VT/SVT Discrimination Algorithm Session

Temporal Logic approach

TU Wien UPenn

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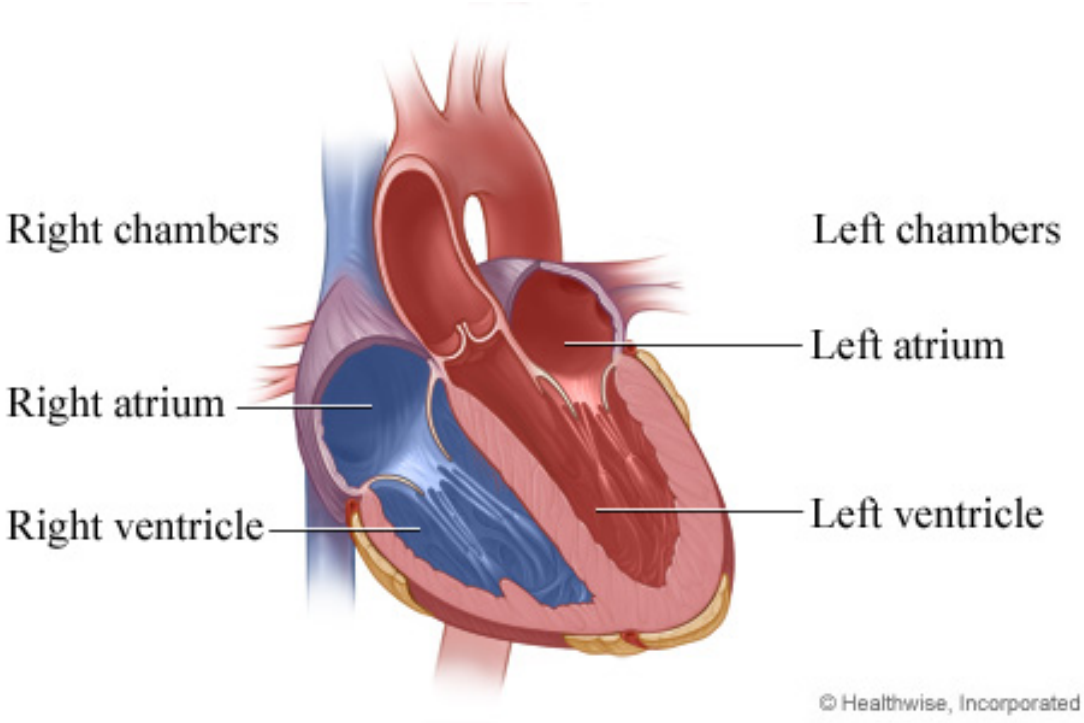
Radu Grosu
Houssam Abbas

CyberCardia Project Meeting
April 22-23, 2016

Cardiac Preliminaries. Anatomy



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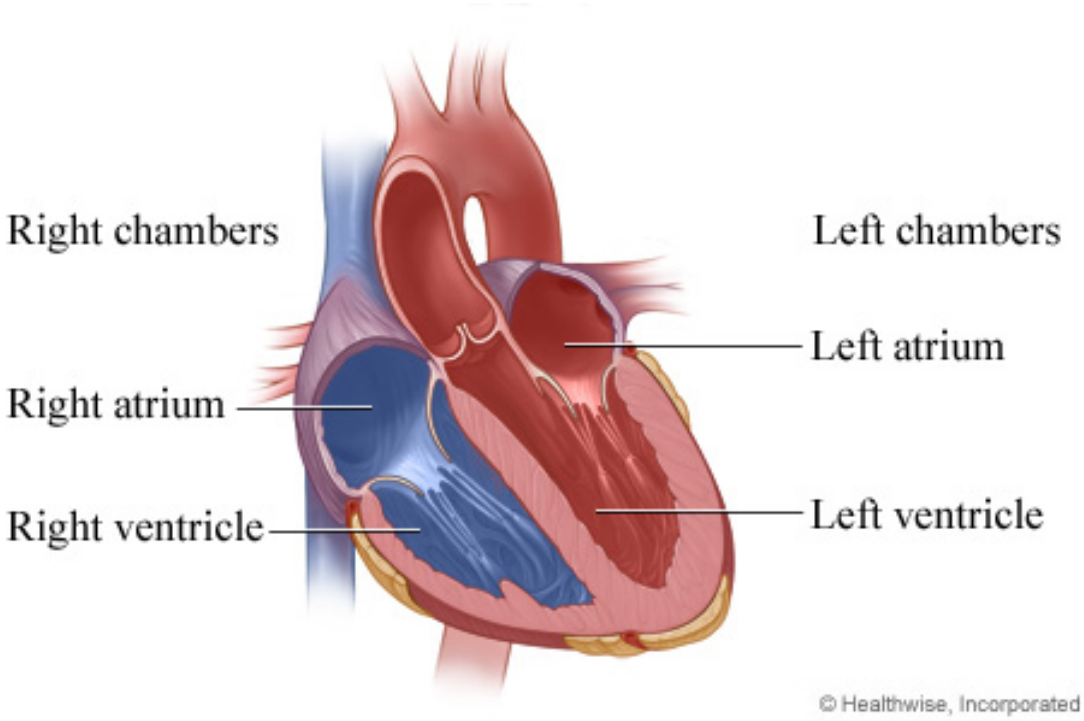

- 4 chambers: 2 atria and 2 ventricles

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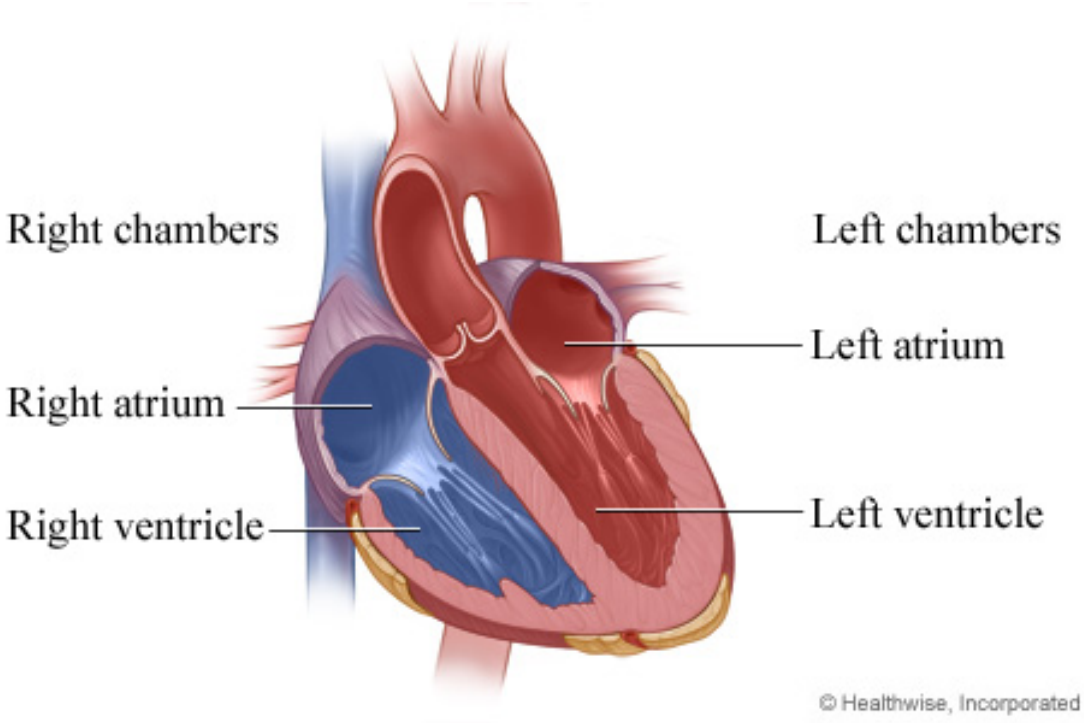

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- Average heart size: 12x10x8 cm, weight: 300 g

