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Unlocking the Cardiac Vector Theory and Einthoven Equilateral Triangle Model for an Efficient Teaching Tool in ECG Interpretation

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Abstract:

Introduction: *Electrocardiogram (ECG) has gained indispensable stature in medical field yet competency in ECG interpretation remains challenging for many of the medical students emphasizing the need for an efficient teaching method. Einthoven applied the vector principle to explain the cardiac electrical activity even before a century but never published a complete explanation for the same. The basic principles of vector concepts are not frequently utilized.The vector theory remains controversial, complicated and not widely utilized in clinical practice.The complete relationship between heart vector and lead vector using the* ***Cardiac Vector Theory*** *and explanation for the* ***Einthoven's equilateral triangle Model*** *was given by the* ***current author*** *in previous research articles.*

Objectives: *To discuss in detail the proposed cardiac vector theory for enhanced understanding and clear picture in ECG interpretation which may serve as an efficient teaching tool*

Methods: *The* ***netvoltage*** *recorded by unipolar and bipolar limb lead electrodes are the* ***vertices*** *of an* ***electrical equilateral triangle*** *in the hex-axial reference system which can be converted into circle.*

Results: *Each cardiac wave can be represented in the form of circles. The combination of 12-lead ECG with this resultant cardiac vector represented by circle provides an easier approach to ECG interpretation.*

Conclusion: *Cardiac Vector Theory and Einthoven's Equilateral Triangle Model forms the basic foundation in the understanding and teaching of ECG interpretation.*

Keywords: *Cardiac vector theory, ECG interpretation, Teaching Tool*

1. INTRODUCTION

Electrocardiogram (ECG) has gained indispensable stature in medical field more than a century yet competency in ECG interpretation remains challenging for many of the medical students and junior health care professionals often seeking expert opinion.[1-4] The commonly used pattern memorization method creates ECG phobia and many research studies have emphasized the need for an effective and an efficient teaching method for ECG interpretation to be implemented in their undergraduate studies.[5-10]

The basic principles of vector concepts in ECG are not frequently discussed and utilized.Einthoven applied the vector principle to explain the cardiac electrical activityeven before a century.[6,11,12]InEinthoven's Model, the right arm, left arm and left leg are the vertices of an equilateral triangle with heartat the centreof the homogeneous volume spherical conductor. Voltage recorded in aECGlead is due to the projection of Heart (Cardiac) vector on Lead vector.[1,2,13,14] But he never published a complete derivation and explanation for the same. Many researchers had attempted to solve this problem but resulted in vain. The vector theory remains controversial, complicated and not widely utilized in clinical practice.[15-19] The complete relationship between heart vector and lead vector using the Cardiac Vector Theory and explanation for the Einthoven's equilateral triangle Model was given by the current author in previous research articles.[20-22]

The standard ECG consists of 3 different sets of leads, Bipolar limb leads (I, II and III), Unipolar limb leads (aVR, aVLandaVF) and Unipolar precordial (V1-V6) leads.[1,2,13]Cardiac Vector Theoryproposed by the current author states that voltage measured in a particular lead system (either bipolar limb lead, unipolar limb lead or precordial chest lead) is due to the dot product between the two vectors namely cardiac vector and lead vector. The recorded voltage is a scalar quantity and it depends on both the strength and orientation of the cardiac vector but only on the orientation of the lead vector. Cardiac vector is an electrical field vector (in volt/metre). Lead vector (in metre) denote the orientation of the electrode position only.[20-22] The lead vector also has strength (magnitude) but the relative strength of the 3 different sets of leads can be compared using their correction factor and augmentation factor between the three lead systems.[19-20]

Vector has both magnitude and direction butscalar has only magnitude and no direction.[20]Position vectors represent the location of a moving point. As the point moves, the position vector changes in magnitude and direction. Displacement vector is the change in position vector. It is defined as the vector joining its initial position to its final position whose length is the shortest distance between initial and final point.Displacement and velocity are vectors. Distance, speed and time are scalars.The formation of waves and segments in ECG (P, QRS & T waves; ST, PR & TP segment) are represented by one or multiple position vectors that denote the location of a moving point. As the point moves due to the electrical activity of the heart, the position vector changes in magnitude and direction.[20]

The aim of this present study is to discuss in detail the proposed cardiac vector theory for enhanced understanding and clear picture in ECG interpretation which may serve as an efficient teaching tool in ECG teaching for the undergraduate and junior medical staffs.

