Main normal and pathological electro-vectordiographic aspects of the atria

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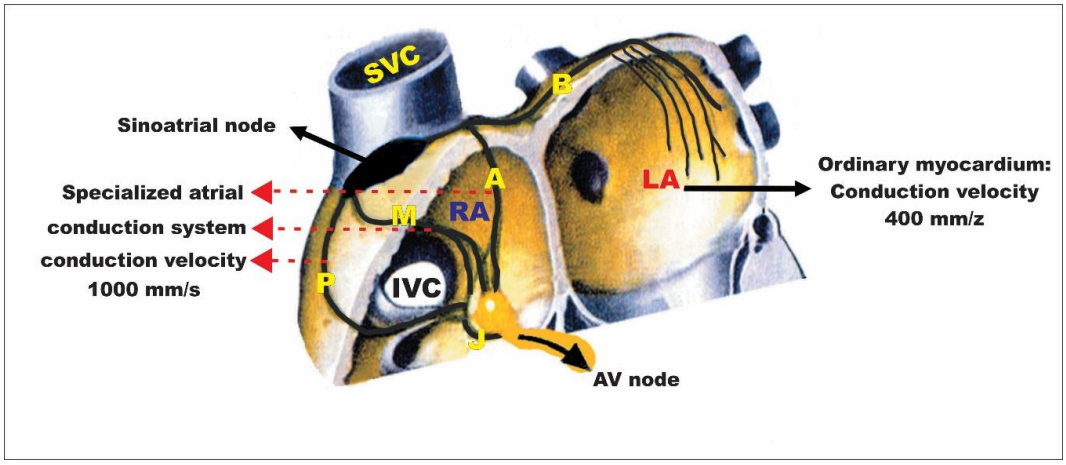
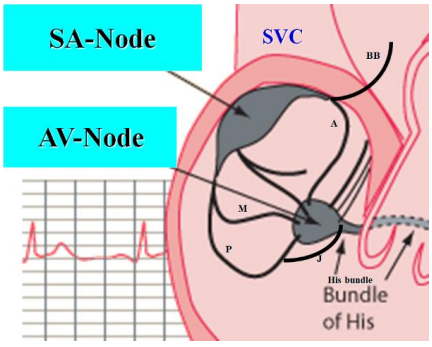
Mode of atrial depolarization: hypothesis A: preferential pathways (James 1971)

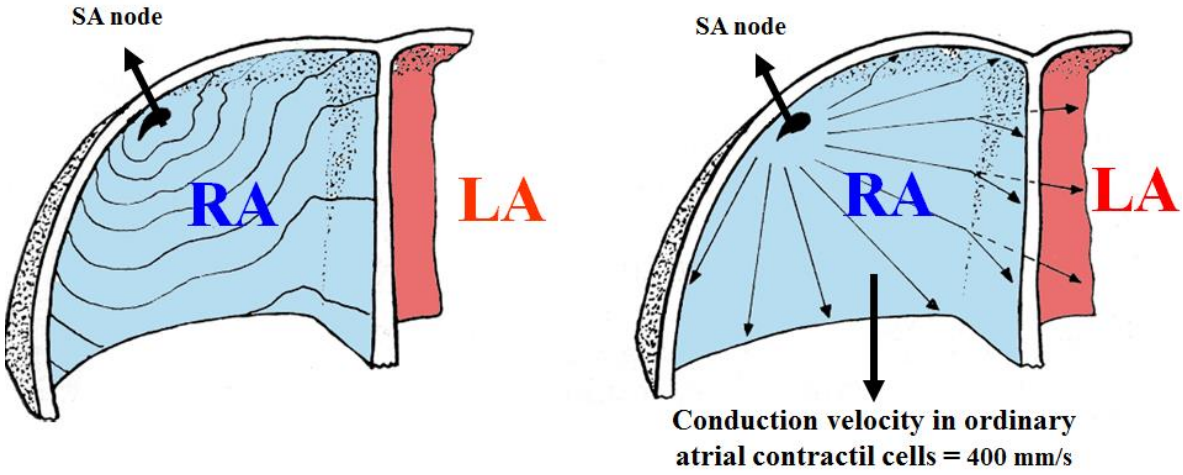
In the following two figures we can see the representation of the currently accepted mode of atrial activation. The stimulus originates in the SA node and is conducted up to the AV node through three preferential pathways: anterior, middle and posterior. The left atrium activates by a branch of the Bachman's anterior internodal bundle. These preferential pathways are formed by Purkinje cells, which make conduction velocity be greater (1 m/sec) in relation to the atrial muscle (400 mm/sec). In the Thorell's posterior internodal bundle a branch originates, which ends directly in the proximal area of the His bundle: James' bypass bundle.





A - Anterior internodal bundle ; M – Middle internodal bundle; P - Posterior internodal bundle; BB – Bachman's bundle; J - James's tract.

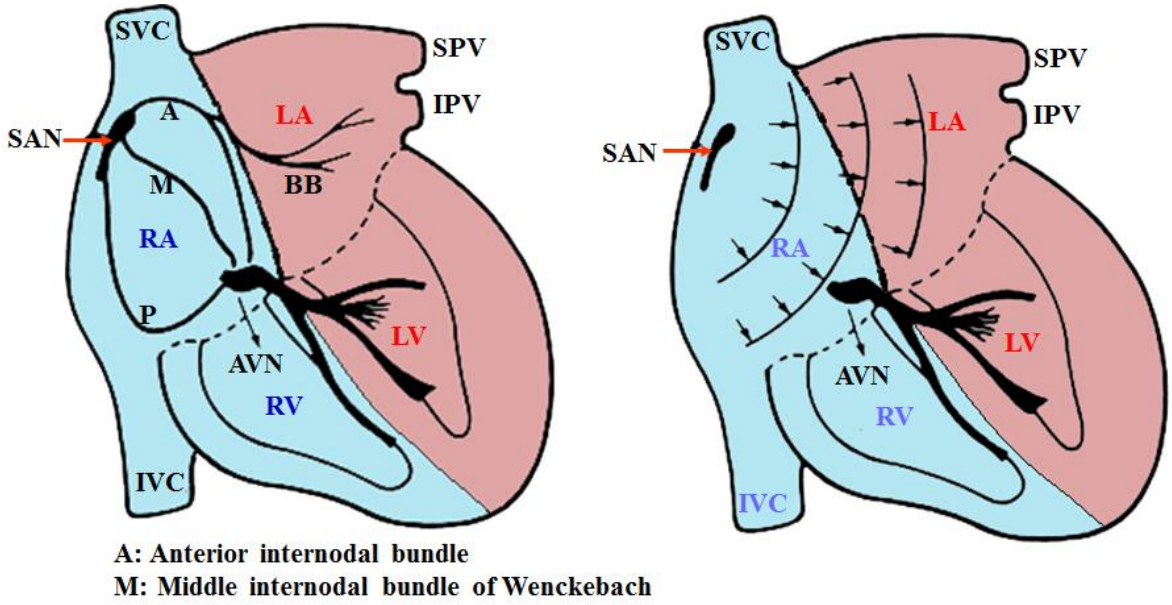
Hypothesis B – The activation wave spreads in a radiated way through the atria, just as the waves in a lake when you throw a stone in it.



Outline representation of an old concept of biatrial activation. It was believed that it was processed in a radiated way, as when a stone is thrown in calm water.

Comparison between two theories of biatrial chamber activation

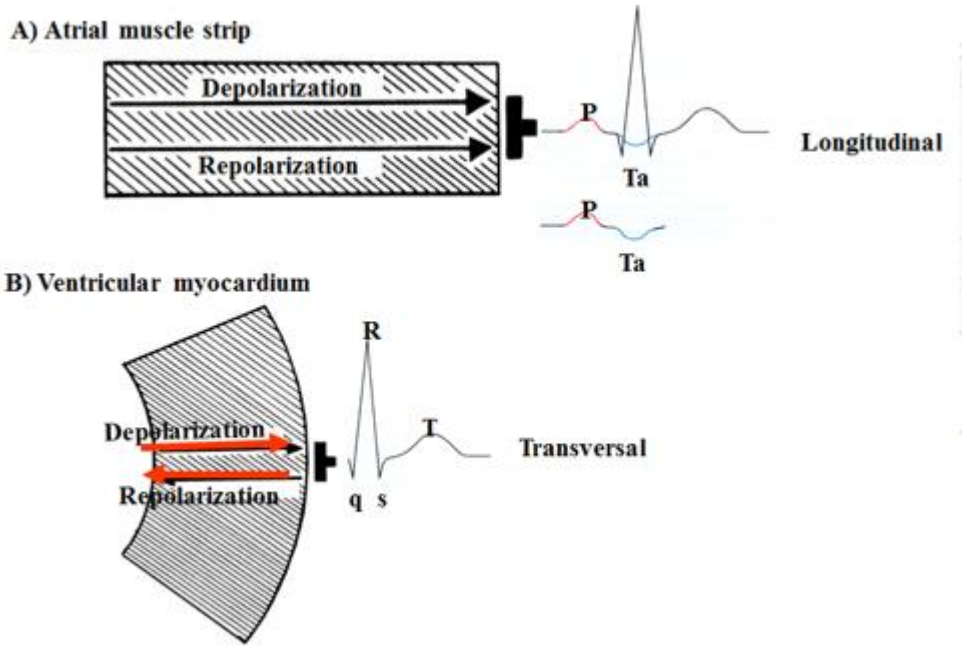
Hypothesis A **Hypothesis B**



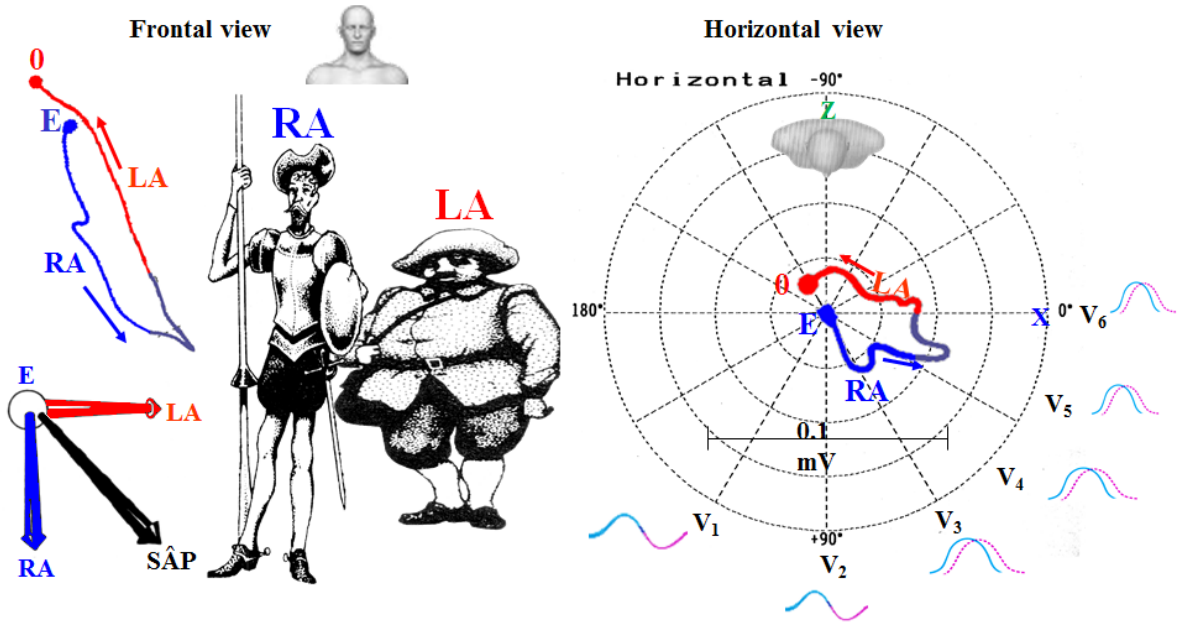
A: Anterior internodal bundle
M: Middle internodal bundle of Wenckebach

Bachman bundle Bachman fascicle, also knowns as the anterior interatrial band is the only track that conveys impulses to the left atrium (Bachman 1916)

Comparison of mode of atrial (A) & ventricular (B) depolarization & repolarization



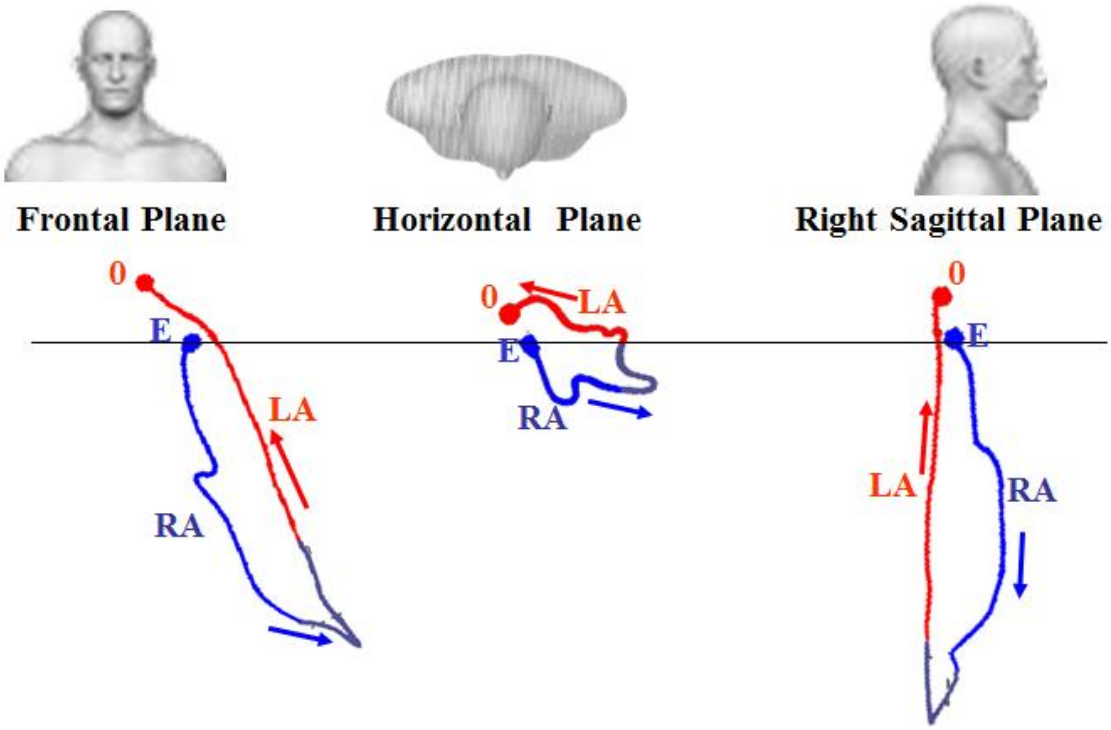
Spatial outline of biatrial chamber activation in both planes: the FP and HP