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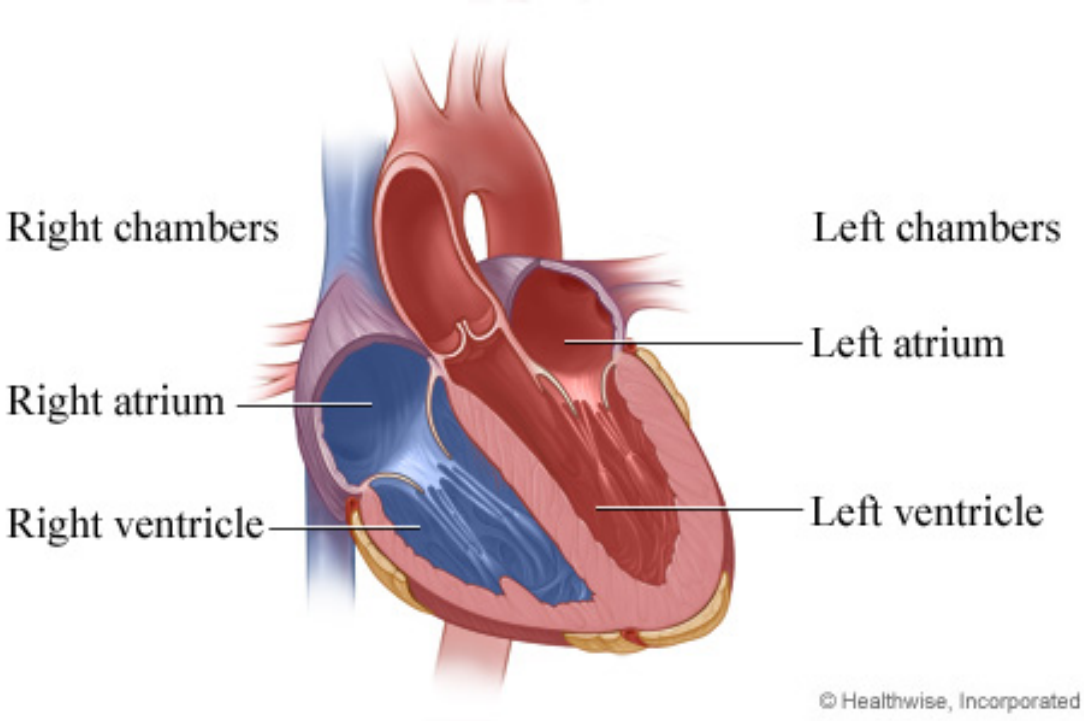
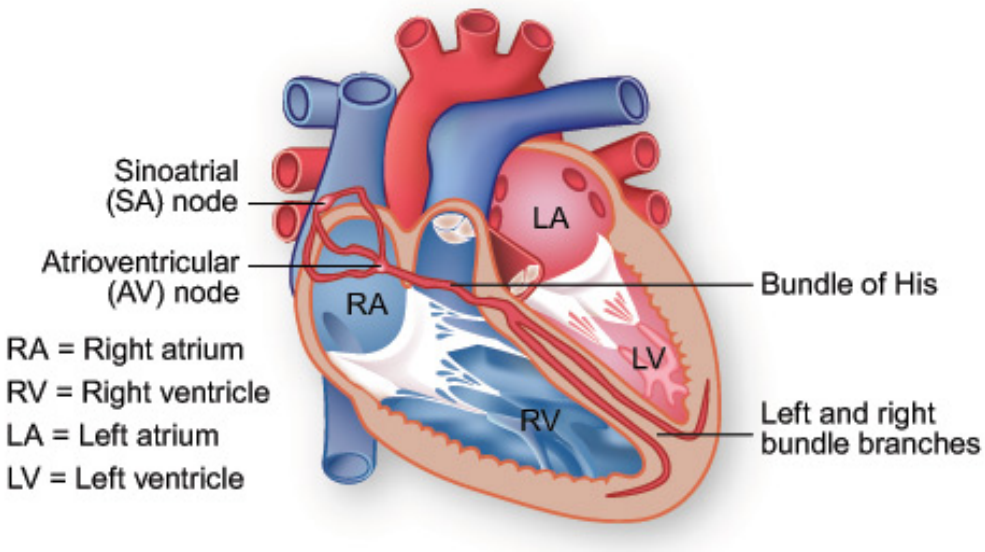
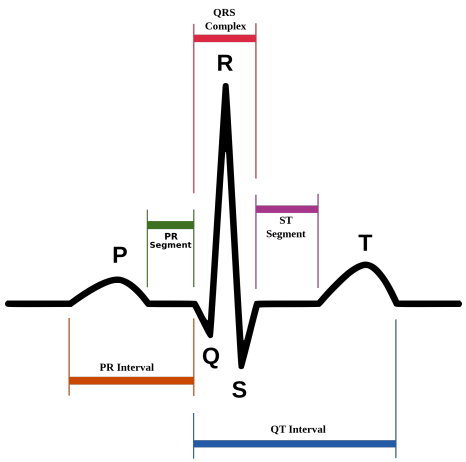


- 4 chambers: 2 atria and 2 ventricles
- Average heart size: 12x10x8 cm, weight: 300 g
- It pumps 70 ml of blood each heart beat = 5 litres in one minute (in a big stress: $\leq$200 ml, $\leq$40 litres)

Image Credit: *Healthwise. Incorporated.*

Cardiac Preliminaries. Conductivity





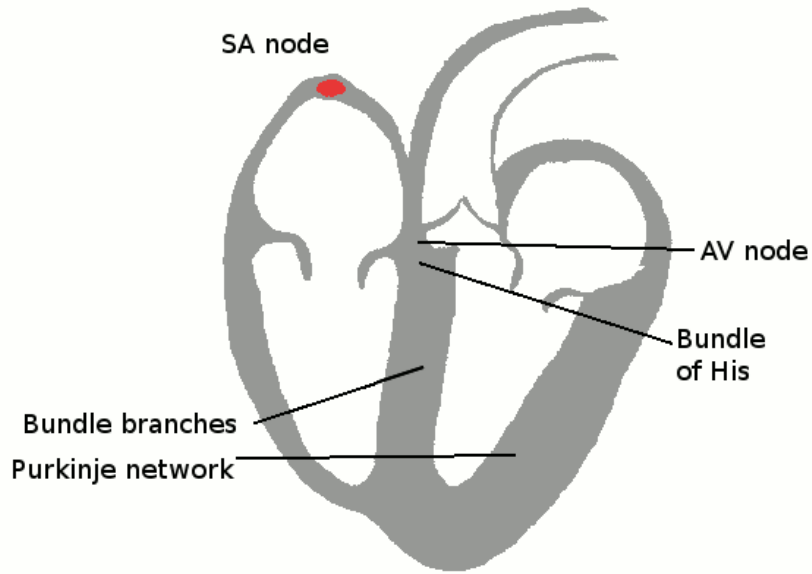


Figure: Electrical impulse propagation

Cardiac Preliminaries. Arrhythmia

- ☞ abnormal heart beats
- ☞ any change from the normal sequence of electrical impulses

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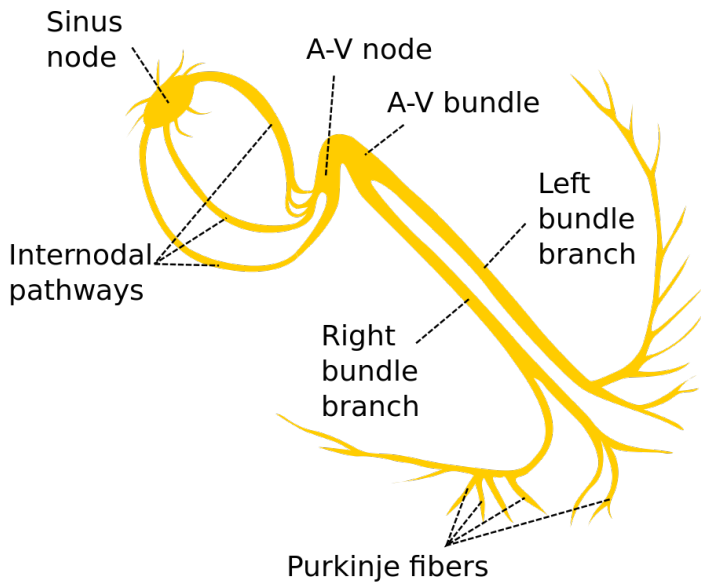

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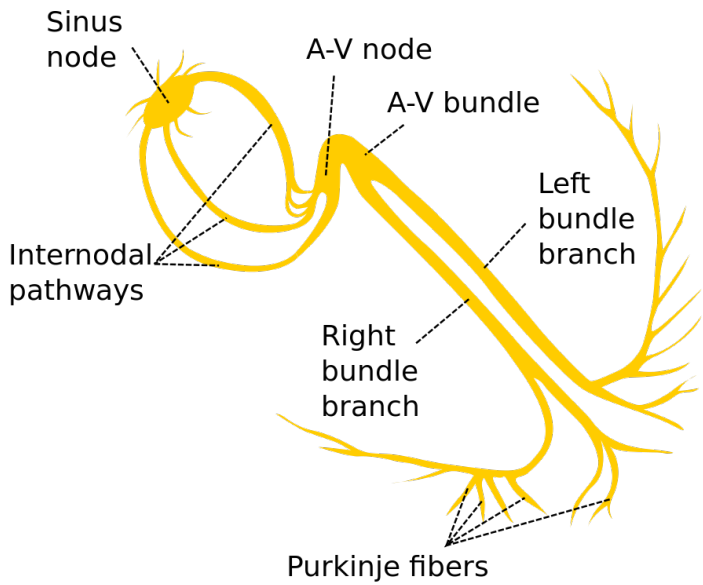
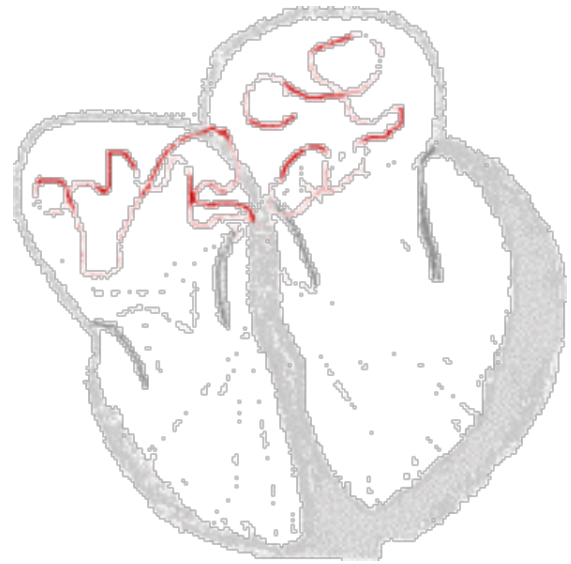


Causes:

- ➤ The heart's natural pacemaker (SA) develops an abnormal rhythm.
- ➤ The normal conduction pathway is interrupted.
- ➤ Another part of the heart takes over as pacemaker.