2. Materials and Methods

2.1. Hex-axial References System

The relationship between bipolar and unipolar limb lead voltages in the Einthoven Triangle are depicted in the figure 1.Centre of the Hex-axial Reference System is the zero point which denotes the origin. Angle determination can be done by applying tan angleusing the voltage recorded in aVF and lead I (depicted in figure 2).[20,23,24]Correction factor 1.154 is used to correct for the difference in strength (resistance) between the bipolar and unipolar limb leads.[20-22,25]

Tanα = {(1.154 X aVF) / Lead1}

(whereTanα =opposite side/adjacent side in Right angled triangle)

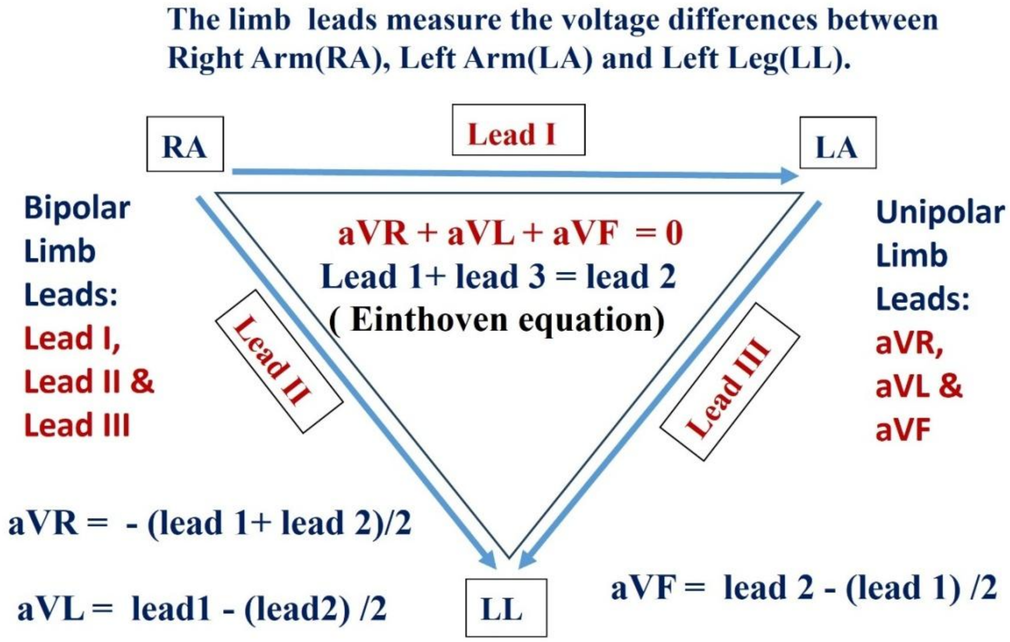

Figure1. *Einthoven Triangle*

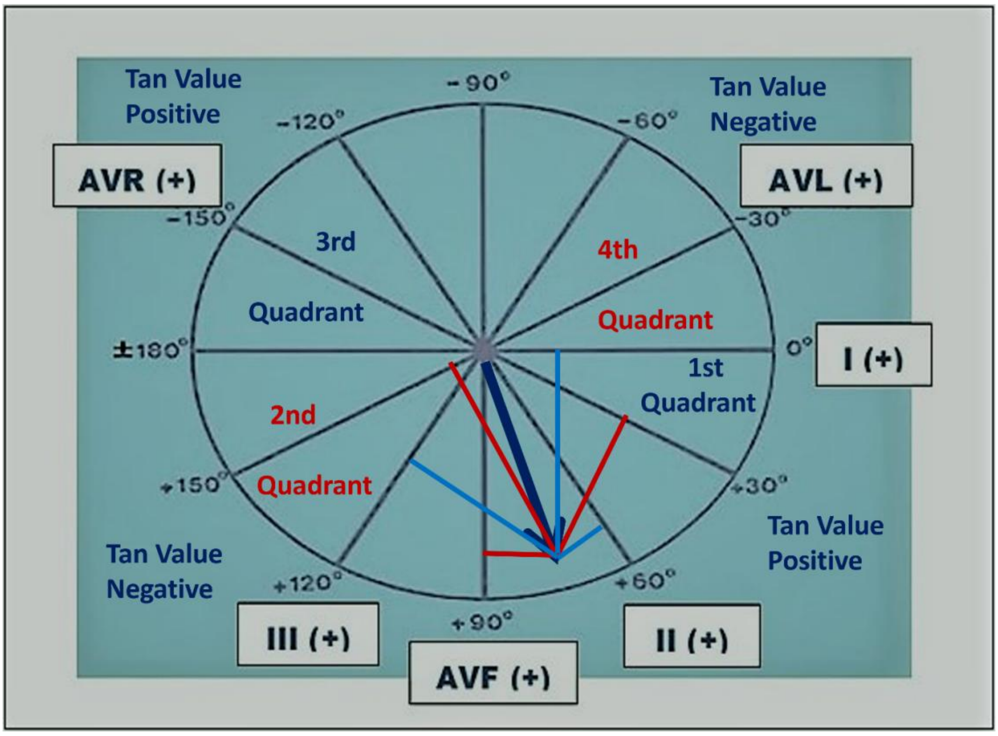

Figure2. *Tan angle determination in Hex-axial reference system*

2.2. Electrical Equilateral Triangle

The heart in zero potential is at the origin in the centre of the hex-axial reference system. This does not denote the Wilson's central terminal. The heart acquires certain potential during depolarization and repolarization. The net voltage recorded by the Bipolar limb lead electrodes (Lead I, II, III) and