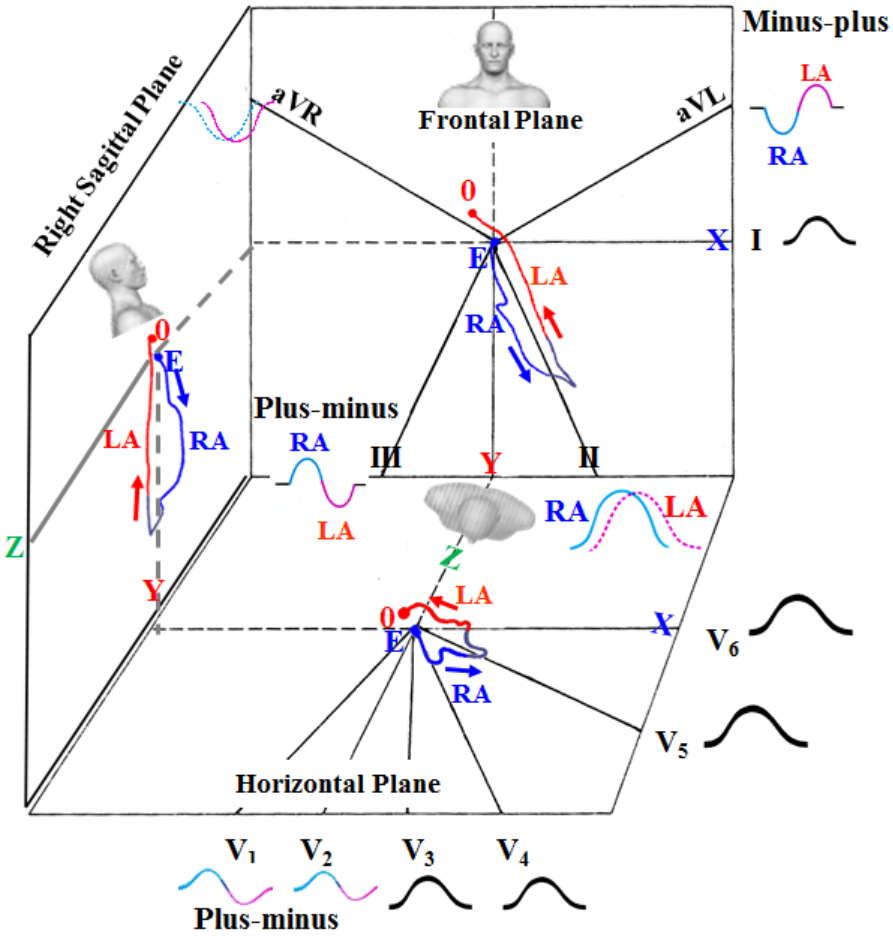
RA - "Don Quixote of la Mancha". In the front & to the right; LA - "Sancho Panza". In the back and to the left. **E** point: it constitutes the zero point of VCG and it remains stationary before the onset of the P loop. It corresponds to the isoelectric line between the T wave and the P wave of ECG. The **E** letter corresponds to the cardiac dipole. It is the beginning of the P loop and ends in the so-called **0** point.

The P loop has small voltage corresponding to the depolarization of the biatrial chamber. The initial part corresponds to the right atrium (**RA**) (between 0 and 70 ms), next the interatrial septum (between 20 and 45 ms), and finally the left atrium (**LA**) (between 30 and 90 ms). To make an analysis possible, it is necessary to amplify: 1 mV = 30 cm. The P loop begins in the **E** point and ends in the so-called **0** point. The former has an anterior and inferior location in relation to the latter. The P loop is open because atrial repolarization (Tp loop) is diametrically opposite to the P loop.

Normal P loops shape in the three planes



Normal P loops and P waves projected in the FP, HP and RSP



Normal P-wave of the ECG and normal P-loop of the VCG

The P wave is the first wave of ECG that represents the depolarization wave of the biatrial chamber.

Items to be analyzed:

I) **Normal polarity of the P wave: P-axis**
II) **Voltage or amplitude**
III) **Duration**
IV) **Morphology (aspect or shape)**
V) **P-wave dispersion**

I) Normal polarity of the P wave

In the frontal plane (FP) P wave is always positive in II, I and aVF, always negative in aVR, and variable in III and aVL. In III it could be plus-minus, negative or positive. In aVL it could be minus-plus, positive or negative.

In the Horizontal plane (HP) P wave is always positive from V3 to V6 and variable in V1-V2: positive or plus-minus.

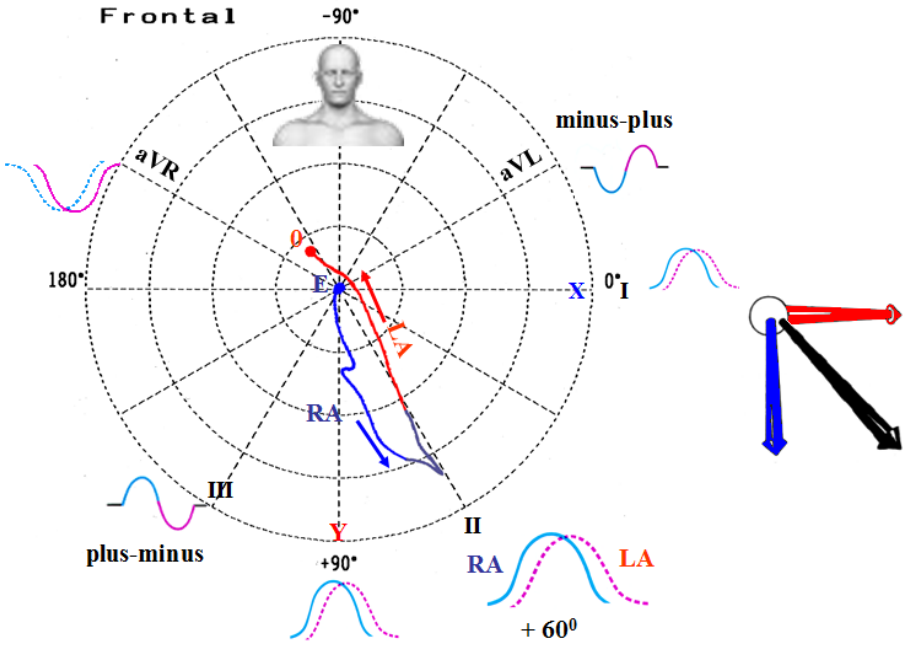
Positive P-wave: 

Negative P-wave: 

Positive-negative or "plus-minus" ± P-wave: 

Negative-positive or "minus-plus" P-wave: 

P-wave polarity and P-loop in the Frontal Plane



P wave polarity is always negative in aVR, always positive in II, I and aVF, and variable in III and aVL. Normal P wave axis is between 0° and +75°.

III could be plus-minus and aVL minus-plus

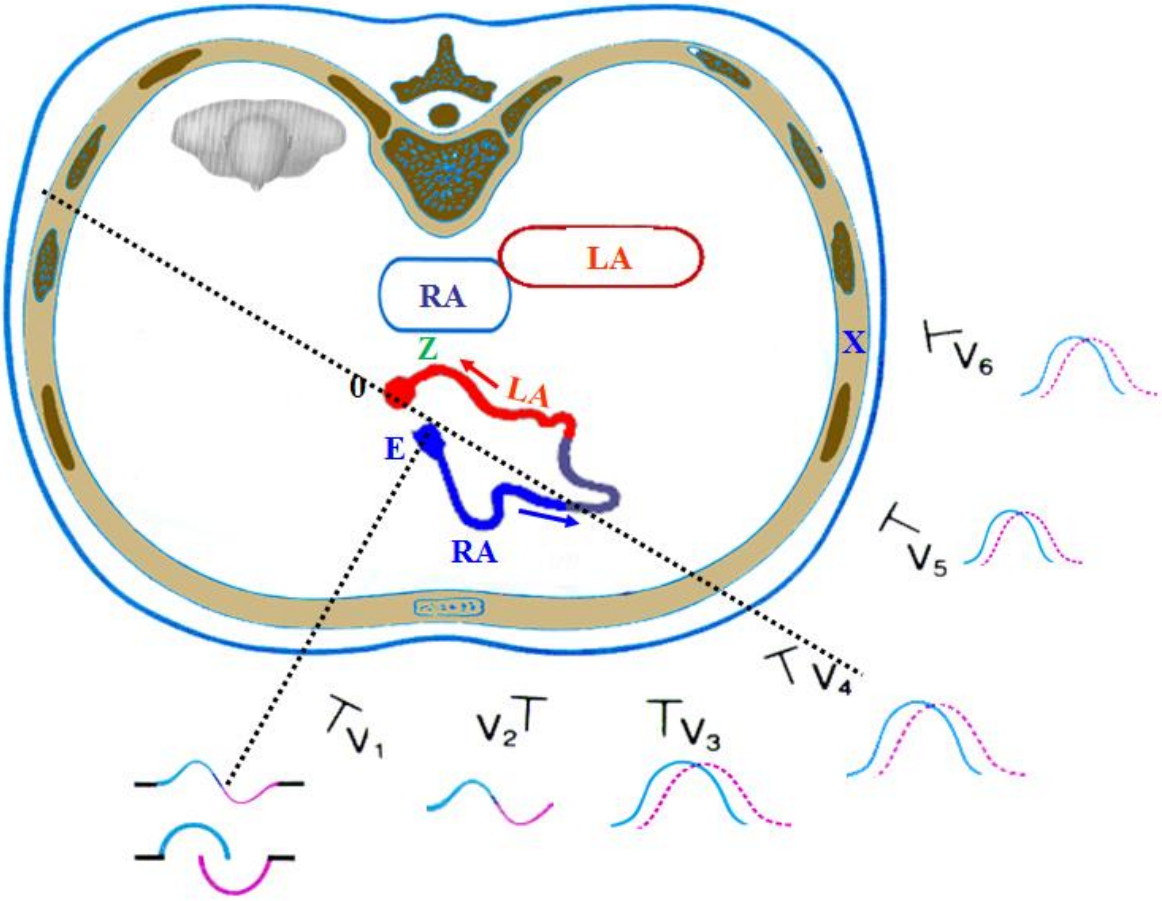
The P-loop begins in the E point located below and to the left of the 0 point.

P-loop ends in the 0 point.

Recently, Rangel et al observed that P-wave axis deviation is associated with atrial fibrillation (AF). The authors examined the association between abnormal P-wave axis and AF in 4,274 participants (41% men and 95% white) from the Cardiovascular Health Study. Axis values between 0° and +75° were considered normal.

AF cases were identified from study ECGs and from hospitalization discharge data. During a median follow-up of 12.1 years, a total of 1,274 participants (30%) developed AF. Abnormal P-wave axis was associated with a 17% increased risk of AF after adjustment for age, gender, race, education, income, smoking, diabetes, CAD, stroke, heart failure, heart rate, systolic blood pressure, body mass index, total cholesterol, HDL-C, antihypertensive medications, aspirin, statins, and abnormal P-wave axis, is associated with an increased risk of AF. This finding suggests a potential role for P-wave axis in AF risk assessment (**Rangel 2015**).

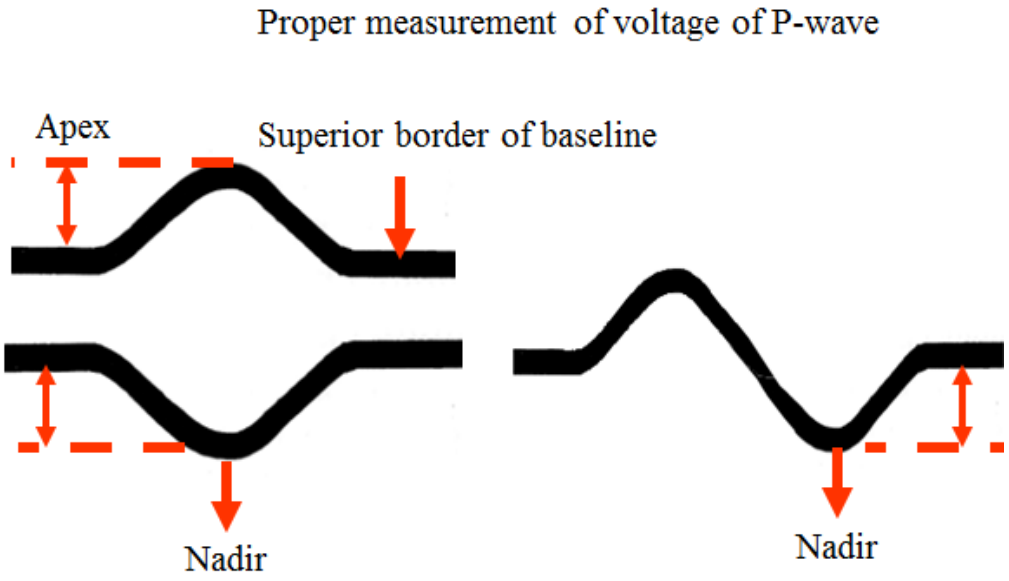
Representation of normal P loop/P wave of biatrial chamber in the HP



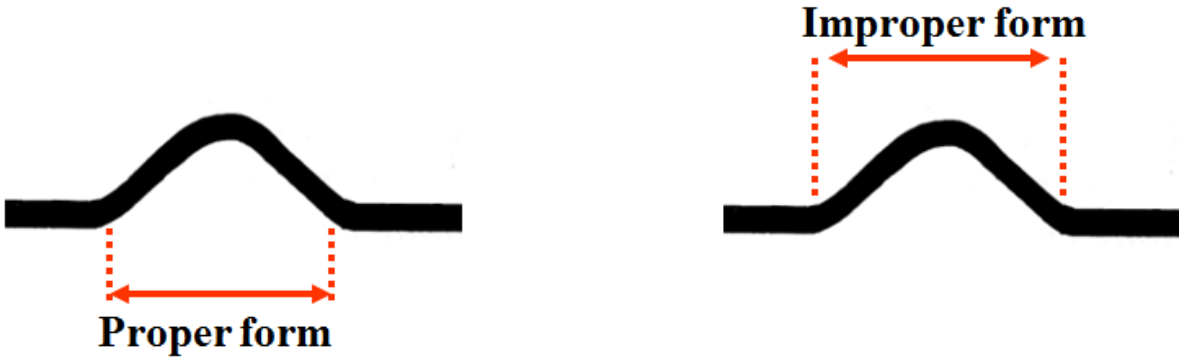
The P wave is always positive from V3 to V6 and eventually plus-minus in V1-V2

II) Normal P-wave voltage or amplitude

Since 1935, it is admitted that the normal maximal value of P wave voltage or amplitude is 2.5 mm, within the range of 0.5 mm to 2.5 mm (or 0.05 to 0.25 mV). However, this value has been questioned by Asad et al, because of low sensitivity in patients carriers of COPD, who suffer frequent exacerbations of pulmonary decompensation. Both the amplitude and the direction of the vector of the P wave are dynamic and may reflect the stress of the right atrial wall or "**RA** strain" **(Asad 2003).**