Cardiac Preliminaries. Tachycardia

Types of tachycardia:



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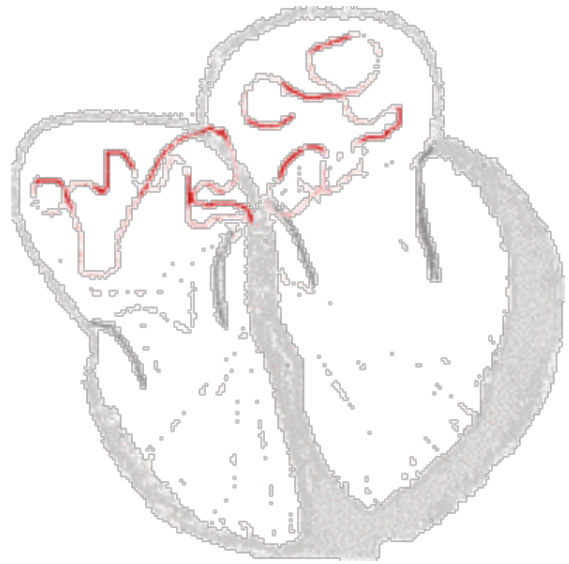

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- *Supraventricular tachycardia (SVT)* begins in the upper portion of the heart, the atria
  - Sinus Tachycardia
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  - Wolff-Parkinson-White Syndrome
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- *Ventricular tachycardia (VT)* begins in the heart's lower chambers, the ventricles
  - Premature Ventricular Contractions
  - Ventricular Fibrillation
  - Ventricular Flutter

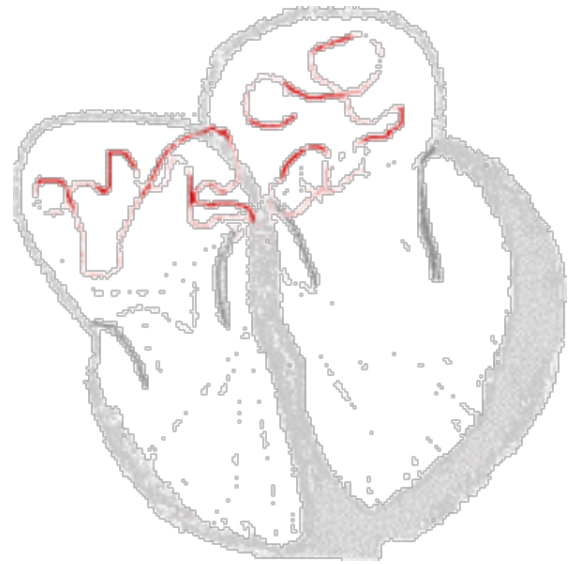
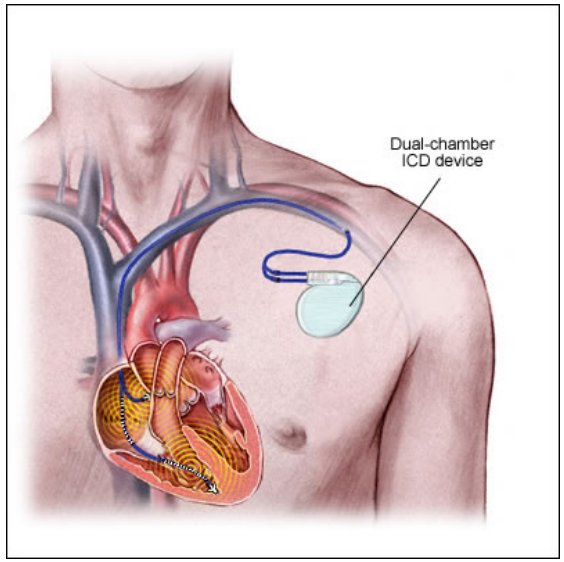
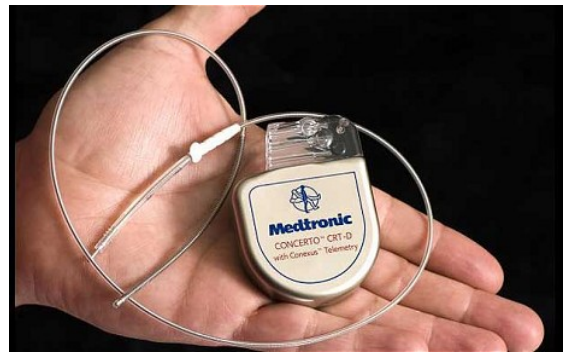


Image Credit: *Wikipedia. Electrical conduction system of the heart.*

Cardiac Preliminaries. Implantable Cardioverter Defibrillator (ICD)





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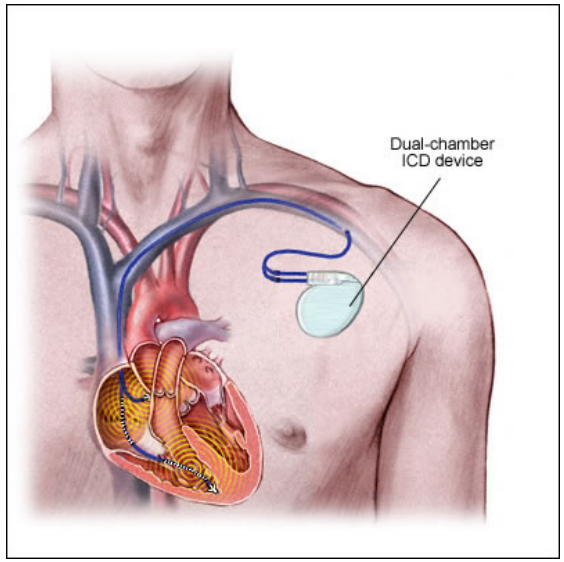

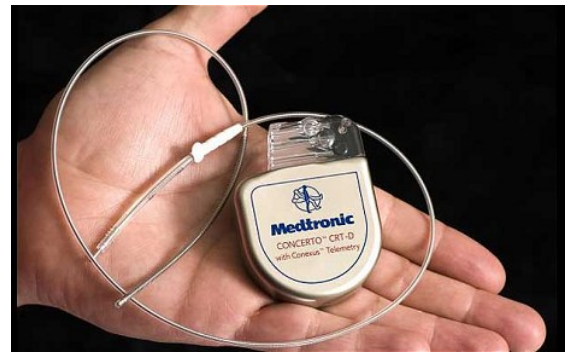

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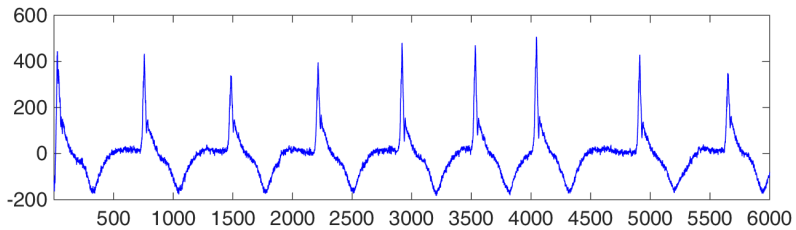
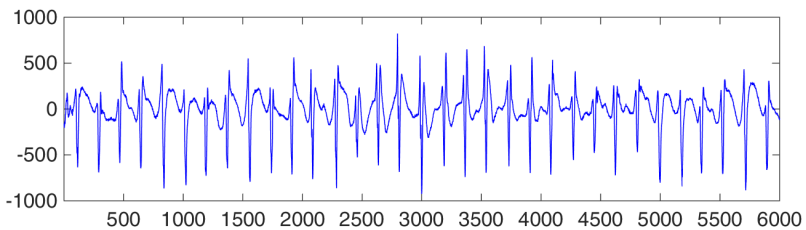


EGM signal: Ventricular lead



EGM signal: Atrium lead

Cardiac Preliminaries. Inappropriate shocking

Up to 40% of patients experience inappropriate therapy during long-term follow-up*.