unipolar limb lead electrodes (aVR, aVLandaVF) plotted in any of the 4 quadrants of the hex-axial reference system form two equilateral triangles and it can beconverted into circles (shown in figure 3).

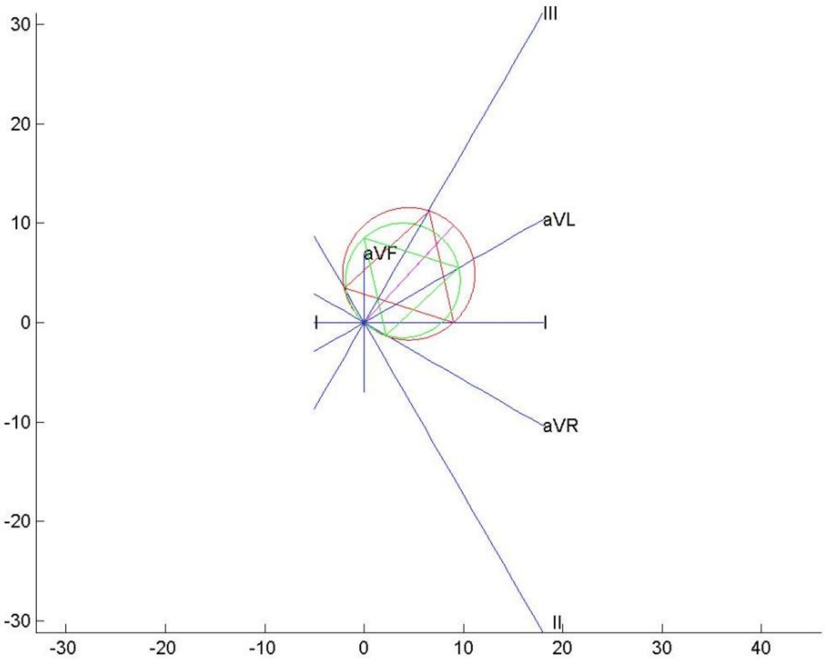

Figure3. *2 Electrical Equilateral Triangles on 2 Circles*

Both the circles have same origin, same orientation, but with different radii because bipolar and unipolar limb leads have different resistance. The ratio of their resistance is 4/3.The square root of 4/3 is 1.154. Multiply each unipolar limb lead voltages by correction factor 1.154 and then plot. Then the two equilateral triangles are on the same circle (shown in figure 4). Each cardiac wave can be represented in the form of circles. The diameter of the circle denotes the resultant cardiac vector. The circumference of the circle denotes the electrical field of the heart with heart at the center of the circle. The right arm, left arm and left leg are the extensions of its electrical field and vertices of an electrical equilateral triangle which was compared by Einthoven to a homogeneous volume spherical conductor with heart at the centre of the sphere.