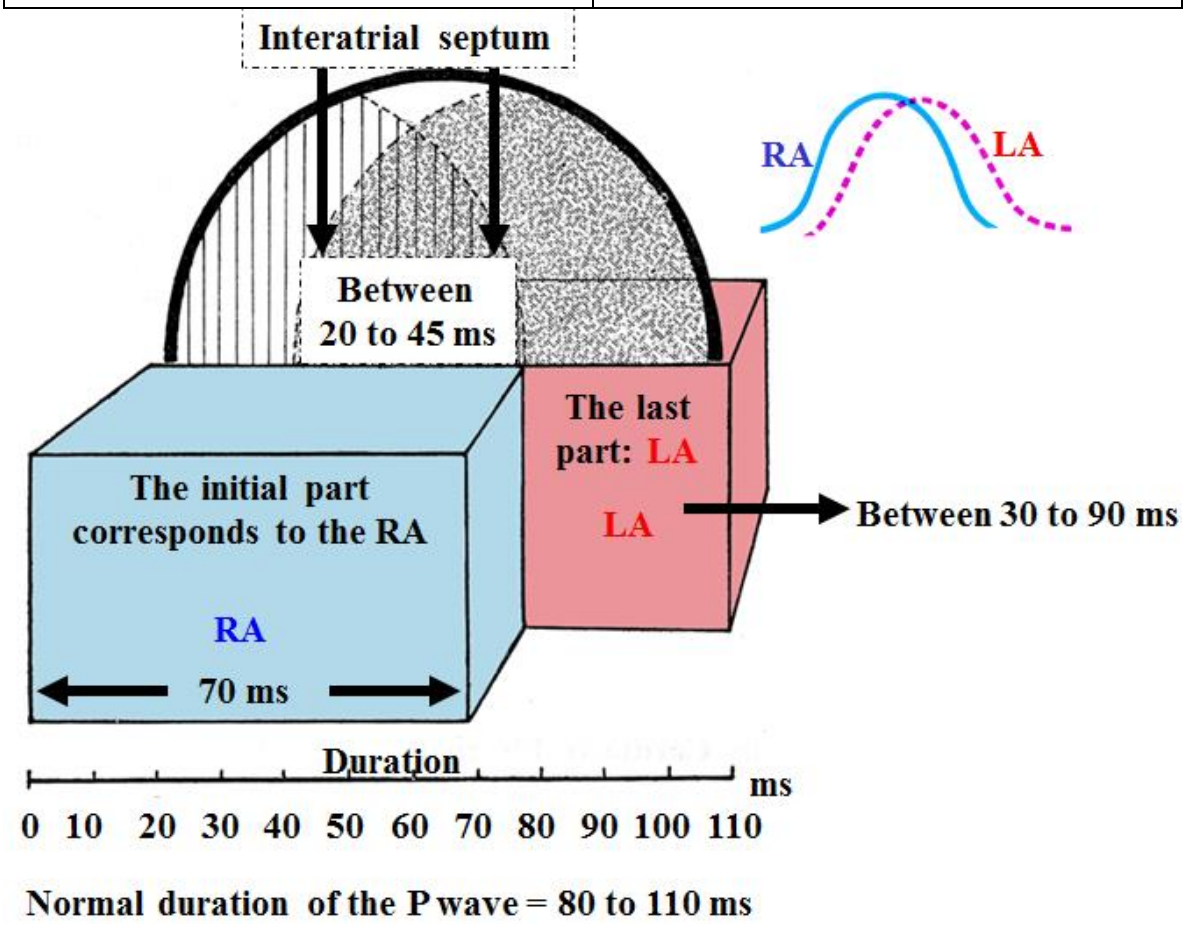


III) Normal P-wave duration and measurement



Normal P duration according to age

Age range	Normal maximal value of P-wave
0 to 12 Month	80 ms(2 little square)
1 to 12 years	90 ms
>12 years	100 ms
Seniors	110 ms



Long-term risk prediction is a priority for the prevention of AF. P wave indices are ECG measurements describing atrial conduction. The role of P wave indices in the prospective determination of AF and mortality risk has had limited assessment. Magnani et al quantified by digital caliper the P wave indices of maximum duration and dispersion in 1,550 Framingham Heart Study participants ≥ 60 years old (58% women) from single-channel ECGs recorded from 1968 through 1971. The authors examined the association of selected P wave indices and long-term outcomes using Cox proportional hazards regression

incorporating age, gender, body mass index, systolic blood pressure, treatment for hypertension, significant murmur, heart failure, and PR interval. Over a median follow-up of 15.8 years (range 0 to 38.7), 359 participants developed AF and 1,525 died. Multivariable-adjusted hazard ratios (HRs) per SD increase in maximum P wave duration were 1.15 (95% confidence interval [CI] 0.90 to 1.47, p = 0.27) for AF and 1.02 (95% CI 0.96 to 1.08, p = 0.18) for mortality. The upper 5% of P wave maximum duration had a multivariable-adjusted HR of 2.51 (95% CI 1.13 to 5.57, p = 0.024) for AF and an HR of 1.11 (95% CI 0.87 to 1.40, p = 0.20) for mortality. The authors found no significant associations between P wave dispersion with incidence of AF or mortality. In conclusion, maximum P wave duration at the upper fifth percentile was associated with long-term AF risk in this elderly community-based cohort. P wave duration is an ECG endophenotype for AF (**Magnani 2011**).

IV) Normal P-wave shape

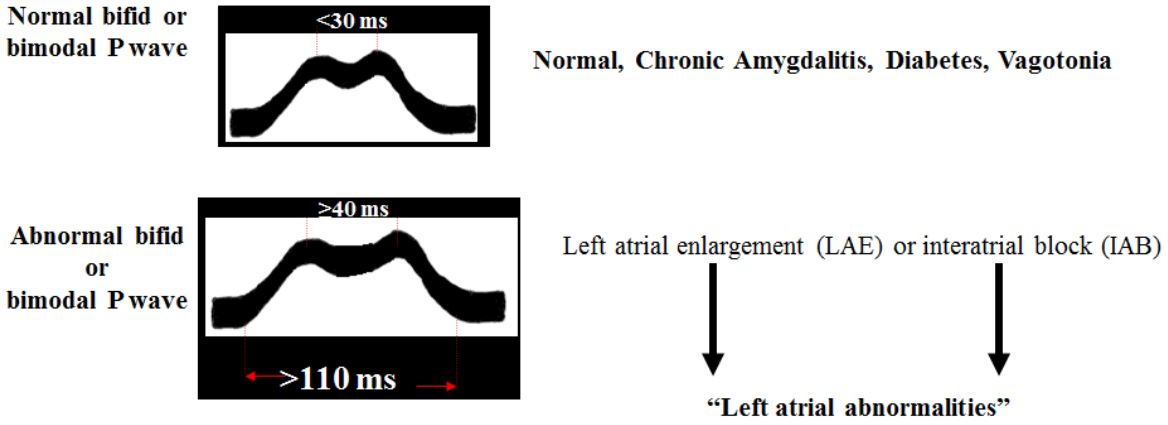
Norma P-wave shape is rounded and monophasic. Sometimes is bimodal: The factors that determine P-wave shape are:

I) The origin of the sinus rhythm that defines right atrial depolarization vector,
II) Localization of left atrial breakthrough that defines left atrial depolarization vector, and
III) The shape and size of atrial chambers.

Unfortunately, it is often difficult to distinguish whether P-wave abnormalities are caused by atrial enlargement or IAB. Recent advances in endocardial mapping technologies have linked certain P-wave morphologies with interatrial conduction patterns and the function of major interatrial conduction routes. The value of P-wave morphology extends beyond cardiac arrhythmias associated with atrial conduction delay and can be used for prediction of clinical outcome of a wide range of cardiovascular disorders, including ischemic heart disease and congestive heart failure (**Platonov 2012**).

Abnormal P-wave morphology was found to be independently predictive of non-sudden cardiac death and AF development (**Holmqvist 2010**).

A P wave signal-averaged ECG can predict the risk for new onset of AF in patients with heart failure. The value of signal-averaged filtered P wave duration FPD is probably the result of reflecting the intra-atrial conduction delay, which is a pathophysiological condition for AF. The chemoreflexsensitivity is not a suitable method for predicting AF (**Budeus 2007**).



V) P-wave dispersion

P-wave dispersion (PWD) is defined as the difference between the longest and the shortest P-wave duration recorded from multiple different surface ECG leads. PWD is an ECG marker that reflects discontinuous and inhomogeneous (heterogeneous) atrial propagation of sinus impulses, and is a useful predictor of paroxysmal AF. PWD is a sensitive and specific ECG predictor of AF in the various clinical settings. However, no electrophysiologic study has proven up to now the suspected relationship between the dispersion in the atrial conduction times and PWD. The methodology used for the calculation of PWD is not standardized and more efforts to improve the reliability and reproducibility of PWD measurements are needed. PWD constitutes a contribution to the field of noninvasive ECG and seems to be quite promising in the field of AF prediction (**Dilaveris 2001**). Recently, Lazzeroni et al observed that PWD predicts AF following cardiac surgery (**Lazzeroni 2015**).

Mechanical and electrical changes in atrial myocardium may cause greater P maximum and PWD in patients with atrial septal defect (ASD). Its surgical closure can regress these pathological changes of atrial myocardium with a result in decreased P maximum and PWD. However, higher P maximum and PWD at baseline, which have not decreased after surgery, may be associated with postoperative paroxysmal AF, especially for older patients (**Guray**

2004). PWD increased risk for paroxysmal AF, higher in patients ≥ 65 years of age than in those ≤ 45 years of age (**Turhan 2003**).

Erbay et al have shown for the first time that long-term β-blocker therapy causes a significant decrease in maximum P-wave duration and PWD in patients with rheumatic mitral stenosis (**Erbay 2005**).

Impaired LV relaxation in hypertensive patients contributes to the heterogeneous atrial conduction (and consequently PWD) (**Dogan 2003**).

Summary of normal characteristics of the P loop in the three planes

	FP	HP	RSP
Rotation	CCW	CCW or in eight	CW
Direction	Inferior and left	Anterior initial and posterior final part	Antero-inferior initial and posterior final part
Morphology	Oval	Oval	Spear point or triangular
Location	Left inferior quadrant	$^1/_3$ in anterior quadrant and $^2/_3$ in posterior quadrant	$^1/_3$ anterior and inferior and $^2/_3$ posterior and inferior
Location of maximal vector	+65° (+20° to +20°)	+50° to –45°	+55° to –20°
Voltage of maximal vector	0.2 mV or less.	≤ 0.1 mV	≤0.18 mV
Maximal anterior forces		Adults up to 0.06 mV Children up to 0.08 mV.	Adults up to 0.06 mV Children up to 0.08 mV
Maximal posterior forces		Up to 0.04 mV	Up to 0.04 mV
Maximal left forces	Adults up to 0.09 mV Children up to 0.13 mV	Adults up to 0.09 mV Children up to 0.13 mV	

The P loop has a short slow conduction in the onset, in at least 2 planes.

Two small notches are usually observed: one in the efferent limb and another in the afferent limb.

The interatrial blocks versus atrial enlargements

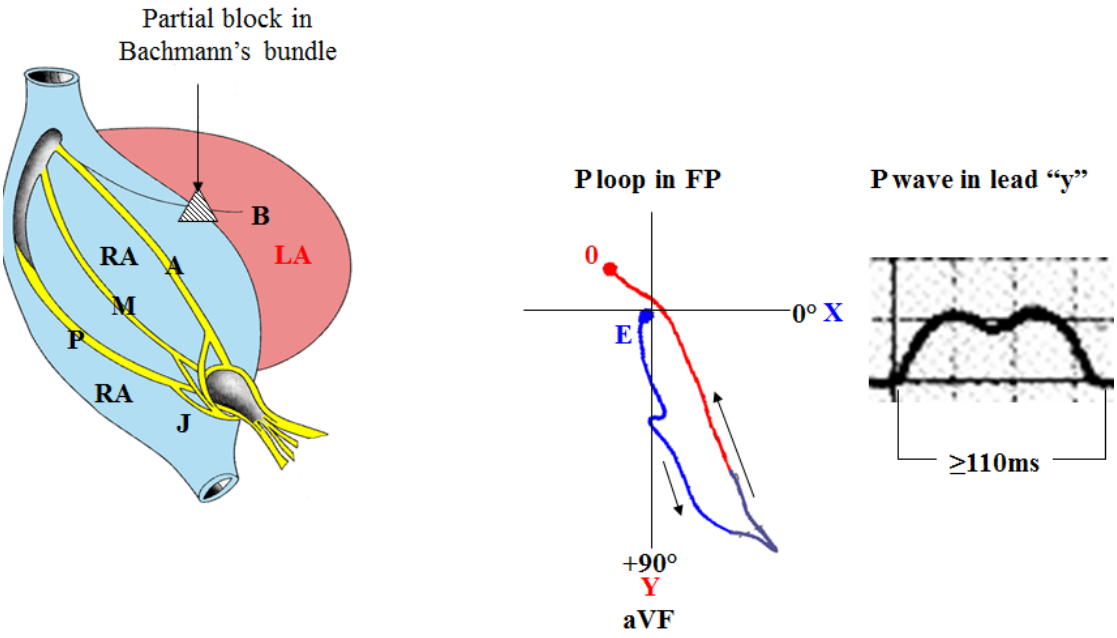
Overview

IAB exists as an anatomical-electrical entity, which should be considered a true block. IAB presents with different degrees as other blocks in the conduction system. It shows a correlation with the left atrium size, however, it can be seen in patients with normal atrial size too. IAB is strongly associated with AF, and PACs and it could be considered a predictor of cardioembolic stroke. IAB is an expression of atrial electrical remodeling and dysfunction. IAB can be transient and in certain clinical circumstances, may be reversible. The contribution of endocardial mapping has increased our knowledge of the anatomy and pathophysiology of IAB.

The IAB classification should include first, second and advanced or third degree IAB. The P wave morphology should always be taking into consideration when diagnosing this condition. Finally, without the initial description of IAB made by Dr. Bayés de Luna, it would be impossible to understand IAB as an anatomical and electrical substrate for atrial arrhythmias. This represents a major contribution to the knowledge of electrocardiography and electrophysiology, and makes commendable that this arrhythmic syndrome should be called «Bayés' syndrome»(**Conde 2014; 2015**)

I) First-degree (Partial IAB)

The electrical impulse is conducted from the right atrium (RA) to the left atrium (LA) trough Bachmann's bundle, but conduction is delayed. The ECG shows a P wave of ≥ 110ms in several leads with a variable negative wave in V_1. The P-wave morphology is similar to that in left atrial enlargement, but usually a negative P wave in V_1 is less evident.



Prevalence

High. Several studies have reported that the prevalence of IAB is more than 40% in hospital inpatients. Despite this, IAB remains largely underdiagnosed and commonly ignored. Advanced form is much less common that partial form (**Kitkungvan 2009**). Spodic consider this ECG abnormality is present in pandemic proportions especially at ages 60 and over and in unselected hospital patients. Because of its pathologic implications it requires widespread attention as a "pandemy". (**Spodic 2009**)

Associated conditions

1. Coronary Artery Disease
2. Hypertension
3. Diabetes Mellitus
4. Atrial fibrillation (strong associations)
5. Potential risk for embolism
6. Left Atrial Enlargement(LAE).
7. Left atrial electromechanical dysfunction.