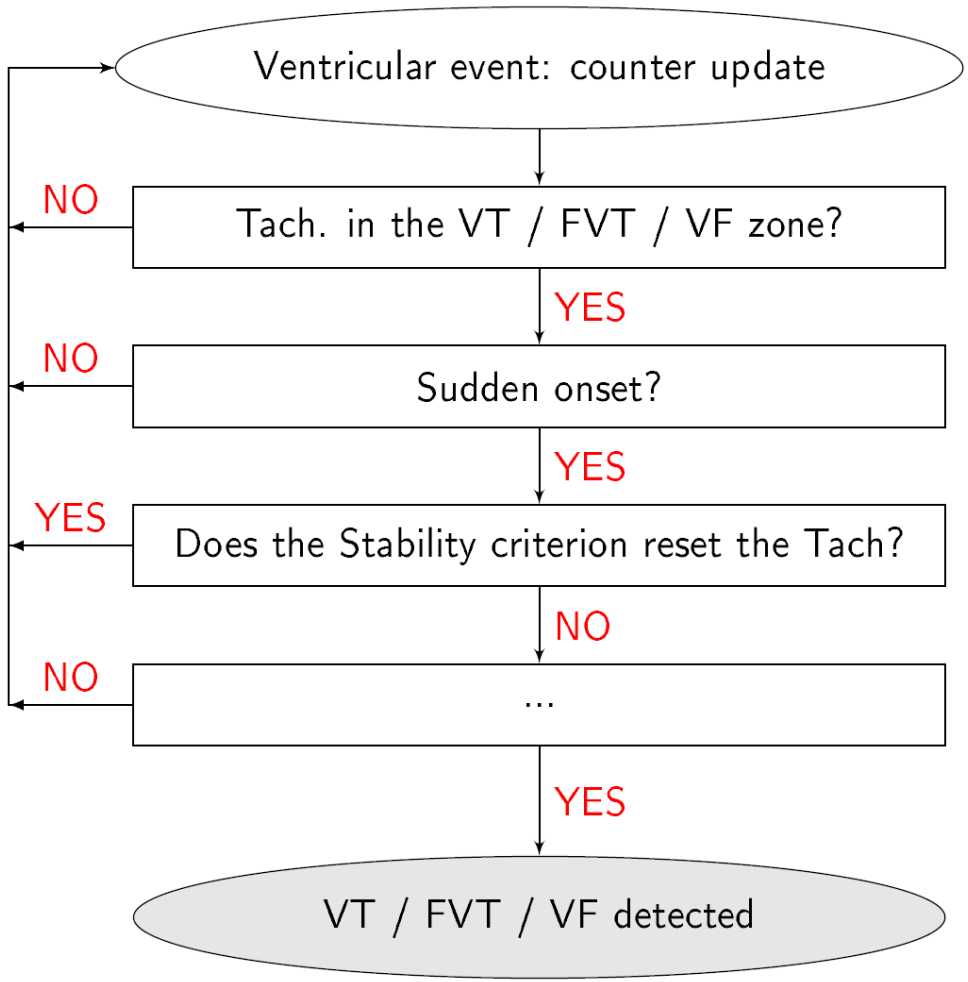
- Pain
- Anxiety
- Anger
- Stress
- Depression
- Fear $\Longrightarrow$ poor quality of life

[Video]

Image Credit: *UPenn.*

* *C. Dougherty et al., J Cardiovasc Nurs. 2009.*

Medtronic Discrimination Algorithm [5]



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Discrimination as a Logical Formula

We propose to formulate the VT/SVT discrimination problem as a *Runtime Verification* problem:

$$\mathcal{M} \models \Phi$$

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- Express desired operations as a logical formula Φ.
- During runtime, monitor whether the heart's electrical activity satisfies the formula.

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- During runtime, monitor whether the heart's electrical activity satisfies the formula.

Advantages:

- Parameters synthesis (e.g., Better thresholds set)
- Automatic monitors synthesis
- Combined approach: Sensing + Discrimination
- $\Longrightarrow$ Better performance

LTL: Linear Temporal Logic [6]

➤ *LTL Syntax*

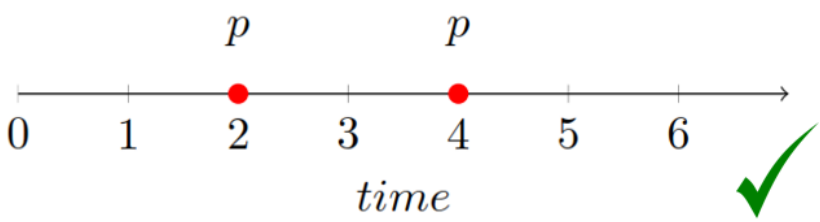
$$\Phi = \{ p \mid \neg\varphi \mid \varphi \vee \psi \mid \bigcirc \varphi \mid \varphi \, \mathcal{U} \, \psi \}$$

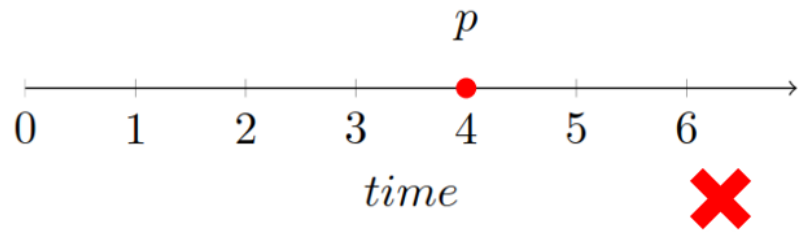
- $\varphi \wedge \psi = \neg(\neg\varphi \vee \neg\psi)$
- Finally operator: $\Diamond \varphi = \top \mathcal{U}_I \varphi$
- Globally operator: $\Box \varphi = \neg \Diamond_I \neg\varphi$

LTL: Linear Temporal Logic [6]

Example.