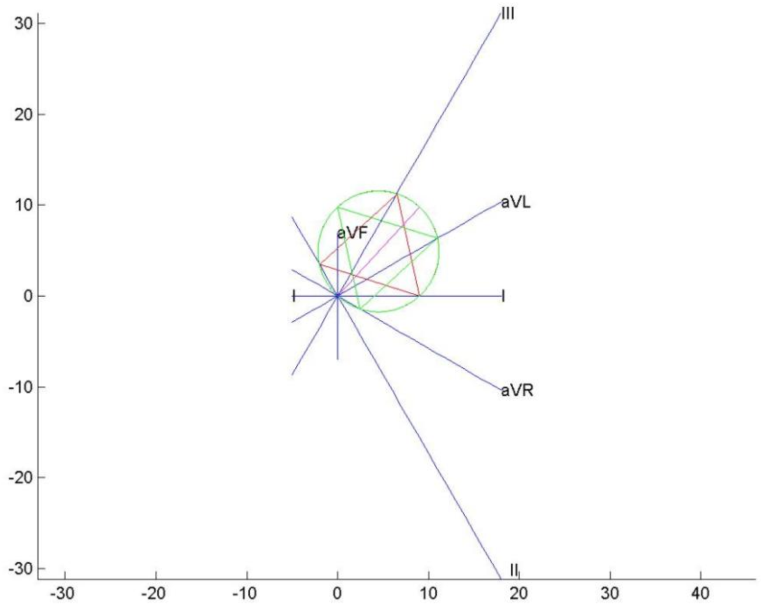

Figure4. *2 Electrical Equilateral Triangles on 1 Circle*

2.3. Lead Vector Concept

The bipolar limb lead has higher resistance than unipolar limb leads so the correction factor 1.154 is used to compare theirrelative strength.The augmentation is 3/2(or 50%higher) for UnipolaraVR, aVL and aVF leads recorded through the changing Goldberger's Central Terminal (GCT) compared with Unipolar precordial (V1-V6) leads recorded through the stable Wilson's Central Terminal(WCT). If the strength for the unipolar limb lead is taken as one, then the strength of Bipolar limblead is multiplied by 1.154(correction factor) and the strength of unipolar precordial lead is multiplied by 2/3 (or 50% lower than the unipolar limb lead).[1,20,25,26]

Vector = Vector's magnitude x Unit Vector

(O L$^{\rightarrow}$) = (OL)(OL^);

(OL^): Unit vector (has **no unit** and denotes direction only)

(O L$^{\rightarrow}$): This vector has **unit measured in meter**.

If the magnitude (OL) of this vector is taken as one, then (O L$^{\rightarrow}$) = 1x(OL^)

This Lead vector (O L$^{\rightarrow}$) is a unit vector multiplied by magnitude of one, so it is measured in meter and it denotes the orientation of the electrode. The relative strength of the 3 different set of leads can be compared using the correction and augmentation factor.[20]

2.4. Projection of Heart Vector on Lead Vector

The projection of Heart vector (OH$^{\rightarrow}$ or h$^{\rightarrow}$) on Lead vector (OL$^{\rightarrow}$ or l$^{\rightarrow}$) is shown in the figure 5.If two vectors are multiplied and the product is a scalar quantity, then it is called as scalar or dot product. It is equal to the product of the magnitudes of the two vectors and the cosine of the smallest angle between them.[20-22]

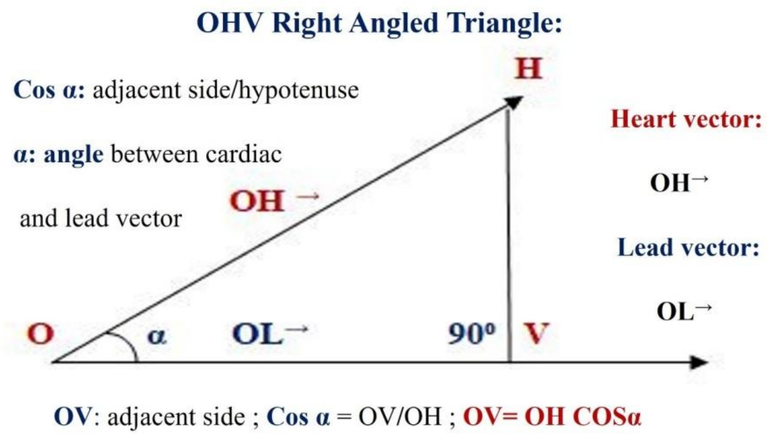

Figure5. *Projection of heart vector on lead vector*

2.5. Formulation of Cardiac Vector Theory

$$(OH^{\rightarrow}).(OL^{\rightarrow}) = (OH)(OL)\cos\alpha$$

The magnitude (OL) of this vector is taken as one and their relationship [(O L→) = 1x(OL^)] is substituted, the following is obtained.

$$(OH^{\rightarrow}).(OL\hat{}) = (OH)\cos\alpha \quad \text{OR}$$

$$(h^{\rightarrow}).(l\hat{}) = (OH)\cos\alpha$$

Cardiac Vector Theory states that voltage recorded in a particular lead system depends on both the magnitude(strength) and direction(orientation) of the cardiac vector but only on the direction(orientation) of the lead vector. The 3 different lead system can be compared using their relative strength of the vectors.