Electrocardiographic characterization

1) **P-wave duration ≥ 120ms (Ariyarajah 2006).** P-wave duration is generally accepted as the most reliable non-invasive marker of atrial conduction and its prolongation is stronger associated with AF. However, patients with paroxysmal AF without structural heart disease may not have P-wave prolongation thus suggesting that the global conduction slowing is not an obligatory requirement for development of AF **(Platonov 2008).**

2) P terminal force (Ptf) plus-minus P wave (biphasic configuration) in lead V1≥ the area of one small square the final minus portion indicates left atrial abnormality, particularly LAE, which is a strong correlate of IAB.

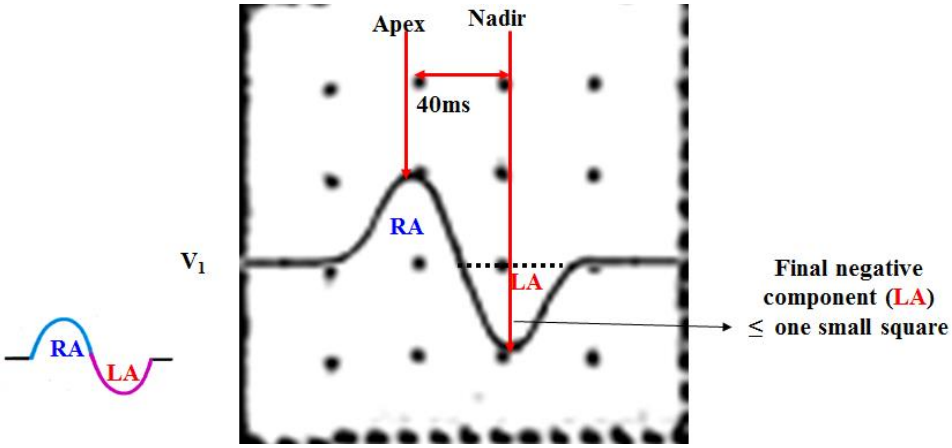
3) Prolonged in intrinsecoid P-wave deflection (from the apex to nadir) of the biphasic P wave in lead V1 ≥ 40ms.

4) Often bifid ("notched") P waves

5) "Dome-and-spike" P-waves. 4 and 5 predominantly on leads II and from V_3 to V_6. (**Ariyarajah2006**)

P-wave morphology and duration reveals several aspects of the atria: Proper function, fibrosis, dyssynchrony, final diastolic end LV pressure and activation paths can be inferred from the surface P-wave analysis. ECG can help differentiating atrial enlargements from conduction defects including intra- and IAB. (**Baranchuk 20015**)

Representation of normal P wave in V_1



Rarely partial IAB is not associated with LAE.

For some authors the name "atrial abnormalities" encompass the concept of atrial enlargement and IABs (**Bayés de Luna 2013; Lee 2007**). Both concepts, emphasizing, as it happens with ventricular hypertrophy and ventricular blocks, that often the ECG/VCG pattern of atrial enlargement especially of left atrial enlargement (LAE) is explained by the coexistence of IAB. However there are clear evidences that the pattern of IAB may exist without the association of atrial enlargement/hypertrophy. Therefore IABs and atrial enlargement are separate entities that are often associated with each other. Therefore we do not consider it appropriate to use the "umbrella" term atrial abnormalities to include both concepts without distinguishing between them (**Lee 2007**), as some authors do (**Bayés de Luna 2013; Tsao 2008**).

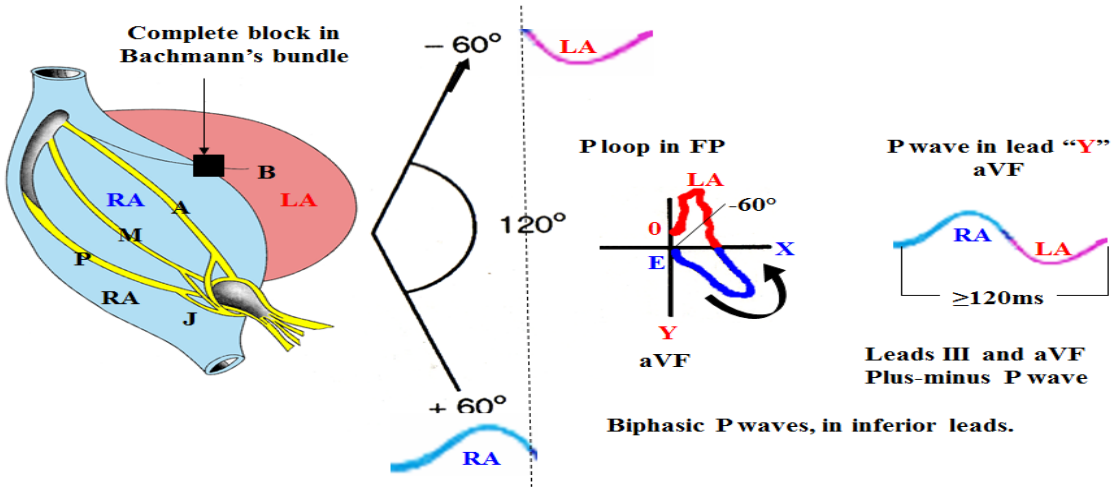
Treatment

Pharmacological approach: Angiotensin-converting enzyme inhibitors and Angiotensin receptor blockers

Pacing

Advanced interatrial block or third degree interatrial block

Electrical impulse is blocked in Bachmann's bundle, but retrograde left atrial activation usually occurs.



Bayés de Luna A et al (**Bayés de Luna 1988**) studied 16 patients with ECG evidence of advanced interatrial block and retrograde activation of the left atrium (**LA**): P duration ≥ 120ms, and plus-minus biphasic (+/-) P waves in inferior leads II, III, and VF.

Eight patients had valvar heart disease, four had dilated cardiomyopathy and four had other forms of heart disease.

Patients with valvar heart disease and cardiomyopathy were compared with a control group of 22 patients with similar clinical and echocardiographic characteristics, but without this type of interatrial block.

Patients with advanced interatrial block and retrograde activation of the **LA** had a much higher incidence of paroxysmal supraventricular tachyarrhythmia's (93.7%) during follow-up than did the control group. Eleven of 16 patients (68.7%) with advanced interatrial block and retrograde activation of **LA** had atrial flutter (atypical in seven cases, typical in two cases, and with two or more morphologies in two cases). Six patients from the control group (27.7%) had sustained atrial tachyarrhythmias (five atrial fibrillation and one typical atrial flutter). The atrial tachyarrhythmias were due more to advanced interatrial block and retrograde activation of **LA** and frequent PACs than to LAE, because the control group with

a LA of the same size, but without advanced interatrial block and retrograde activation of **LA** and with less incidence of PACs, had a much lower incidence of paroxysmal tachycardia.

Bayés de Luna et al (**Bayés de Luna 1989**) demonstrated the value of preventive antiarrhythmic treatment in patients with advanced interatrial block

Diagnosis criteria of advanced interatrial block and retrograde activation of the left atrium (Bayes de Luna 1977; 1988)

1. Biphasic P waves, in inferior leads.
2. P duration ≥120ms
3. Angle between the first portion (RA) and end portion (**LA**) >90º
4. Orthogonal Y lead plus-minus with the final negative portion ≥ 40ms
5. ≥ 40ms final portion of P loop upstart orthogonal X and Z leads.
6. Final portion of P loop delayed, notches and slurrings in the last part of the P loop
7. High Esophageal lead with positive P wave polarity and delayed
8. Low Esophageal lead with plus-minus P wave polarity and delayed
9. Intracavitary ECG with P wave activation craniocaudal inside the RA.
10. Intracavitary ECG with P wave activation caudal-cranial inside **LA**.

From 81,000 ECGs Bayes de Luna et al (**Bayes de Luna 1985**) collected 83 cases that fulfilled the criteria of Interatrial Conduction Disturbances with Left Atrial Retrograde Activation (IACD-LARA) (P +/- in II, III and VF with P width ≥ 120 msec).

The authors present the detailed study of 35 cases with surface ECG and VCG and 29 cases with orthogonal ECG leads.

The results are then compared against two control groups: with cardiopathy (30 cases) and without cardiopathy (25 cases).

The prevalence of IACD-LARA was nearly 1% globally, and 2% among patients with valvar heart disease.

The diagnostic criteria for Interatrial Conduction Disturbances with Left Atrial Retrograde Activation (IACD-LARA) are:

1) ECG: P +/- in II, III and VF with P ≥ 120 m.
2) Open angle > 90 º between the first and the second part of the P.
3) Orthogonal ECG: P +/- in Y lead with a negative mode greater than 40 m.
4) VCG: More than 50 msec. above the X or Z axis
5) Duration of the P loop ≥ 110 ms
6) Open angle between the two parts of the P loop in both frontal and right sagittal planes
7) Presence of notches and slurring in the last part of the P loop.

Martínez-Sellés et al studied 80 centenarians (101.4±1.5 years, 21 men) with follow-ups of 6 to 34 months. Among these, 71 subjects (88.8%) underwent echocardiography. The control group comprised 269 septuagenarians. A total of 23 subjects (28.8%) had normal P wave, 16 (20%) had partial IAB, 21 (26%) had advanced IAB, and 20 (25.0%) had AF /AFl. The IAB groups exhibited premature atrial beats (PABs) more frequently than the normal P wave group also, other measurements in the IAB groups frequently fell between values observed in the normal P wave and the AF /AFl groups. These measurements included sex preponderance, mental status and dementia, perceived health status, significant mitral regurgitation, and mortality. The IAB group had a higher previous stroke rate than other groups. Compared to septuagenarians, centenarians less frequently presented a normal P wave (28.8% vs. 53.5%), and more frequently presented advanced IAB (26.3% vs. 8.2%), AF/AFl (25.0% vs. 10.0%), and PABs (28.3 vs. 7.0%) (p-values <0.01).

Relatively few centenarians (<30%) had a normal P wave, and nearly half had IAB. Particularly advanced IAB, is a pre-AF condition associated with PABs. Atrial arrhythmias

and IAB occurred more frequently in centenarians than in septuagenarians (**Martínez-Sellés 2015**).

Age-related changes in P-wave morphology in healthy subjects (Havmoller 2007)

1) Orthogonal P-wave morphology in healthy individuals are predominantly positive in Leads X (0+ - 180° in I) and Y (+90° to -90° in aVF).

2) In Lead Z (near the V2 line), 35% had negative morphology and 65% a biphasic one with a transition from negative to positive. The latter P-wave morphology type is significantly more common after the age of 50.

3) P-wave increased with age being slightly longer in subjects older than 50 years old.

4) Changes of signal averaged orthogonal P-wave morphology (biphasic signal in Lead Z), are common in healthy subjects and appear predominantly after the age of 50.

5) Subtle age-related prolongation of P-wave duration is unlikely to be sufficient as a sole explanation of this finding that is thought to represent interatrial conduction disturbances.

Atrial enlargements

Concept

I. The ECG expression of atrial enlargement is due more to atrial dilation than atrial hypertrophy because the atrial wall is very thin and when submitted to an increase in pressure it usually dilates before increasing its myocardial mass (**Ferroglio 1979**).

II. The standard techniques to correlate ECG changes with the presence of atrial enlargement were previously based on anatomic, radiologic, and hemodynamic standards (**Reynolds 1953; Morris 1964**). The necropsic studies used were feasible only in cases of very advanced heart disease, and thus their utility was limited. For more than 35 years, M-mode echocardiography and especially 2D echocardiography

have been considered the "gold standard" (**Reeves 1981; Kaplan 1994; Rodevan 1999**) (Tables 1 and 2).

TABLE 1 Right atrial enlargement. ECG criteria with high specificity (Bayés de Luna 2013)

ECG criteria	SE %	SP %
A. QRS criteria		
1. QR or qR in V1	≈ 15	> 95
2. QRS V1 ≤4 mm + QRS V2/V1 ≥5	46	93
3. R/S > 1 in V1	≈ 25	> 95
4. SÂQRS > 90°	34	> 95
B. P criteria		
1. P wave in inferior leads < 2.5mm	7	100
2. Positive part of P wave V1 > 1.5mm	17	100
3. Positive part of P wave V2 > 1.5mm	33	100
C. Combined		
1. Positive part of P wave in V2>1.5mm+SÂQRS>+90°+R/S>1 in V1	49	100

TABLE 2 Left atrial enlargement. ECG criteria based on P wave changes with high specificity (Bayés de Luna 2013)

ECG criteria	SE %	SP %
1. Morris index (Morris 1964) (P terminal force in V1 mm/s) (0.04 mm/s)	69	93
2. NYAC score P duration ≥ 120 ms in I or II + Morris index (>0.04 mm/s) + SÂP ≈ 0°	15	98
3. P duration ≥ 120 ms in lead II + Terminal mode negative of P in V1 > 40 ms	50	87
4. P duration ≥ 120 ms in lead II + Morris index (>0.04 mm/s)	69%	49%
5. Interpeaks of P wave >40 ms	15	100
6. Plus-minus P-wave ± in II, III, aVF	5	100
7. SÂP beyond + 30°	8	90
8. P wave duration in II or III leads ≥ 0.12 s	33%	88%

Cardiovascular magnetic resonance (CMR) is currently the gold standard for atrial volume assessment. It has recently been demonstrated that 2D transthoracic echocardiography consistently underestimates the left atria (LA) and right atrial (RA) volume compared with CMR imaging (≈15-20%) (10). However, as the volumes assessed by the two techniques have similar slopes, except for the underestimation by 2D echocardiography, the study

performed using CMR to evaluate LA volume would likely result in similar results to those obtained using 2D echocardiography (**Rodevan 1999**). The accuracy of ECG criteria for left and right atrial enlargement as detected by 2D Echocardiography or CMR has recently been shown as is expressed in Tables 1 and 2. For full information consult Bayés de Luna (Bayés de Luna 2013).

The sensitivity and specificity of different criteria varies with the methodology used, and particularly with the type of population studied. The specificity is usually much higher and the sensitivity lower, but this increases if the population studied presents with a higher degree of atrial enlargement.

Left Atrial Enlargement (LAE): Etiologies

I) Congenital causes:

- Heart disease with pulmonary hyperflux: Ventricular Septal Defect (VSD), Persistence of Arterial Channel (PCA), Complete Atrioventricular Canal defect (CAVC defect).
- Congenital mitral stenosis
- Severe Aortic valve stenosis (AS)
- Coarctation of the Aorta
- Hypertrophic Cardiomyopathy

II) Acquired causes:

- Mitral valvar heart disease: pure mitral valve stenosis, Mitral insufficiency/regurgitation: “P mitrale”;
- Decrease of LV compliance. E.g.: systemic hypertension, HCM, restrictive cardiomyopathies
- LVF: left ventricular failure by increase of Pd_2 of LV. E.g.: extensive infarctions, dilated cardiomyopathy;

Left Atrial Enlargement (LAE) electrocardiographic criteria

I) Direct criteria

1) P wave of increased duration: ≥ 110 ms in adults, ≥ 120 ms in seniors, and 90 ms in children. Specificity: 90% and sensitivity: 40% in old age

2) Notched and bifid P wave in II, with interval between the apexes ≥40 ms. Voltage of 2nd module > than the 1st. A bifid P wave is a rare finding with left atrial diameter ≥ 60 mm. Atrial fibrillation is present in 70% of cases.