$$(x, 1) \models \bigcirc p$$





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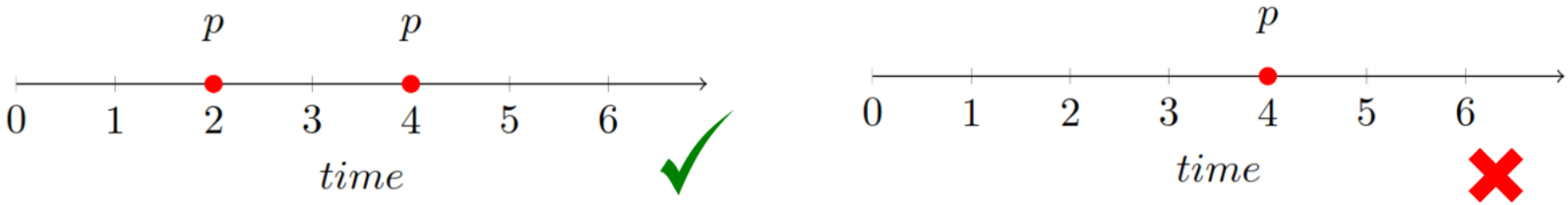
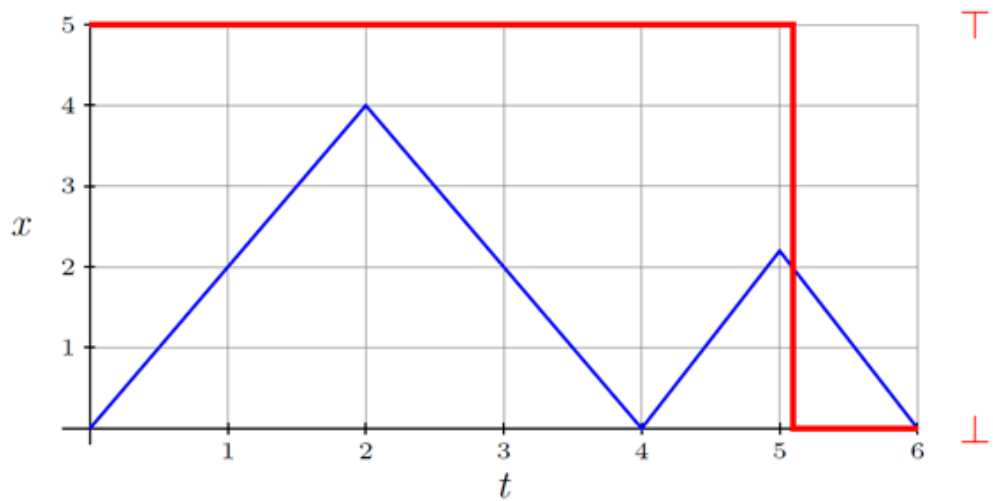
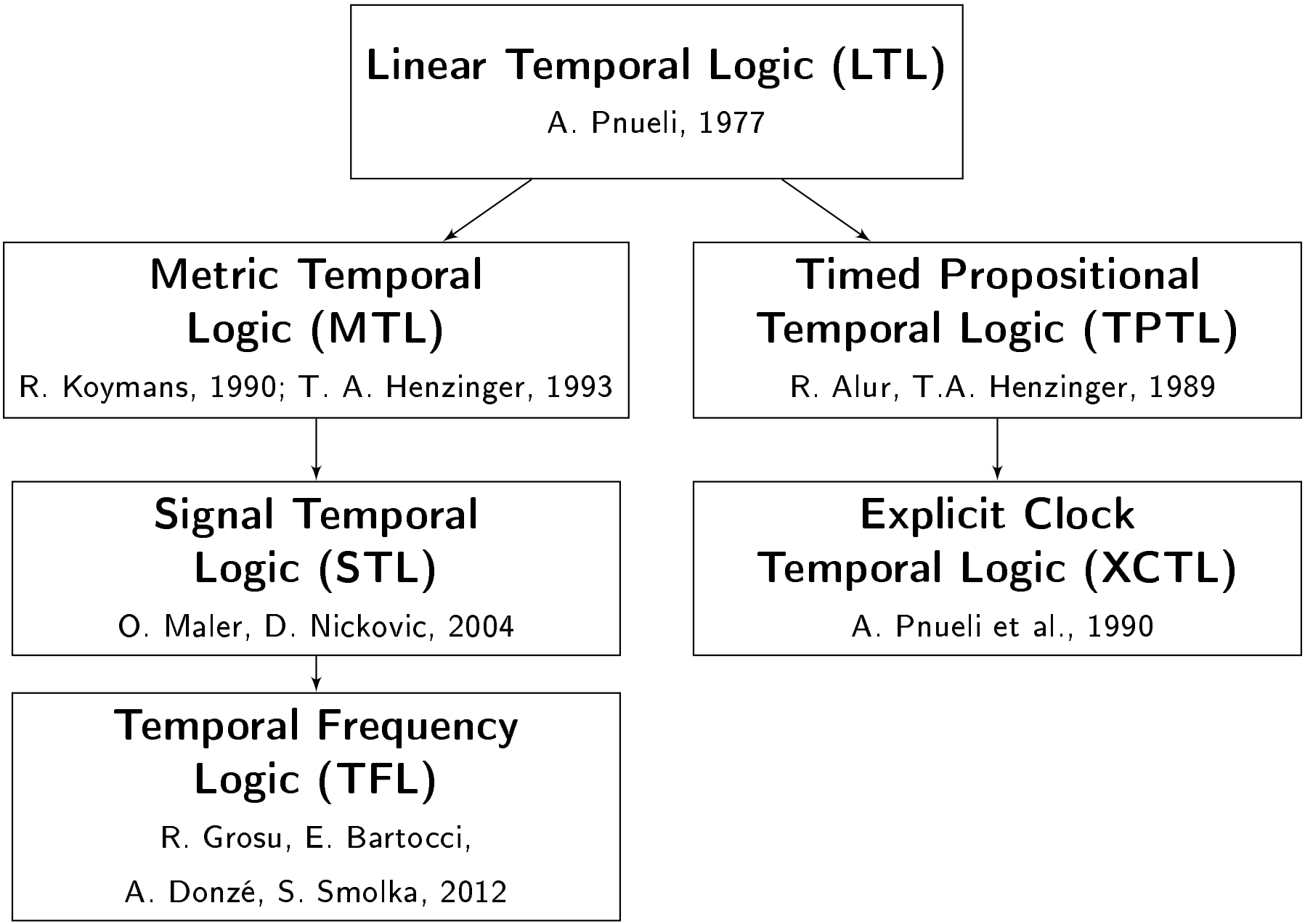


Example.

$$\varphi = \Diamond(x \geq 2)$$



Families of Temporal Logics



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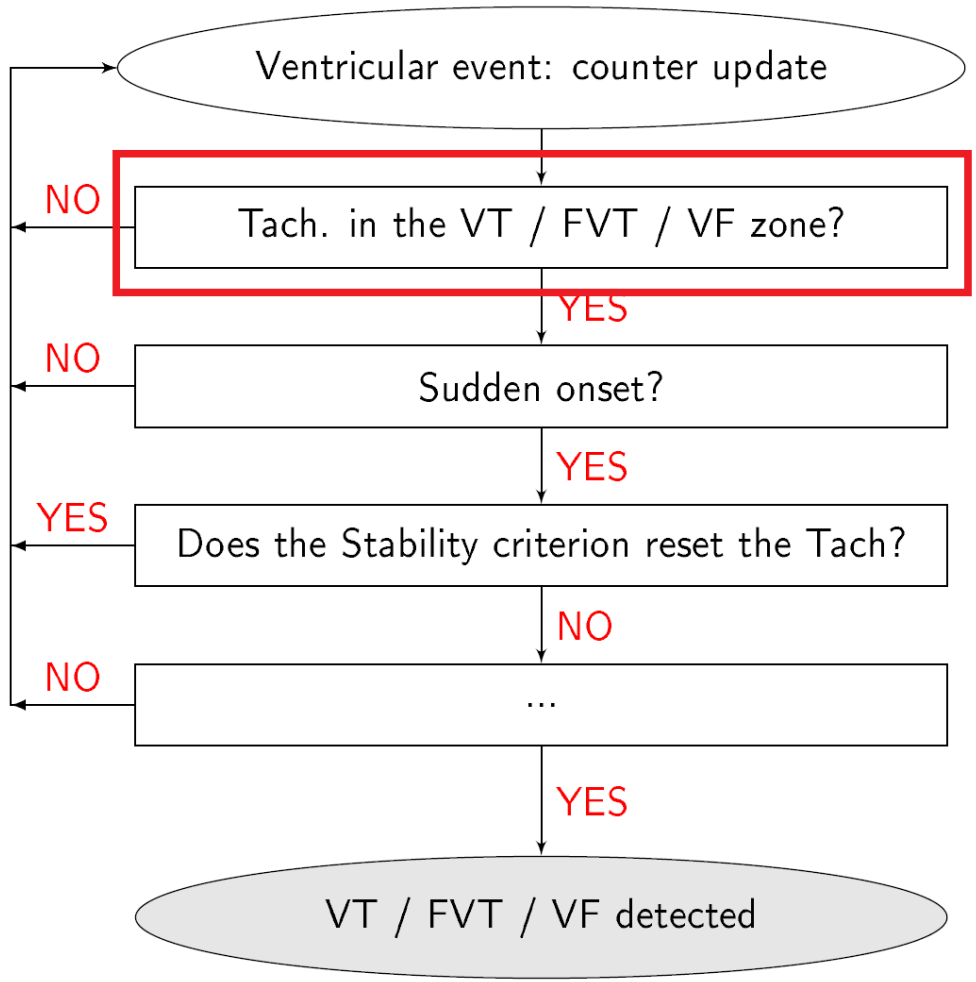

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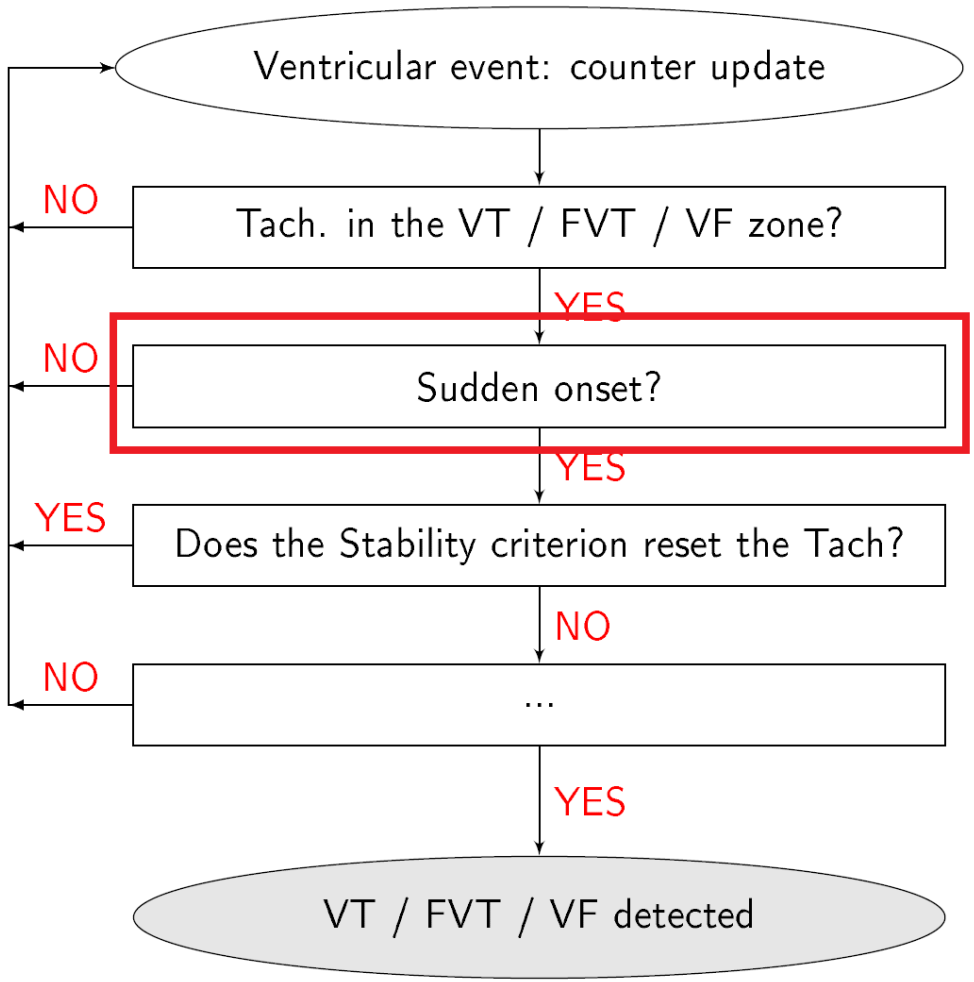