If the magnitude of heart vector (P, QRS, T, &ST vector) is high, the voltage recorded will be high and vice versa. From the cos angle values(cos0º: 1;Cos30º: 0.866 or √3/2; cos45º: 0.707 or 1/√2; cos60º: 0.5 or ½; cos90º: 0; cos value negative for obtuse angle) it very clear as the angle α between cardiac and lead vector increases, the voltage recorded in that particular lead will decrease & vice versa. If a cardiac vector is parallel to a particular lead the ECG will record the maximum deflection (cos0º is 1)on that lead. If a cardiac vector is directed perpendicular (90°) to a particular lead, the net impression on that lead will be either equiphasic or a null deflection (Cos 90º is zero).The voltage recorded will be positive if both the vectors are in the same direction and negative if both the vectors are moving away in opposite direction. (Cos value negative for obtuse angle).[20-22]

3. Results

The relationship between Bipolar and Unipolar Limb Lead Voltages are applied. The net voltagesin mm in each leadwere taken from respective ECGand shown in tables1and 2. Cardiac circles were constructed using MATLAB software and shown in the figures 6,7,8,9 and 10. The P, QRS,ST and Tvector circle between two different ECG were compared and the resultant vector was magnified,focussedand shown in same figure for better appreciation of the changes.

Table1. *Net Lead Voltages of Normal & Abnormal P/QRS/T Angle (from figures 6 &7)*

Vector	Net Voltages in mm in each lead taken from respective ECG						Angle
	LI	LII	LIII	aVR	aVL	aVF	
Normal QRS/ T ANGLE							
QRS	6.5	2.0	- 4.5	- 4.25	5.5	- 1.25	- 12.5°
T	2.0	2.25	0.25	-2.125	0.875	1.25	35.80°
QRS/T	QRS and T vector are directed within normal (Normal upto 60°)						48.30°
Abnormal QRS/ T ANGLE							
Left Bundle Branch Block							
QRS	9.0	- 4.0	-13.0	-2.5	11.0	- 8.5	- 47.46°
T	-0.66	2.66	3.32	-1.0	-2.0	3.0	100.8°
QRS/T	T vector moving away from QRS Vector: **Wide QRS/T angle**						148.26°
P wave of Normal axis or angle							
P	0.833	1.667	0.830	-1.25	0	1.25	60°
Retrograde P wave							
P	0	-2.5	-2.5	1.25	1.25	-2.5	270°

Table2. *Net Lead Voltages of Abnormal QRS, ST and T vector (from figures 8,9 and 10)*

Vector	Net Voltages in mm in each lead taken from respective ECG						Angle
	LI	LII	LIII	aVR	aVL	aVF	
ABNORMAL QRS							
	Abnormal QRS Vector (Left Anterior Fascicular block)						
QRS	2.0	- 1.0	- 3.0	- 0.5	2.5	- 2.0	- 49.0°
INFARCTION							
	Pathological Q wave (Lateral Wall Old Infarct)						
QRS	-1.0	3.0	4.0	-1.0	-2.5	3.5	103.91°
INJURY							
ST	ST Elevation in aVR (Subendocardial Injury)						
	-1.25	-1.0	0.25	1.125	- 0.75	- 0.375	- 160.91°
	ST Elevation in II, III &aVF (Inferior Wall)						
	- 0.8	1.8	2.6	- 0.5	- 1.7	2.2	107.50°
ISCHEMIA							
T	T wave Inversion in I, aVL (Lateral Wall Ischemia)						
	- 2.0	- 0.5	1.5	1.25	- 1.75	0.5	164°
	T wave Inversion in III, aVF (Inferior Wall Ischemia)						
	4.83	1.67	- 3.16	- 3.25	4.0	- 0.75	- 10.15°