3) SÂP (P axis on frontal plane) deviated to the left: between +40° and -30°;

4) Increase in depth and duration of final negative component of the wave in V_1 (left atrial enlargement Morris' index (**Morris 1964**); slow and deep of P in V_1 or V_1-V_2. PTFV1. P terminal force in lead V_1 equal or more negative than 0.04 mm/s Greater than 0.03 mm/s: product of the duration of the final negative component (duration expressed in seconds); while depth is expressed in mm. Values above 0.03 mm per second constitute a highly sensitive criterion for diagnosis of LAE.

5) Macruz index (**Macruz 1958**) > 1.7: $^{\text{Duration of P}}$ / $_{\text{Duration of PRs}}$;

6) Intrinsic deflection of V1 of 30 ms (0.03 s) or greater. This deflection is measured from the apex of the initial positive component until the nadir of the final negative component of the P wave of V1.

7) P-terminal force (PTF-V1) exceeding 0.04 mm/s. This is the terminal, negative part of the P wave in lead V1 expressed as the multiplication of its depth in millimeters and width in seconds (mm/s). The normal PTF-V1 does not exceed 0.04 s wide and 1mm deep, i.e., 0.04 mm/s.

II) Indirect criterion

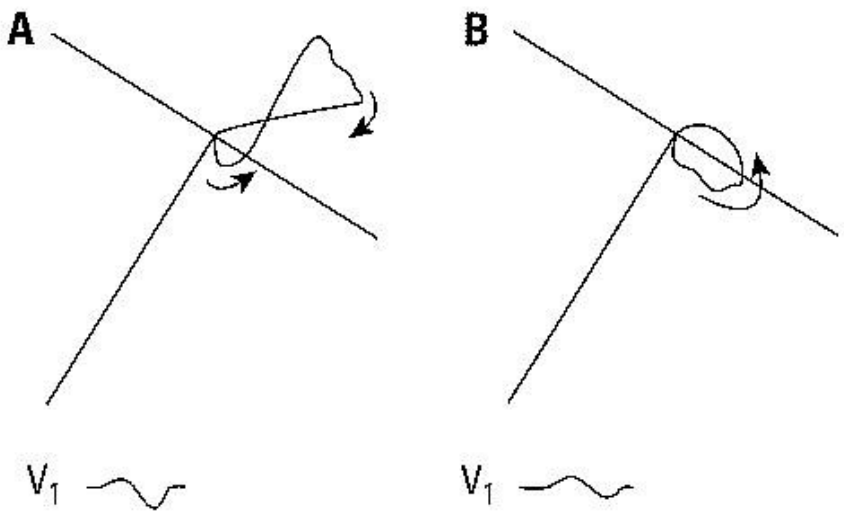
Presence of coarse atrial fibrillation: “f” waves with amplitude equal or higher than 1 mm in V_1 or V_1 - V_2: in 75% of the cases of coarse AF there is LAE coexisting. There is a significant relationship between the size of the f wave and the etiology of AF. Thus, 88%

of the patients with coarse AF have rheumatic valvular heart disease as underlying cause and 88% of patients with fine AF present coronary artery disease.

False positive and false negative diagnoses of left atrial enlargement

The diagnosis of LAE may often be difficult to achieve because of the following factors:

- The presence of isolated interatrial block explains the increase in the duration of the P wave, without the presence of evident teminal negative mode of V1. Thus, in contrast the combination of P wave duration in FP + increase of negative mode of P wave in V1 (Morris index) is a good criterion (**Morris 1964**).
- Some patients with isolated non-advanced left heart disease (e.g. mitral stenosis) without evident IAB show peaked P waves with no increase in duration (pseudo-P-pulmonale). In these cases, the presence of a P wave in V1 with a highly negative mode helps to reach a correct diagnosis (Figures below).



(A and B) P wave morphology in V1 and P loop in a case of isolated partial interatrial block (B) associated with left atrial enlargement (A)

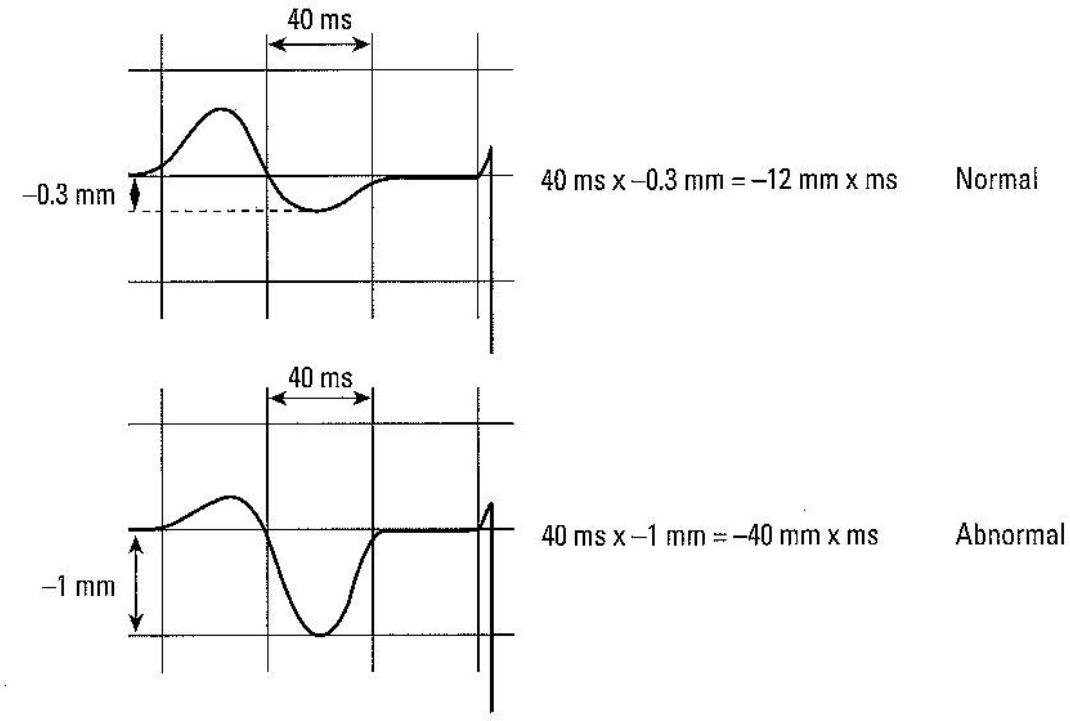
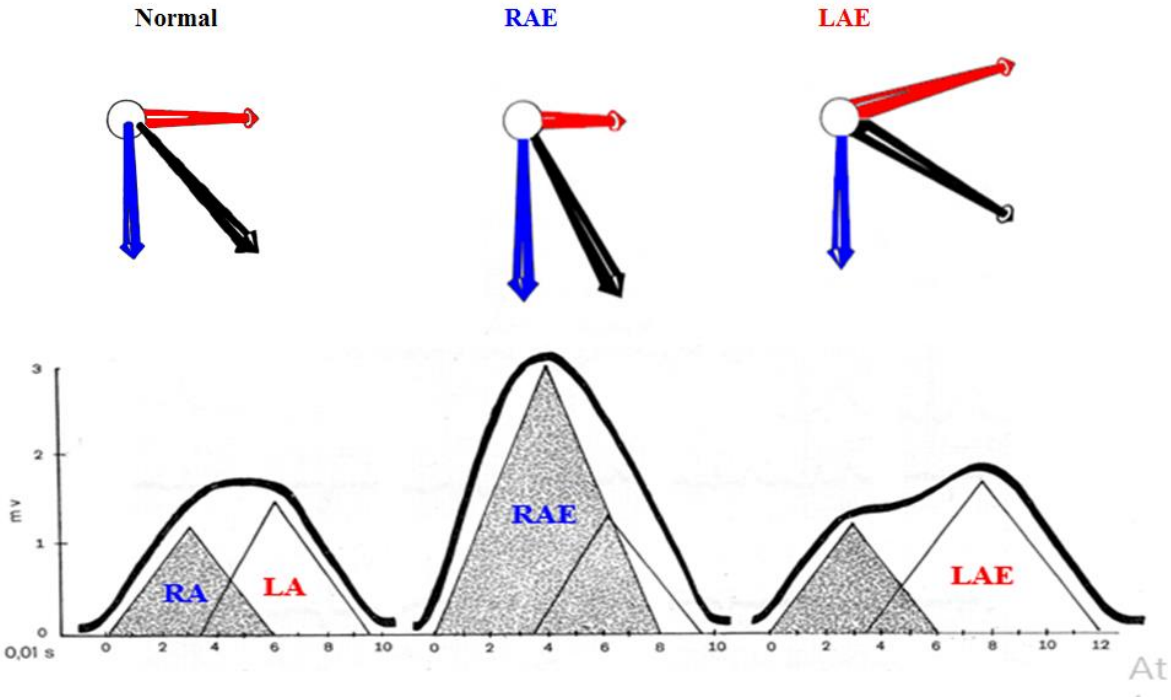


Diagram contrasting normal and abnormal negative components of the P wave in V1. When the value calculated using the width in seconds and the height in millimetres of the negative mode exceeds 40 mm + ms, it is considered abnormal.

- If important atrial fibrosis exists, small and even unapparent P waves (concealed sinus rhythm) may be seen, even in the presence of evident left atrial or biatrial enlargement (**Bayés de Luna 1978**). This problem increases the number of false negatives (low SE).

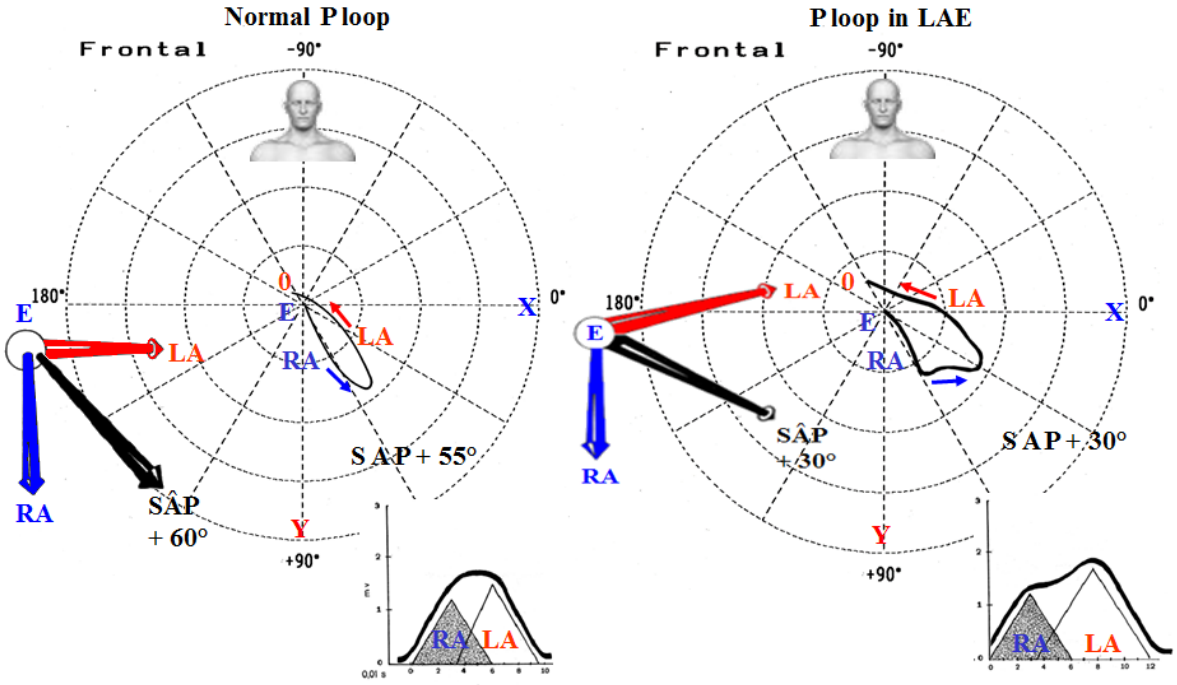
Many patients with COPD or thoracic abnormalities, pectus excavatum, and those with straight-back syndrome present with short but evident negative P waves in V1, a morphology that may be confused with LAE (**Bayés de Luna 2013**).

Profile of normal P wave in RAE and LAE



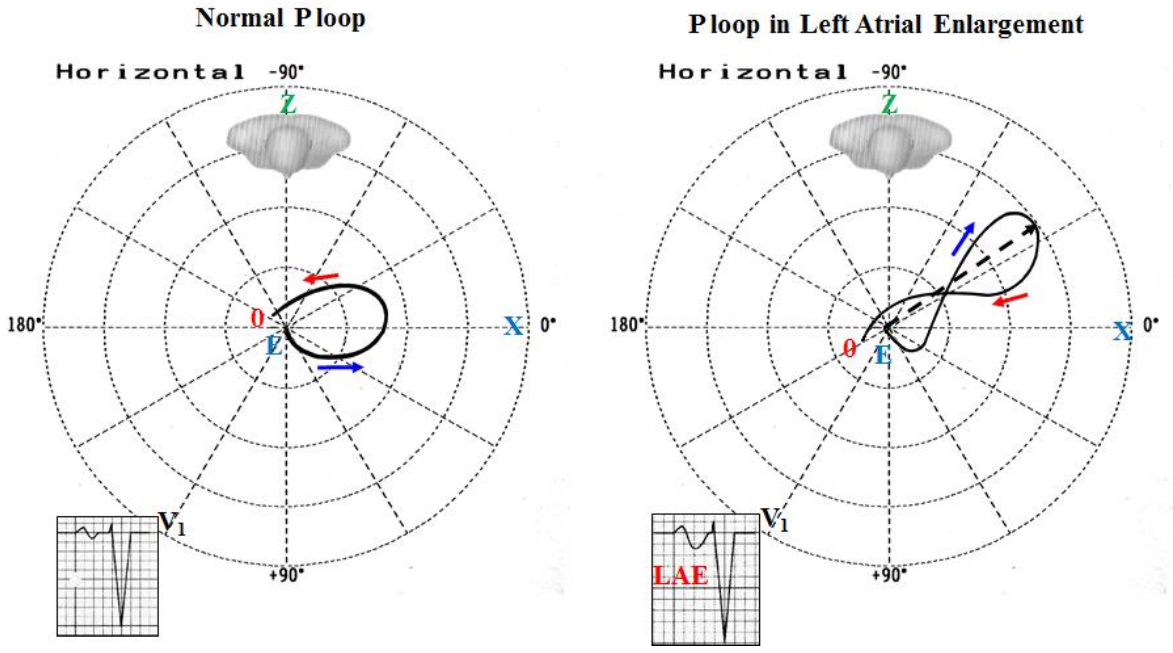
LAE in the Frontal Plane

Note: the findings in the Frontal Plane are not relevant for the diagnosis of LAE.