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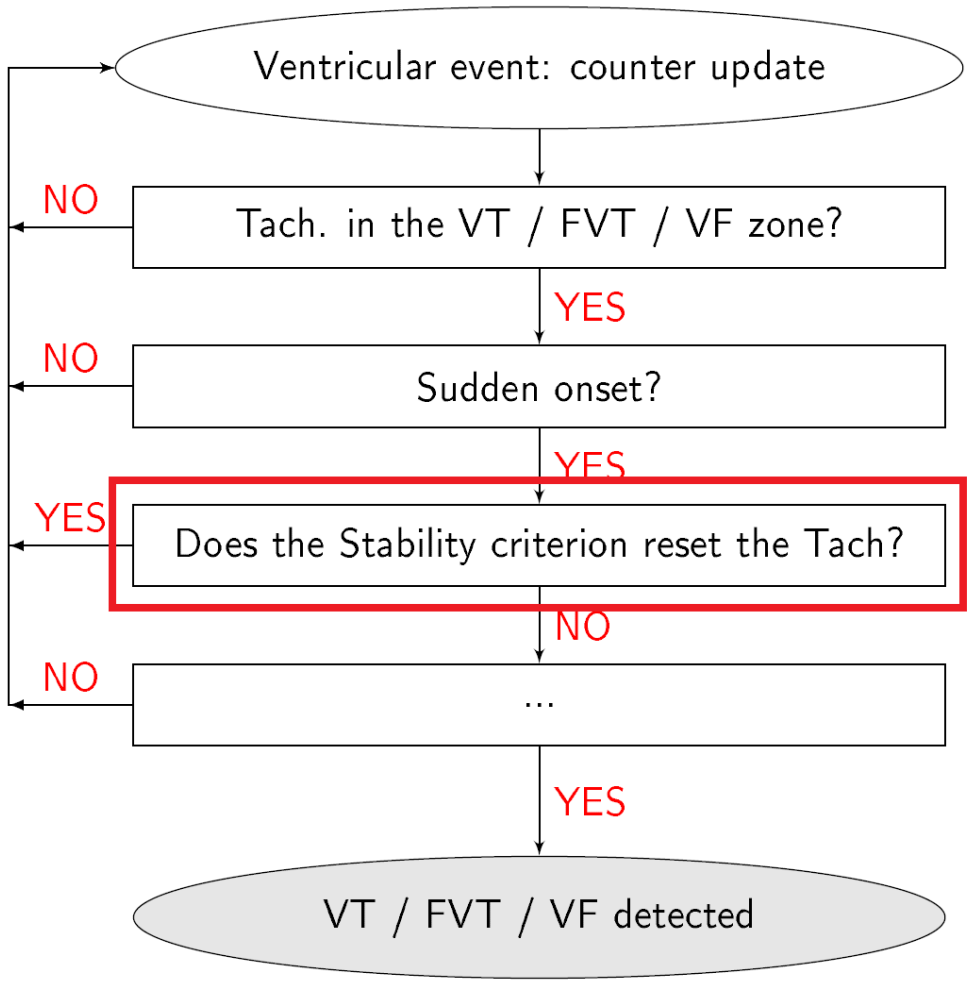

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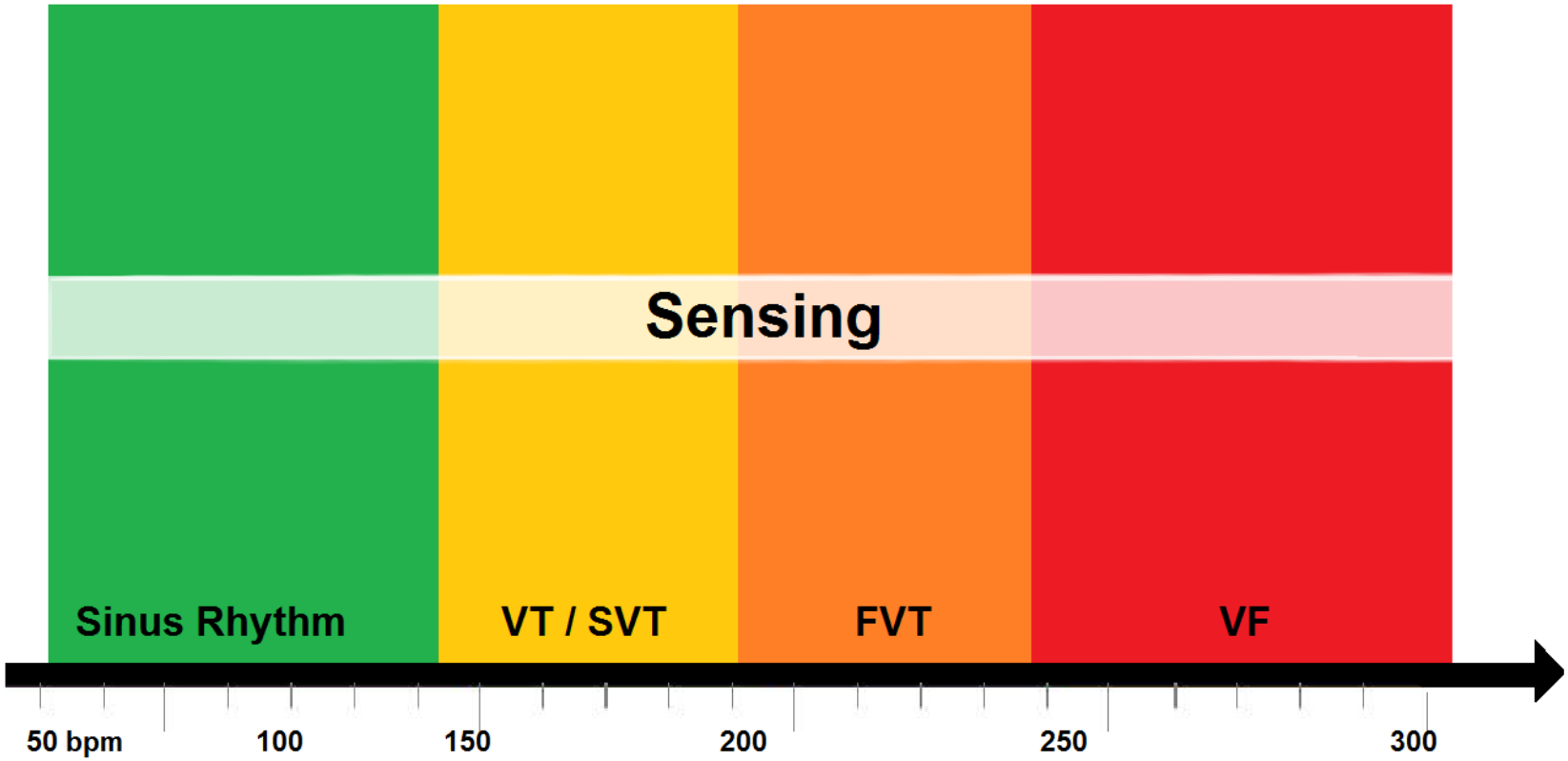
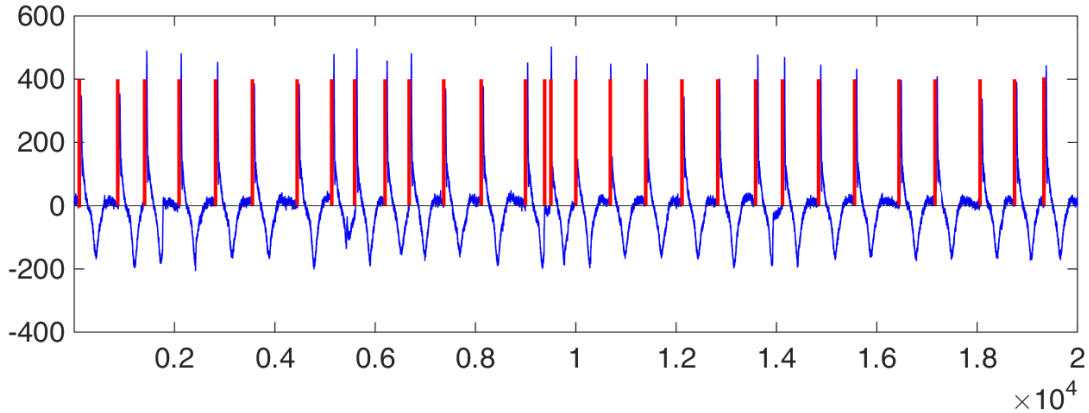
Tachycardia zones



- Is Tachycardia in the VT, FVT or VF zone?
- How to specify it in a logical formula φ, such that $\mathcal{M} \models \varphi$?