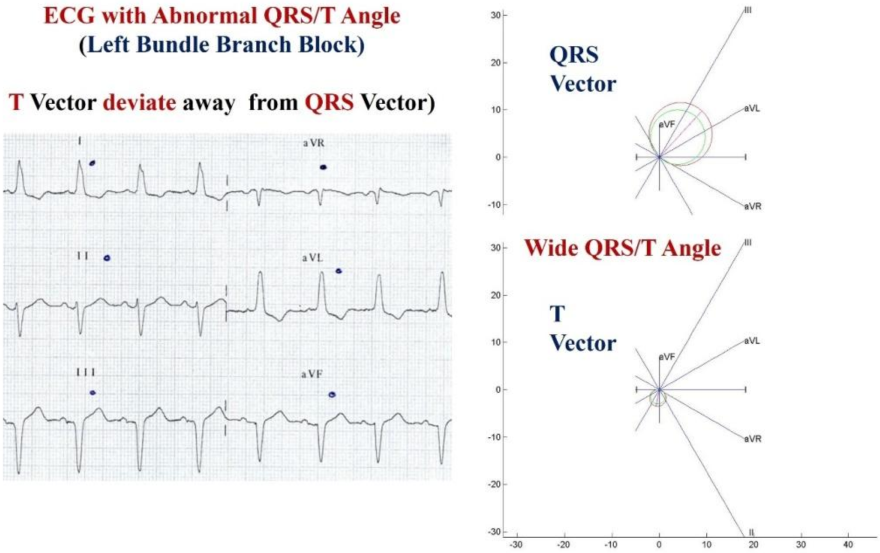

Figure6. *ECG of Left Bundle Branch Block with abnormal QRS/T angle*

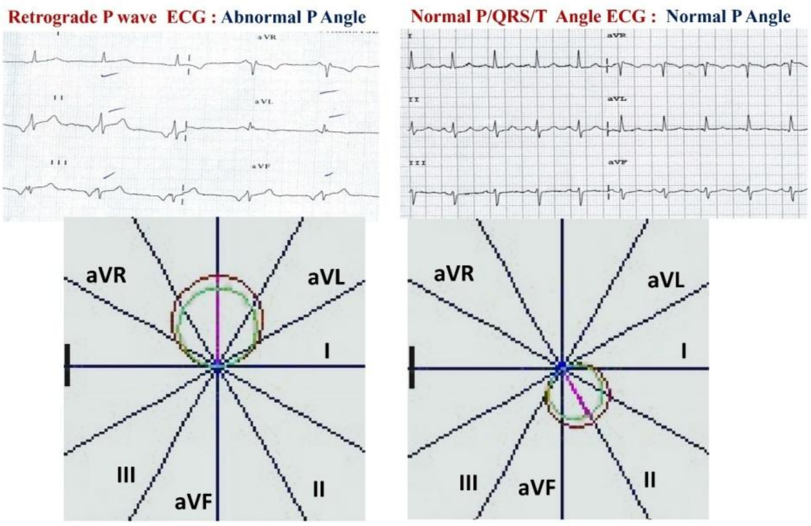

Figure7. *Comparison of Retrograde P vector with Normal P vector axis*

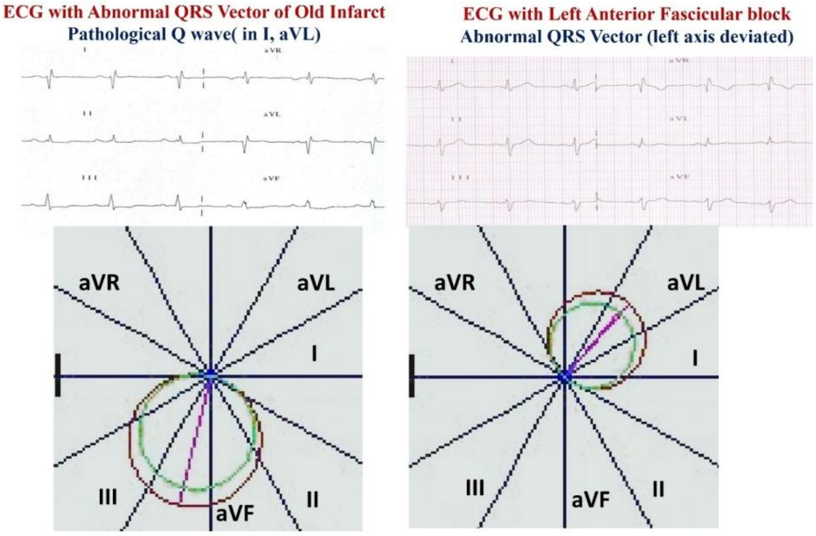

Figure8. *Comparison of QRS vector of Old lateral wall infarct with Left anterior fascicular block*

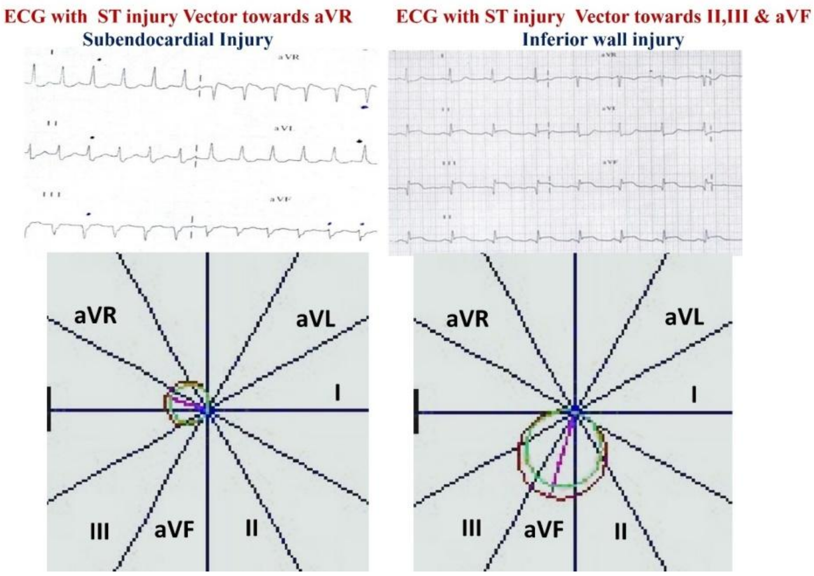

Figure9. *Comparison of ST Vector of Subendocardial Injury with Inferior Wall Injury*