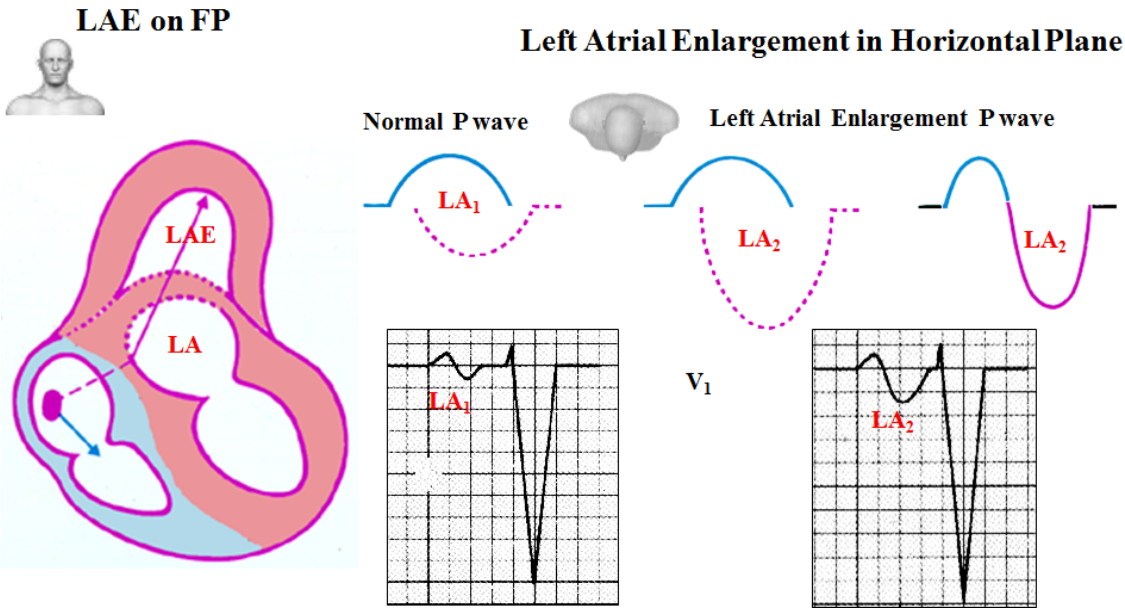


Similar to advanced interatrial block

P loop in LAE on Horizontal plane



- The maximal vector of P is located to the left: ≥0.10 mV in adults and ≥0.14 mV in <15 years old
- Max. vector of P >0.05 mV
- "Bow Tie" morphology



$LA_{2/}$: final deep and slow component: LAE ≥ the area of one small square; the final minus portion indicates left atrial enlargement, abnormality or advanced IAB.

Right Atrial Enlargement: Etiologies

I) Congenital causes: "congenital P"

- Ebstein's anomaly - "Himalayan P waves" of Taussig;
- Tricuspid atresia: "P tricuspidale" of Gamboa (10%);
- Moderate pulmonary stenosis "gothic" P (30%);
- Severe pulmonary stenosis P >2.5 mm 75%;
- Eisenmenger Syndrome;
- Atrioventricular septal defect (shunt from LV to LA). RAE or BAE 60%;
- Tetralogy of Fallot (T4F): only in 5% there are criteria of RAE.

II) Acquired causes

- Cor pulmonale - emphysema - COPD: "P pulmonale"
- Tricuspid stenosis;
- Tricuspid regurgitation/insufficiency;
- Double tricuspid injury;

- Heart failure;
- Increase of RV Pd_2.
- Isolated Pulmonary Hypertension: the ECG is very sensitive in symptomatic patients with isolated pulmonary hypertension **(Bossone 2003).**

"Himalayan P wave"

Ebstein's anomaly is a rare, complex, fascinating, congenital anomaly with a broad pathologic-anatomical and clinical spectrum accounting for <1% of all congenital heart defects. Since its description in 1866, dramatic advances in diagnosis have been made. Very high "Himalaya mountain-like" P waves (**Kaushik 2007**) are observed. (The Himalayan mountain system are the planet's highest peaks around the world). P wave is >3 mm (0.3 mV) in close to 50% of cases (**Armengol 1996**). Tall P waves (≥2.5 mm) are attributable to right atriomegaly. A prolonged P-wave duration is occasionally registred (**Jaiyesimi 1982**).

In association with P wave modifications in Ebstein's anomaly, the following are frequently observed (**Blömer 1975**): Prolonged PR interval (≥170 ms), short PR interval if associated with WPW pattern (≈30% of cases), bizarre low voltage right bundle branch block pattern, initial q wave in the QRS complexes of V1 and V2 leads.

Reduced amplitude of R-wave deflections in V3R and V1, P-dextro-atriale and bizarre low RBBB without right ventricular overload almost certainly constitutes a pathognomonic finding in Ebstein's anomaly. Higher P waves and wider QRS complexes are registered in more severe cases of Ebstein's anomaly of the tricuspid valve. There is a high potential for developing arrhythmia in the vast majority of tachycardia types: atrial ectopic tachycardia, atrial flutter, atrioventricular reentry tachycardia, AV-nodal reentry tachycardia, atrial fibrillation and ventricular tachyarrhythmias.

Tendency towards multiple arrhythmogenic substrates in a single patient (**Hebe 2000**).

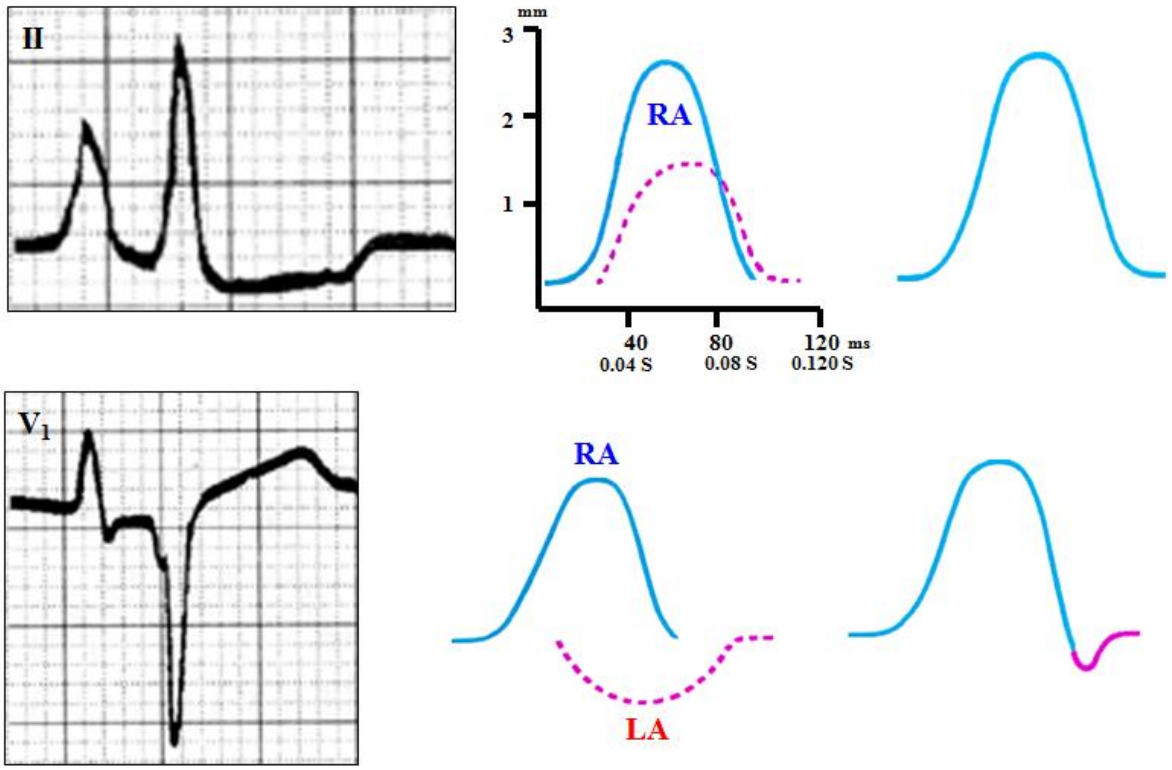
The "Gamboa (Gamboa 1966) P wave"

The association of:

- Right atrial enlargement
- Diastolic, volumetric or eccentric left ventricular hypertrophy
- Extreme left axis QRS deviation in the frontal plane: LAFB pattern
- Counterclockwise rotation of QRS loop in the frontal plane: LAFB pattern
- Cyanotic baby (neonate or infant). It is very suggestive of tricuspid atresia diagnosis.

From 120 children with tricuspid atresia, ECG with left axis axis deviation is observed in 94%, ERA in 58%, LVH in 96% and LAE: 47.5% (**Rosado 1987**).

P wave of RAE in II and V1



Right Atrial Enlargement criteria (RAE)

I) Direct ECG criteria: Direct P wave criteria are very specific but their sensitivity is very low.

- Voltage of P ≥ 2.5 mm in at least one of inferior leads: P pulmonale or P pulmonale parenchymal: tall and occasionally pointed P wave in inferior leads
- Aspect in apex of P wave: "Goth P"
- P wave height >1.5 mm in lead V_2. The criteria has 100% specificity preserved
- P waves with "plus-minus" pattern in right precordial leads with initial plus component ≥1.5 mm
- P wave deeply negative or positive in V_1
- P wave of voltage ≥ at 1.5 mm in V_2 in association to R/S ratio >1
- SÂP to the right of +80º (negative P wave in VL). In congenital heart diseases, SAP is not deviated to the right.
- P wave with increase in voltage and in duration in cases of extreme RAE
- Macruz index lower than 1 = $^{\text{P duration}}/_{\text{PRs duration}}$ (**Macruz 1958**)
- The QRS criteria with a QRS amplitude in V1 <4 mm + ratio V2/V1 > 5 are highly specific (>90%) with moderate SE (≈ 45 %)
- The combined P + QRS criteria with a P wave amplitude in V2 > 1.5 mm + SÂQRS > 90° + R/S ratio >1 in V1 in the absence of RBBB have 100% specificity and ≈ 50% sensitivity.

II) Indirect ECG criteria

- $SÂQRS_F$: > 90º.The criteria has 100% specificity preserved
- Sodi Pallares sign (**Sodi Pallares 1952**): qR, QR or qRs in V_1 and V_2
- Peñaloza and Tranchesi sign: QRS complexes of low voltage in V_1 contrasting with QRS complexes of normal voltage or increased in V_2. pe

- R/S ratio >1 in lead V_1 without RBBB. The criteria has 100% specificity preserved.

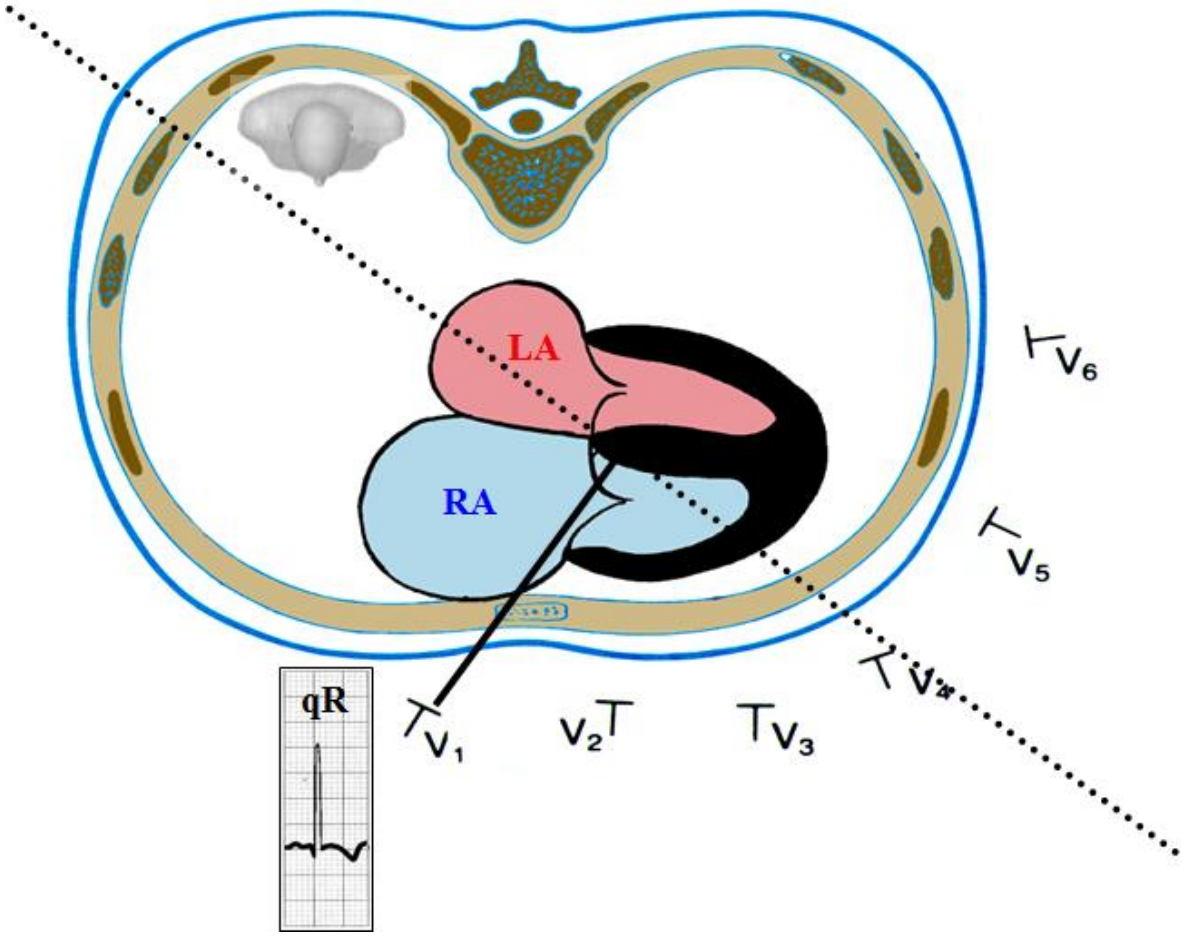
False positive and false negative diagnoses of right atrial enlargement

The ECG diagnosis of RAE may be very difficult to reach for the following reasons:

- The voltage of the P wave is strongly influenced by extra cardiac factors, which may result in increases (hypoxia, sympathetic overdrive, etc.) (false positive) or decreases in voltage (emphysema, other barrier factors, atrial fibrosis, etc.) (false negative).
- The presence of associated fixed or intermittent atrial block may result in the transient or permanent disappearance of the ECG criteria for right atrial enlargement (false negative).
- On the other hand, a high-voltage P wave may be seen in patients with exclusively left heart pathology and possible left atrial enlargement (false positive) (pseudo-P-pulmonale) (**Bayés de Luna 2011**).

These are some of the reasons why changes in the atriogram are generally not very sensitive (many false negatives) for the diagnosis of RAE. Although there are some factors that increase the incidence of false positives, they are fewer and therefore the specificity of ECG criteria for RAE is much higher.