1. Is Tachycardia in the VT, FVT or VF zone?

- Assume we are given a Boolean signal x:



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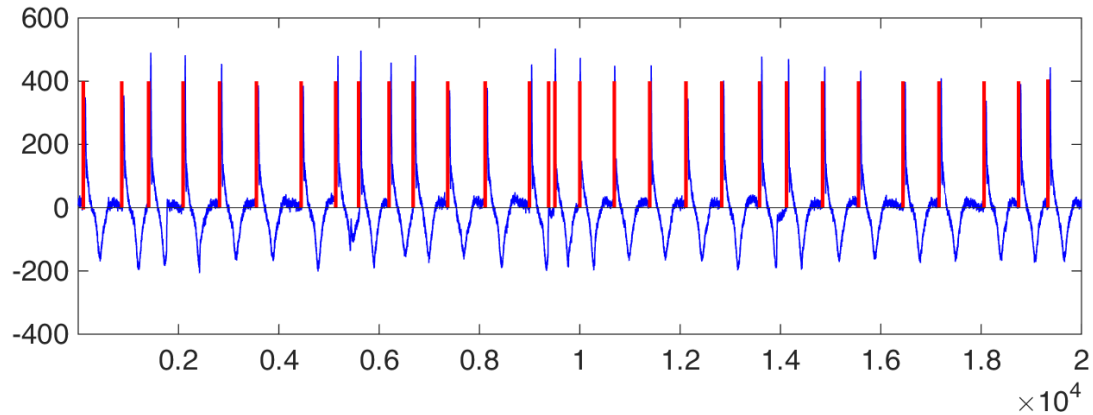

- Syntax

$$\Phi = \{\, p \quad | \quad \neg\varphi \quad | \quad \varphi \wedge \psi \quad | \quad \varphi \, U_I \, \psi \quad | \quad C_I^{\geq n}\varphi \} \qquad (1)$$

Counting modality $(\rho, i) \models C_I^{\geq n}\varphi$ iff $|N^{\rho}[i, I](\varphi)| \geq n$ states, that the number of times formula φ holds within the time interval I is at least n.

[3] *Metric Temporal Logic with Counting, Madnani et al., 2015.*

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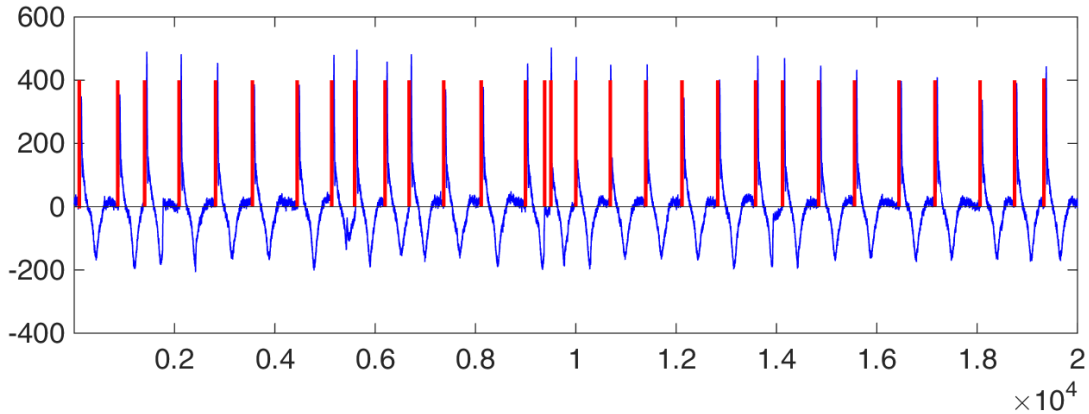

- Example. Two minutes after the start of exercise, the heartbeat should be between 90 and 120.

$$\square \left(st \rightarrow \left(C^{\geq 90}_{[120,180]} p \wedge C^{<120}_{[120,180]} p \right) \right)$$

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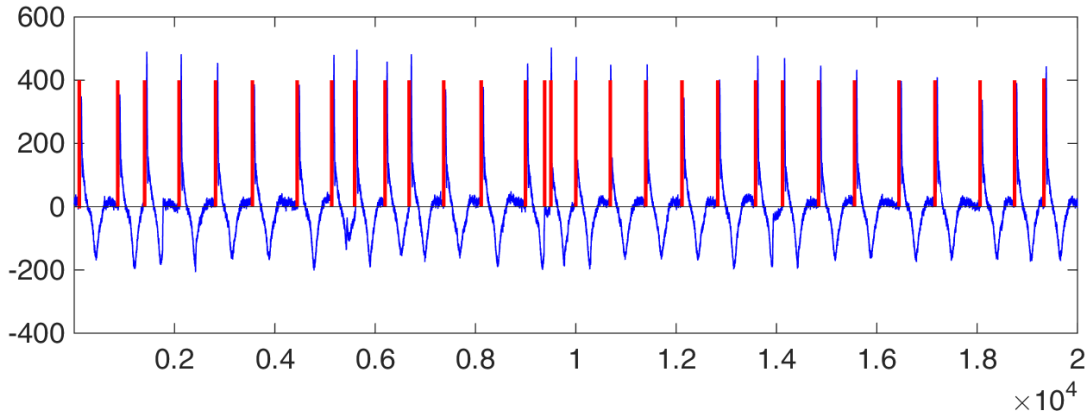

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- Theorem (Expressiveness Hierarchy). MTL $\subset$ CMTL.

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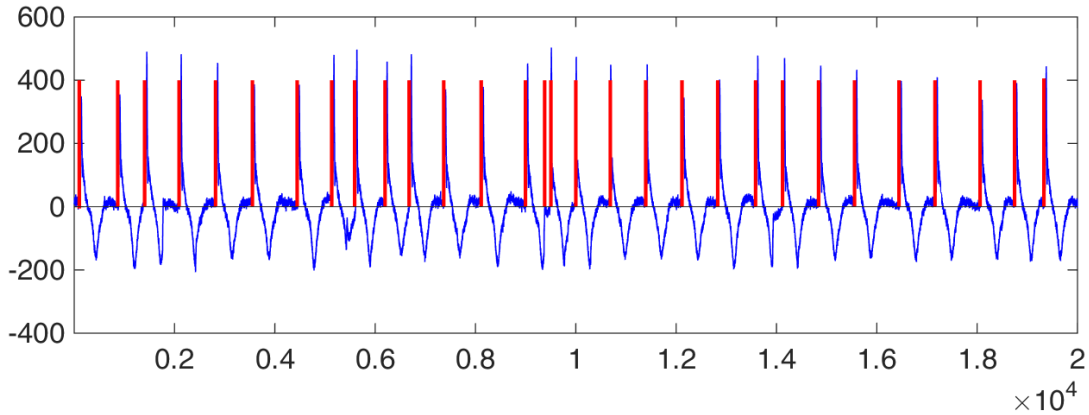