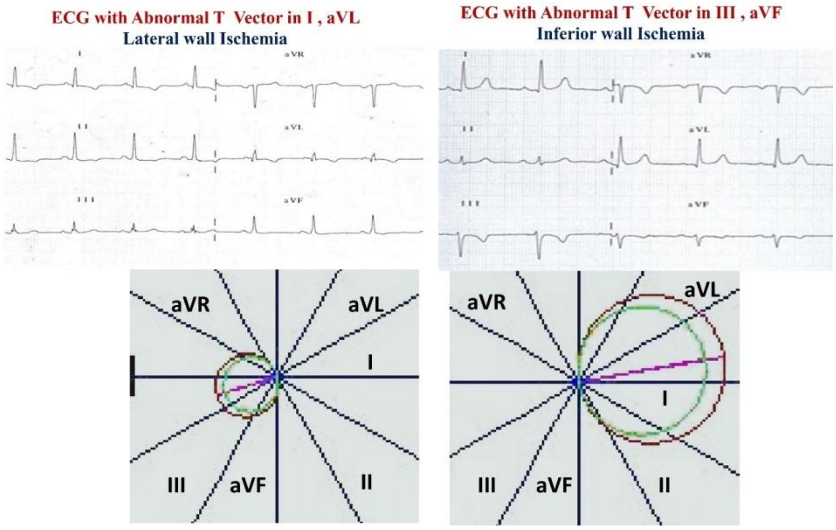

Figure10. *Comparison of T Vector of Lateral Wall Ischemia with Inferior Wall Ischemia*

4. DISCUSSION

The formation and changes inECG wavesin different cardiac diseasescan be easily explained using cardiac vector theory.ECG waves in the unipolar leadaVR will be usually negative because heart vector is moving away from the electrode placed.[20] If the lead is reversed, the direction of the lead vector is changed, so there will be variation in the voltagerecorded (either positive or negative) in that leads due to the technical error. Similarly, if the precordial leads are placed in improper position, the relationship of heart vectorwith lead vector will change producing a false value that may resemble some abnormality resulting in misinterpretation.[20,27,28]

The velocity of the Cardiac Vector is related with time in the Xaxis of ECG. If the conduction velocity of the cardiac vector is lower or the distance travelled by the vector is increased (Eg. any Enlargement or thickness) it results in prolonged duration of ECG intervals or wider waves(shown in figure 6). The ECG intervals will be shortened if the cardiac vector velocity is increased or the distance travelled by the Vector is shortened (Eg.any Bypass Route or Accessory Pathway).[29-30]

The electrical impulses from the SA node spreads and activates the atrial chamber longitudinally.A retrograde P wave is due to an abnormal conduction (shown in figure 7). After a delay at the AV node, supraventricular impulse is transmitted by specialized conduction system very rapidly to the ventricleswhich is activated transversely. Activation of the interventricular septum is then followed by activation of the free walls of both ventricles which occurs transversely from subendocardial to subepicardial regions.[23] The figure 11clearly depicts the resultant septal vector and resultant vector of free wall of both ventricles.