Significant dilatation of Right Atrium: Indirect sign of RAE conditioning qR pattern in V_1 and V_3R (Sodi-Pallares' sign) (Sodi-Pallares 1952)



Outline that explains the indirect sign of RAE: qR in V1 (sign of Sodi-Pallares). The volumetric increase of the RA, gets closer to the exploring electrode V_1, recording initial QRS negativity in this lead, because this electrode records the epicardial morphology of the right atrium.

Significance of RAE in Congestive Heart Failure (CHF)

Patients with electrocardiographic pattern of RAE, atrial flutter, AF, 1st or 2nd degree AV block Mobitz Type I, Complete LBBB and interstitial pulmonary edema with bilateral pleural effusion in chest X-rays, frequently associated to CHF(**Fonseca 2004**).

Atrial high resolution ECG

The duration of P wave in high resolution ECG (signal-averaged P wave (SAPWD)) significantly correlates with the size of the right atrium (**Dixen 2004**).

Pseudo-P-pulmonale

These cases are frequently misdiagnosed. In pure left atrial overload rarely a very high P wave (≥ 2.5 mm in inferior leads) is observed with right axis deviation (P axis located to the right of +60°: negative P in VL) and major duration (≥120 ms).

The vector of left atrial activation is directed not only posteriorly, but also more inferiorly than to the left pointing abnormally downwards. Thus a P wave with two humps is observed: The first one, registered within the first 40 ms and responsible for a slight notch corresponds to the first part of the normal right atrial activation, while the second greater hump corresponds to the activation of the enlarged left atrium (**Chow 1965, Chung 1972, Gertsch 2003**).

P-pulmonale-like patterns causes without RAE

I. Severe hyperkalemia

II. Asthenic habitus

III. Enhanced sympathetic tone

IV. Cyanosis.

Severe hyperkalemia imitating P-pulmonale

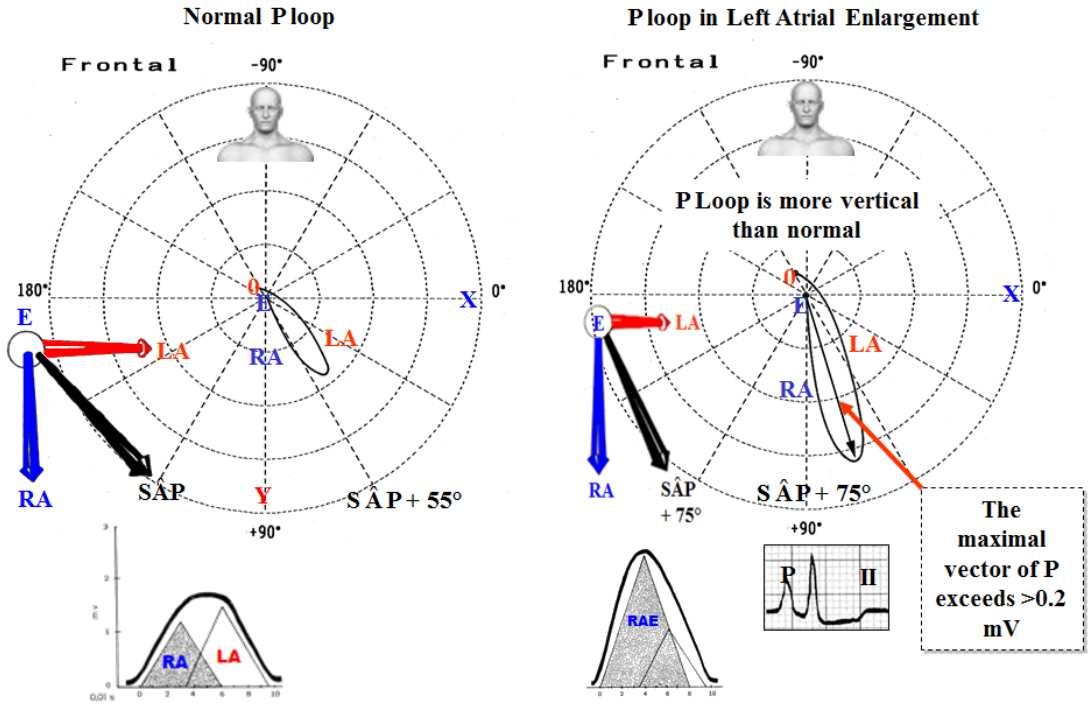
Hyperkalemia is one of the more common acute life-threatening metabolic emergencies seen in the emergency department.

Early diagnosis and empirical treatment of hyperkalemia is dependent in many cases on the emergency physician's ability to recognize the ECG manifestations.

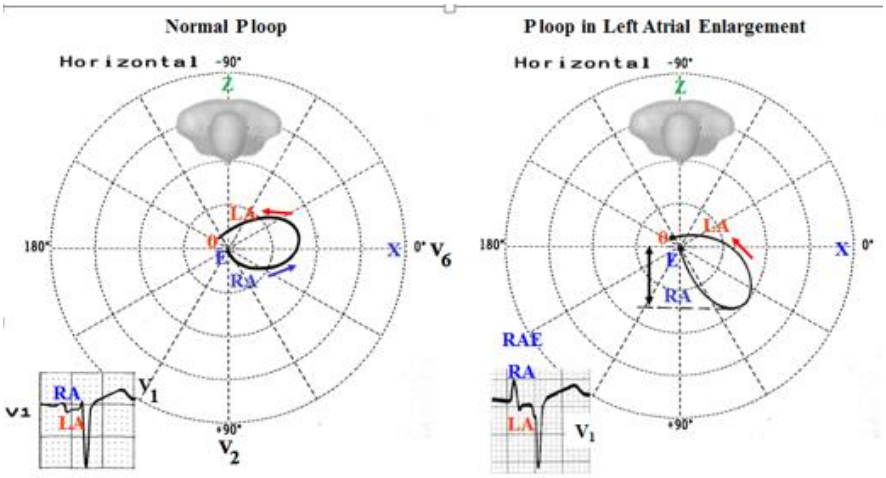
The ECG manifestations of hyperkalemia include (**Mattu 2000**):

- Diminished, flattening or absence of the P wave (sinoventricular conduction)
- Exceptionally enhanced P wave amplitude in the inferior leads imitating P pulmonale (**Gertsch 2003**).
- PR interval prolongation
- Widening of the QRS complexes
- A "sine-wave" appearance at severely elevated levels. The possible mechanism for the genesis of the sine wave, including loss of electrical gradient with resulting phase difference of QRS and T, associated with maintenance of His bundle activity with progressive, distal, Purkinje blockade (**Sridharan 1979**).
- Peaked and narrow based T waves in the precordial leads

P loop in Right Atrial Enlargement in the Frontal Plane

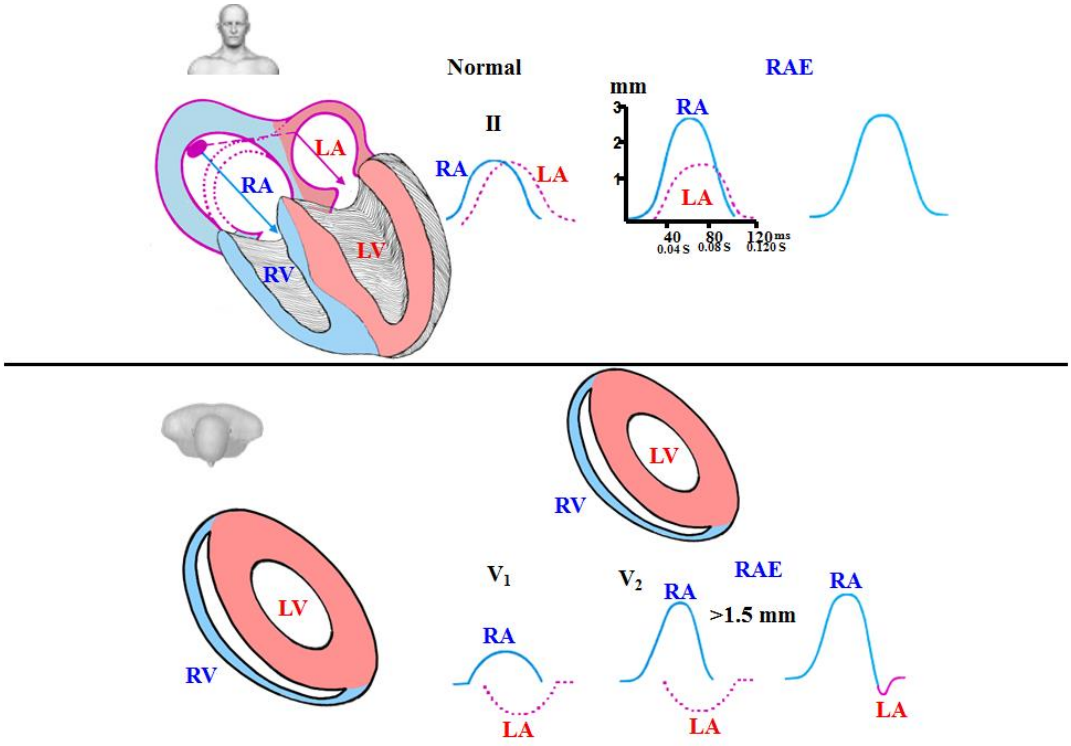


P loop in Right Atrial Enlargement in the Horizontal Plane



- Maximal vector of P may exceed >0.1 mV
- Most of the P loop heads to the front.
- Magnitude of anterior forces: ≥0.07 mV
- Max. anterior forces ≥0.07 Mv.

P-wave components in RAE



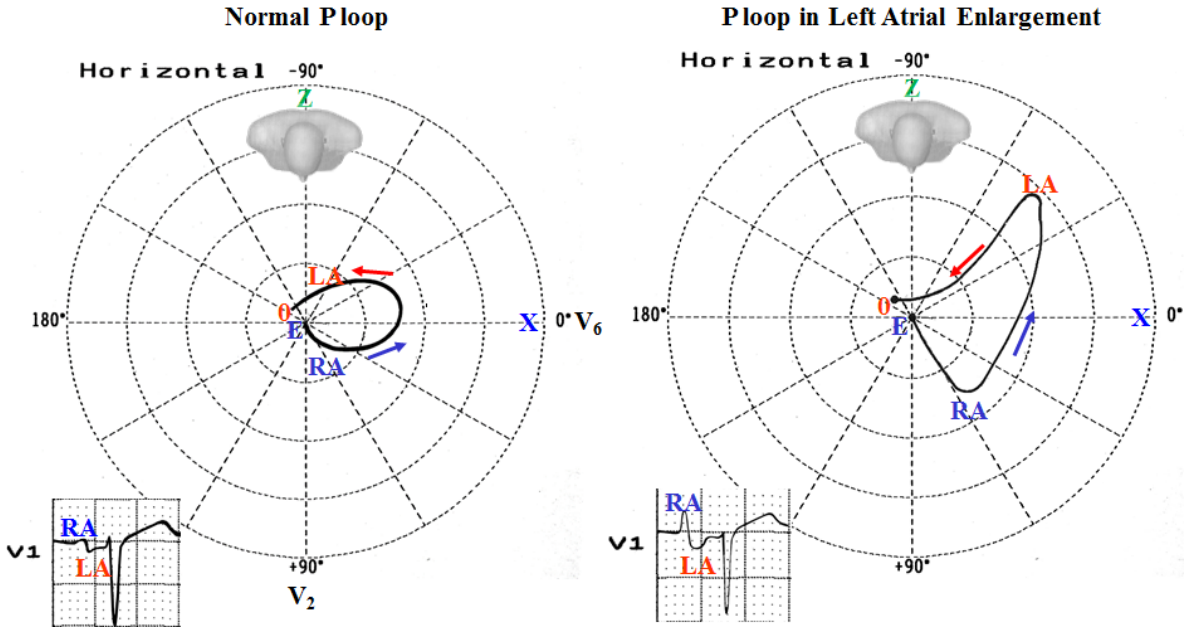
Biatrial Enlargement (BAE) electrocardiographic criteria

The most important diagnostic criteria are as follows

- Initial component of P wave in V1 >1.5 mm and final slow and deep negative component > 1 mm in depth and 40 ms in duration
- P waves of voltage >2.5 mm and duration ≥120 ms in II
- Initial part of P waves is peaked in V_1 and V_2 with voltage >1.5 mm and terminal negative mode slow (width ≥1mm)
- Signs of LAE (P waves of duration >120 ms and bimodal) with right SÂP. The opposite case is not valid because the SÂP can be on the left side in isolated RAE of patients with congenital heart diseases.
- Atrial Fibrillation associated with qR and QR type complexes in right precordial leads in the absence of myocardial infarction in V_1 or V_1-V_2 (Sodi Pallares sign) (**Sodi Pallares 1952**)
- QRS complexes of low voltage in V_1 contrasting with QRS complexes of normal voltage or increased in V_2.

Frequently, more than one criterion is found (P duration ≥ 120 ms in FP + P ± in V1 with first part peaked and the second part broad and deep).

P loop in Biatrial Enlargement in the Horizontal Plane



Increase of anterior and posterior voltages of P loop

Possible causes of negative P wave in lead I

1) Incorrect limbs electrode cable connection during electrocardiographic recording (right to left). The frequency of ECG artifacts due to switched electrodes is 0.4% at the outpatient clinic and 4.0% at the intensive care unit (**Rudiger 2007**). Limb electrode misconnection: Pseudo dextrocardia by exchange of limb electrodes. All P, QRS, and T waves are negative in I, but normal progression of QRS in precordial leads rules out this hypothesis, pointing out the exchange of arm electrodes.

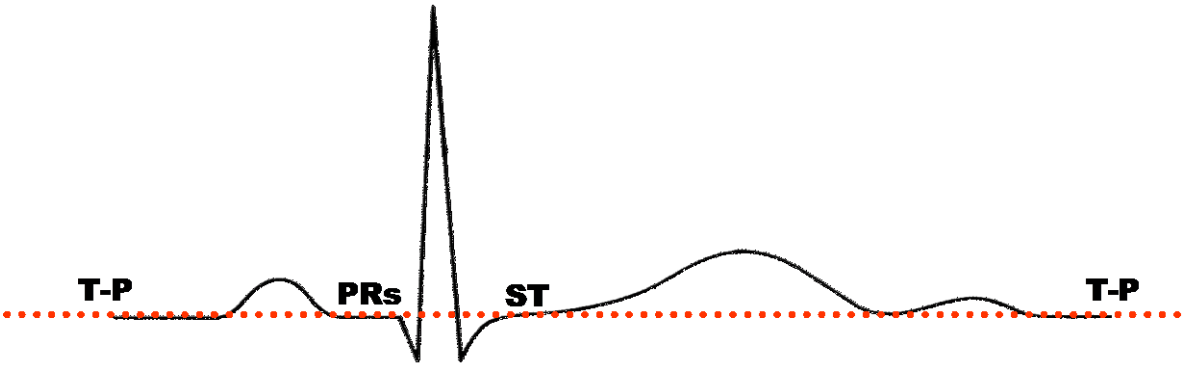
2) Simple true dextrocardia: mirror image. Total atrio-visceral situs inversus with no heart disease. SÂP directed to the right and below, pointing at around +120° (III). Negative P wave in VL and I, positive in III. Reverse progression of r wave in precordial leads V2 to V5 (decreasing).

