the voltage recorded will be a **false value** which sometimes mimic pathologies leading to misdiagnosis.

From this research study, it is very clear that **each cardiac waves** (**P, QRS, T& ST)** can be represented in the **form of circles** which denotes that **heart** is at the **centre of the electric field** it generates and the right arm, left arm and left leg are the extensions of its electrical field which was compared by **Einthoven** to a **homogeneous volume spherical conductor** with heart at the centre of the sphere. The already well known vector concept(**axis deviation**) in **ECG interpretation** is applied here. All circles (orientation of the **diameter** representing the **resultant cardiac vector**) should be formed in the left lower quadrant except QRS which can go upto -30 degree. When the **angle** between the '**QRS**' and '**T' circles increases**, it usually denotes ischemia. The voltage will be higher if the size of the circle is larger. Since **ST-segment** is an **isoelectric** period, **no circle** will be formed. The formation of circle and it's magnitude during the ST-segment indicate the amount of **myocardial injury**.

From the results, it is very clear that it is easy to observe the vector direction represented in the form of circles. Only 4 examples of ECG graph with different conditions (1^{st} normal QRS/T angle, 2^{nd} inferior wall ischemia, 3^{rd} inferior wall injury and 4^{th} intra-ventricular conduction defect with wide QRS/T angle) are shown here. But the **same vector principle** (cardiac vector hypotheses and representation of resultant vector in the form of circle) can be **applied** for most of the common cardiac conditions.

Many of the medical students and even most of the specialist doctors find difficult to understand the concept of electrocardiogram.[12] ECG interpretation plays a vital role in emergency conditions. The early diagnosis can reduce the morbidity and mortality of the number one killer disease in the world The quicker and proper interpretation of ECG report will result in saving millions of cardiac patients.

So, the combination of the **12-lead ECG** with this **resultant cardiac vector** represented by **circle** provide the optimum approach to ECG interpretation.

CONCLUSION

Coronary artery disease remains a great threat to the humankind and also poses a major challenge to the scientific community in the 21^{st} century. The concept of Einthoven triangle and cardiac vector hypotheses forms the most important part in the understanding and interpretation of ECG which when properly and quickly applied at the right time for the patient care results in saving millions of lives.

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