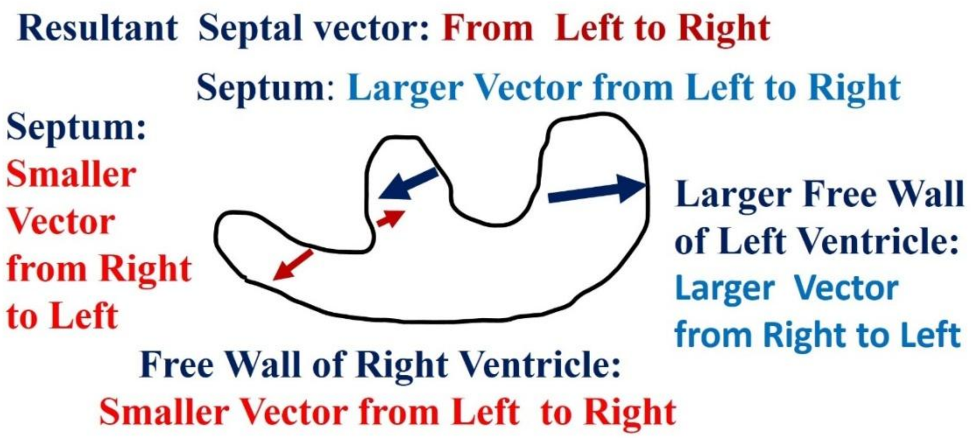

Figure11. *Vector Analysis of the Ventricles with their septum*

The leads oriented to the right ventricle (right oriented leads V 1 or V 2) reflect rS complexes due to small resultant septal vector(r wave) and large resultantvector of free wall of left ventricle(S wave). The leads oriented to the left ventricle (left oriented leads I, V4,V5 & V6) reflect qR complexes due to small resultant septal vector(q wave) and large resultant vector of free wall of the left ventricle(R wave).[20,23]The multiple movements of the positionvectors of these complex will change shape and size of ECG waves in hypertrophy and bundle branch block. 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 (shown in figure 6).[20,23]

QRS vector denotes the ventricular depolarisation. In myocardial infarction, the necrosedtissue is electrically inert and is called electrical hole. So, 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.[20,23] The QRS vector move away from the infarcted or necrosed region(shown in figure 8).

The displacement of ST segment (either elevation or depression with reference to the isoelectric line) is clinically the most important part of ECG. The position vectors change the shape and slope of ST segment. The displacement vector denotes the difference between the initial (J point) and final point (merging with T wave).ST segment is an iso-electric period in the ECG. When the myocardium of the heart is injured, it results in leakage of current called as the current of injury vector (ST vector) which move towards the injured surface.[20,23]

If the current of injury vector (direction of the vector is from endocardium to epicardium) are oriented towards inferior leads(II, III,aVF) it results in positive deflection (ST elevation) in that particularlead. Reciprocal ST-depression will be seen in the leads (I,aVL) oriented awayfrom the current of injury vector (shown in figure 9).Similarly, the ST vector deviation can be applied to explain the myocardial injury of the other walls of the heart.[20,23,31] Insubendocardial injury, ST-depression is present, because the direction of the current of injury vector is from epicardial to endocardium.This is opposite to those associated with transmural or subepicardial infarction(shown in figure 9). The subendocardial injury can result in ST elevation in leadaVR.[31]

In normal ECG the T waves and QRS waves are similarly directed. More blood is needed to repolarize than to depolarize, so during ischemia the resultant Tvector is deviated away from the affected region. If the leads are oriented towards thisischemic region, it results in negative deflexion indicating T wave inversion. If the cardiac vector is moving away from the inferior leads (either in L III (120º) &aVF(90º) or in L III (120º), aVF(90º) & L II(60º), resultant T vector will deviate and getsshifted to other quadrant (0º to -90º) denoting inferior wall ischemia. If the cardiac vector is moving away from the lateral leads (aVL(-30º), LI(0º)), resultant T vector will deviate and gets shifted to the next quadrant (90º to 180º) denoting lateral wall ischemia (shown in figure 10). Similarly, thevariations in magnitude and direction of T wave in precordial leads can be explained to represent the anteroseptal Ischemia and apical or lateral wall ischemia.[20,23]

Each cardiac waves (P, QRS, T& ST) can be represented in the form of circles in the Hex-axial reference system.Normal QRS Vector axis is from -30° to 90°. Normal T wave axis is between 0° and 90°(left lower quadrant :1st quadrant). The normal QRS/T angle does not exceed 60° in the frontal plane.[23]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- 30º degree. Theincreasedangle between the 'QRS' and 'T' circlecan indicate strain, abnormal electrical conduction and ischemia. The size of the circle indicates the voltage recorded. ST-segment is an isoelectric period, so circle will not be seen during this period. If the myocardium is injured, it can generate a resultant ST circle vector whose magnitudeindicate the amount of myocardial injury.Thevector principle can be applied to interpret most of the common cardiac diseases.[20,21] The understanding of the cardiac vector concept will make ECG interpretation much quicker and easier that helps to overcome the arduous task of pattern memorization method.

5. Conclusion

Coronary artery disease continues to remain as the number one killer disease of the world. The understanding of Cardiac Vector Theory and Einthoven's Equilateral Triangle Model forms the basic foundation in the teaching of ECG interpretation So, the combination of the 12-lead ECG with this resultant cardiac vector represented by circle provide the optimum and easier approach to ECG interpretation resulting in saving countless lives of patients.

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