Atrial T vector

Atrial repolarization (Ta vector) is responsible for the P loop being open and not closed (0 point does not coincide with initial E point). A straight line from the onset of the P loop to the end of it, shows the magnitude and direction of the Ta vector.

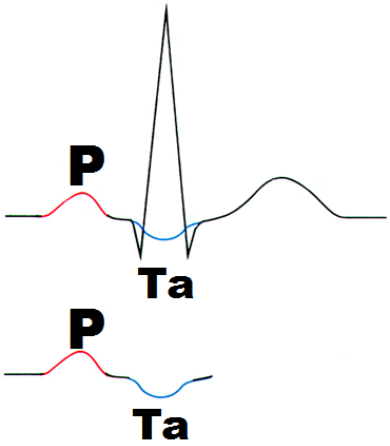
Atrial T vector (Ta vector): atrial repolarization (Ta vector) is responsible for the P loop being open and not closed (0 point does not coincide with initial E point). A straight line from the onset of the P loop (**E** point) to the end of it (**0** point) indicates the magnitude and direction of the Ta or Tp vector.

Exteriorization of segments in vectorcardiography



In vectorcardiography, isoelectric lines corresponding to PR (PRs), ST and T-P segments are not recorded if they do not show depression or elevation. Thus, the segments manifest as stationary points. This non-manifestation is the reason why the ECG is superior to VCG in the analysis of segments and intervals.

P loop is open because atrial repolarization (TP or TA loop) is completely opposite to the P loop



In ECG, Ta or Tp wave: wave generally not visible because it is hidden by QRS. It represents atrial repolarization. Ta polarity is opposite to the P wave and its magnitude is 100 to 200 muV.

It may possibly reach the ST segment and the T wave, causing ST segment depression and resembling myocardial ischemia (**Sapin 1991**).

Atrial infarction

Infarction of the cardiac atria occurs more frequently than is commonly considered. Ischemic damage to the atrial myocardium is usually associated with infarction of cardiac ventricles, but isolated infarction of an atrium can occur and may be of clinical significance (**Cunningham 2008**).

Atrial infarction is rarely diagnosed before death because of its characteristically subtle and nonspecific electrocardiographic findings.

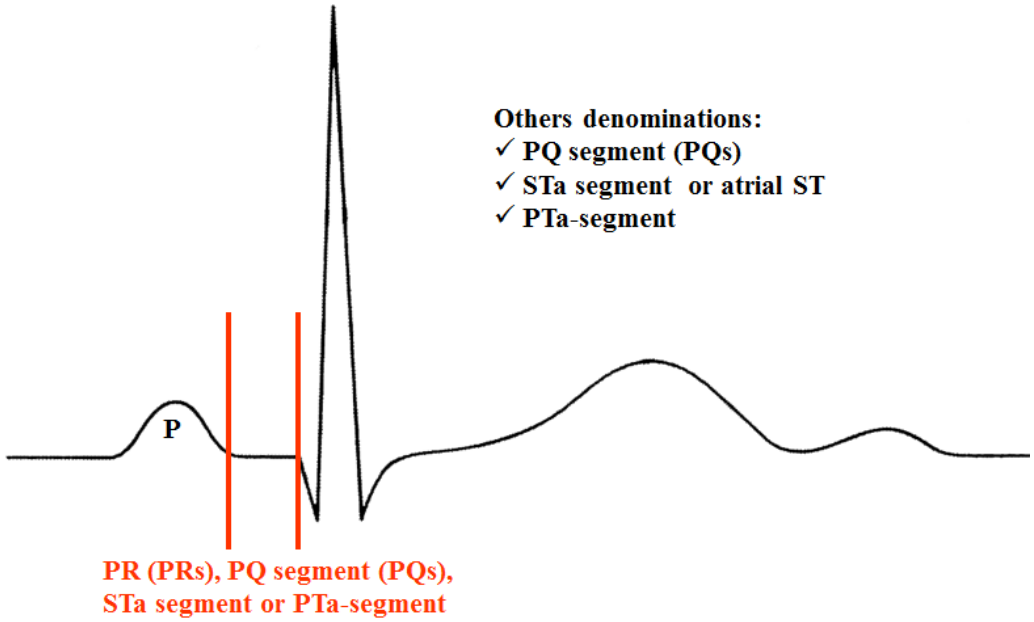
Atrial infarction is a neglected electrocardiographic sign with important clinical implications.

These findings may be overshadowed by changes associated with concomitant ventricular infarction (**Shakir 2007**).

ECG diagnosis criteria

PR (PRs), PQ segment (PQs), STa segment or PTa-segment: it stretches from the end of P wave to the onset of QRS complex. Displacement of this segment (depression or elevation), which represents part of the atrial ST (STa) segment only ostensive when associate with AV block as a consequence of atrial infarction (figure below).

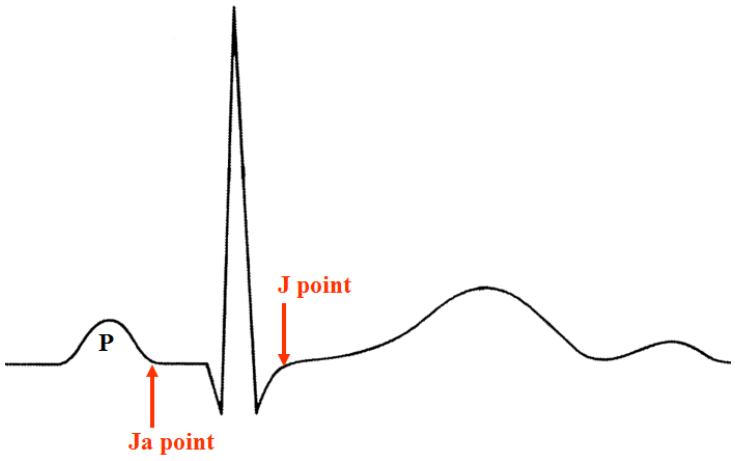
PR segment (PRs)



PRs: from the end of P wave to the onset of QRS complex.

Ja point: Point of junction between the end of the P wave and the onset of PRs (Figure below).

Ja point & J point

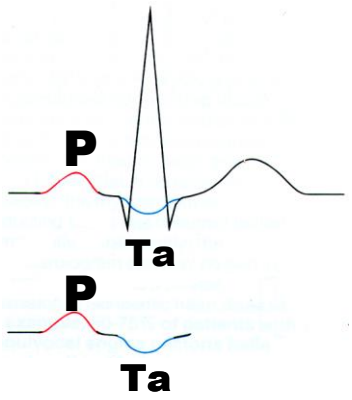


Ja Point: junction between the end of the P wave and the onset of PRs.

J Point: of junction between the end of the QRS complex and the onset of ST-segment.

Normal location of atrial repolarization (Ta or TP wave). It coincides with ventricular depolarization (QRS complex), what explains its absence for being concealed by the ventricular phenomenon (Figure below).

Ta or TP wave

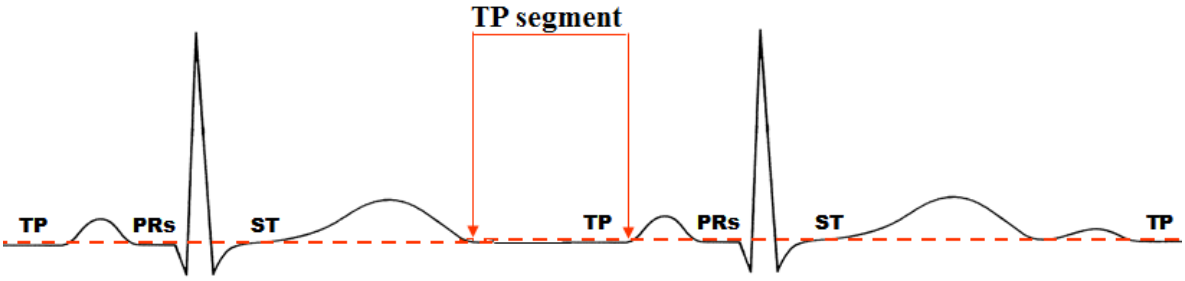


Normal location of atrial repolarization (Ta or TP wave). It coincides with ventricular depolarization (QRS complex), what explains its absence for being concealed by the ventricular phenomenon. Its polarity is opposite to the P wave and its magnitude is 100 to 200 mμV. Sometimes it may appear in the ST segment and the T wave.

During exercise, it may in theory, cause ST segment depression and resemble myocardial ischemia (**Sapin 1991**).

The 3 segments PRs, ST and TPs normally are at the same level (Figure below).

Correlation of level between PRs, ST & TP



The PR segment is leveled when it is at the same level of the PR segment of the beat being studied.

TP segment: from the end of the T wave up to the onset P wave of the following cycle.

Usually, PRs (end of P wave up to QRS complex onset), ST (from J point or the end of QRS up to the beginning of the T wave) and TPs (from the end of the T wave up to the onset P wave of the following cycle) segments ***are at the same level***. The figure shows a normal ECG and a line of dots pointing out the level of the three segments: PRs, ST and TPs.

Ta wave may cause falsely positive strain tests in the presence of important PR segment depression in maximal strain, longer time of exercise and maximal strain faster than those truly positive, absence of effort-induced pain and P wave of voltage higher in maximal strain.

In acute right ventricular MI high degree AV block is present in almost half of the cases.

STa segment elevation may produce a diagnostic monophasic pattern during the early stage of ventricular ischemia.

ECG criteria for atrial infarction

- Depression of the STa segment alone is not a reliable sigh unless the degree of depression is marked.
- P shape with M or W morphology during the acute MI episode.
- Frequently atrial arrhythmias (35% of cases): Higher incidence of supraventricular arrhythmias in acute atrial fibrillation compared with ventricular infarction, atrial flutter, supraventricular tachycardia, changing pacemaker, junctional rhythm, sinus bradycardia, and AV conduction disturbances. Ischemia of the sinus node due to coronary occlusion proximal to the origin of the sinus node artery is a likely cause of arrhythmias (**Kyriakidis 1992**).

Mayor and minor ECG Liu criteria for atrial infarction (Liu 1961)

I) Major criteria

- PRs elevation >0.5mm in leads V5 and V6 with reciprocal depression of PRs in V1 and V2 leads.
- PRs elevation >0.5mm in leads I with reciprocal depressions in II and III.

- PRs depression >1.5mm in precordial leads an 1.2mm in I, II, associated with any atrial arrhtymia.

II) Minor criteria

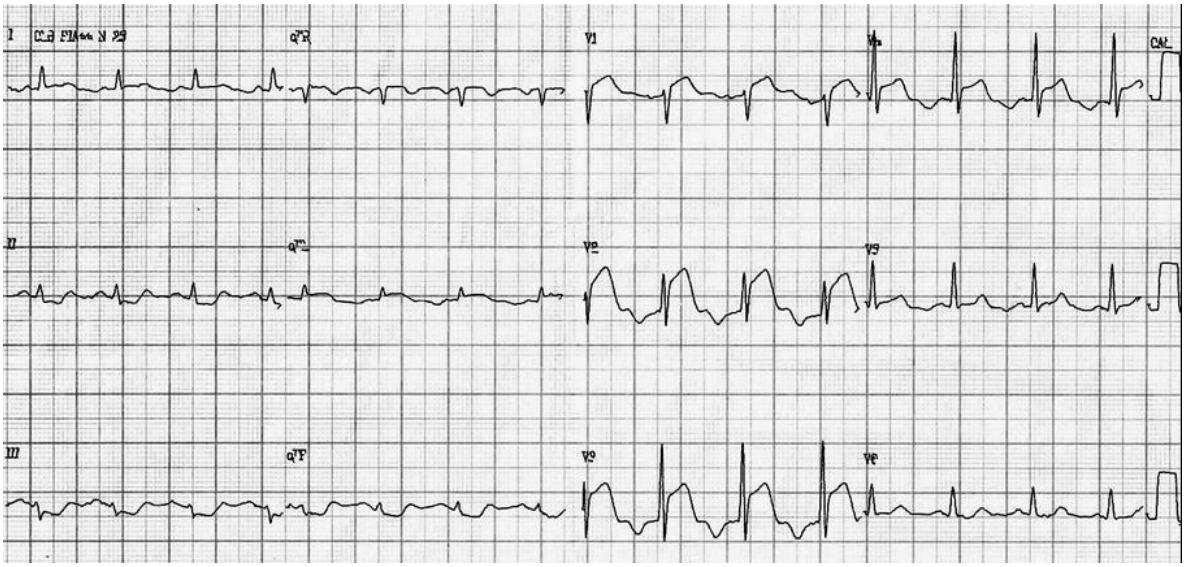
- Abnormal P waves, flattening of P-wave in M, flattening of P-wave in W, irregular or notched P wave.

Atrial infarction complications

- Atrial arrhythmias (present in 35% of cases): ischemia of the sinus node due to coronary occlusion proximal to the origin of the sinus node artery is a likely cause of arrhythmias (**Kyriakidis 1992**) (Figure below).
- Pump failure of the right and left ventricle
- Atrial wall rupture
- Thromboembolization (**Neven 2003**).

Example of atrial infarction during AMI of anterior wall

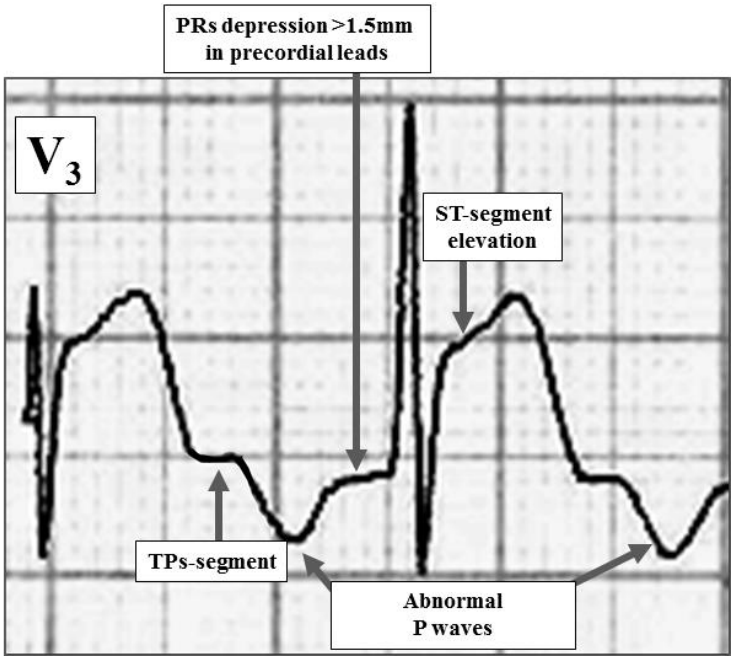
Intra-stent acute thrombosis in LAD artery



Acute STSE injury in anteroseptal wall. “Mirror image” in inferior leads.

Abnormal shape inverted P wave followed by PR segment depression in V2 and V3 (next figure).

Atrial infarction



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