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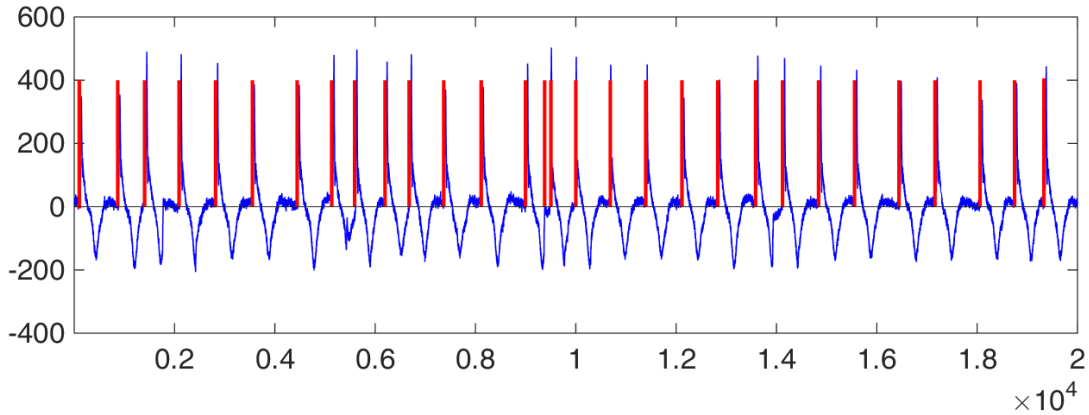
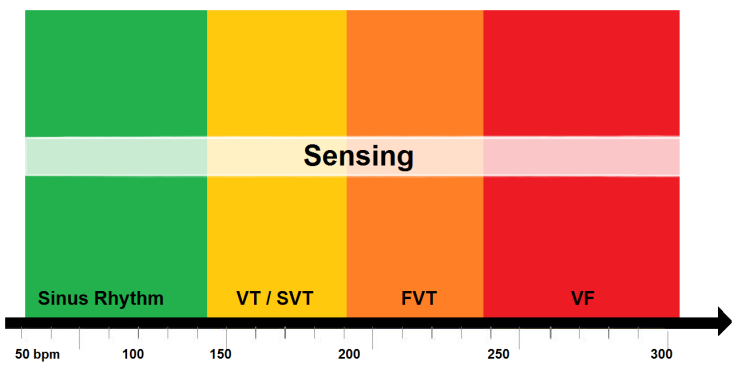


- CMTL-specification

$(\xi, t) \models$ "Tach is in the VT/FVT/VF"

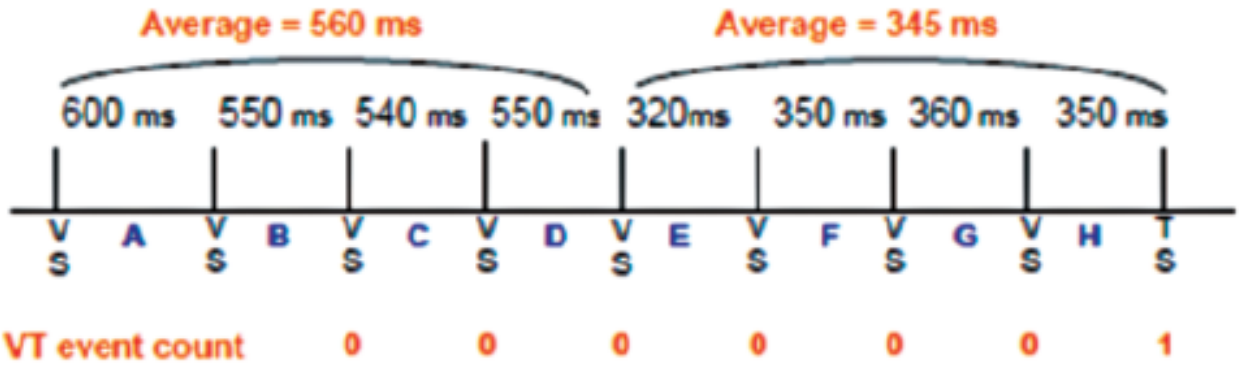
$\Longleftrightarrow$



$$(\xi, t) \models \{C^{\geq thr_1}_{[0,60]} p \wedge C^{<thr_2}_{[0,60]} p\}$$

2. Is the Sudden Onset detected?

$$[\text{A, B, C, D}] \cdot 81\% > [\text{E, F, G, H}] \implies \text{Sudden Onset detected}$$



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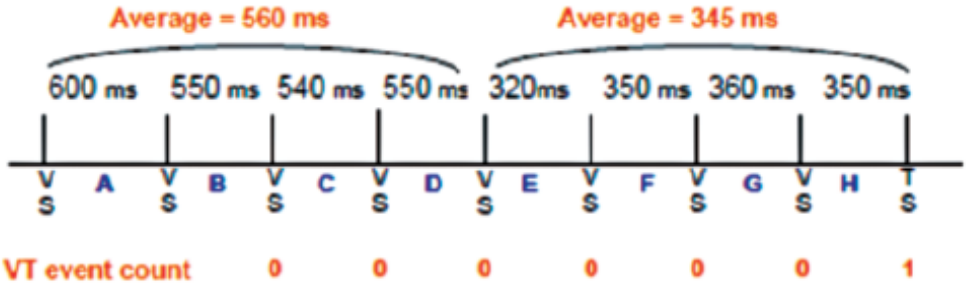

Example: onset criterion programmed at 81 %

[E,F,G,H] < [A,B,C,D] x 81 %
345 < 560 x 81 %

=> sudden onset detected.

PROGRAMMING RECOMMENDATION

Nominal value : 81 %

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$$(\xi, t) \models \text{“Sudden Onset”} \iff (\xi, t) \models \Phi$$

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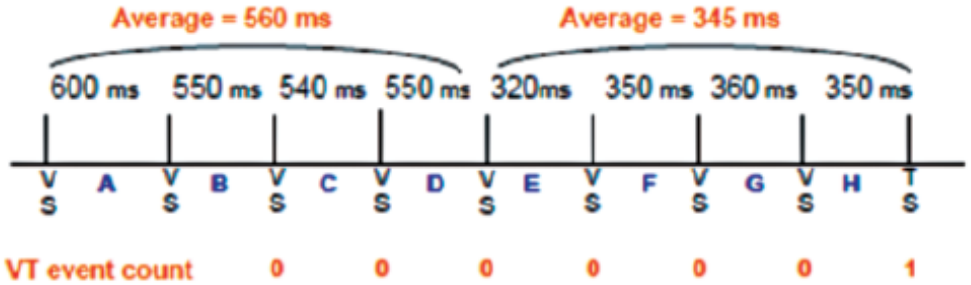

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$$\Phi := \Big\{ p \wedge (x_1 = T) \wedge \diamondsuit(p \wedge \ldots \diamondsuit(p \wedge (x_9 = T))))) \\ \wedge\ (x_5 - x_9) * 0.81 \geq x_1 - x_5 \Big\}$$

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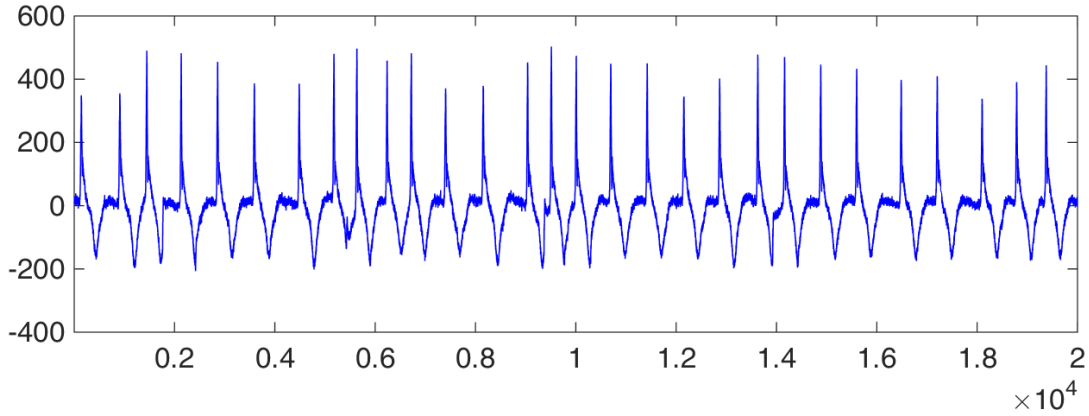

Figure: EGM signal. Sensing

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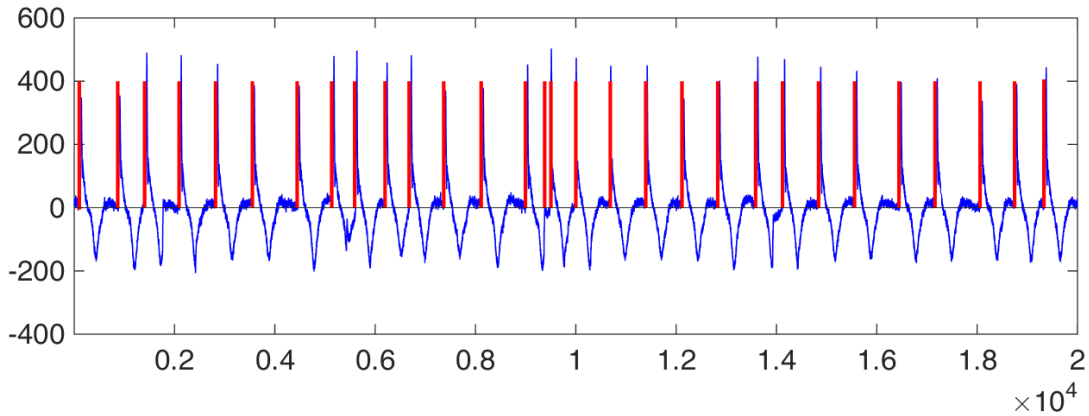

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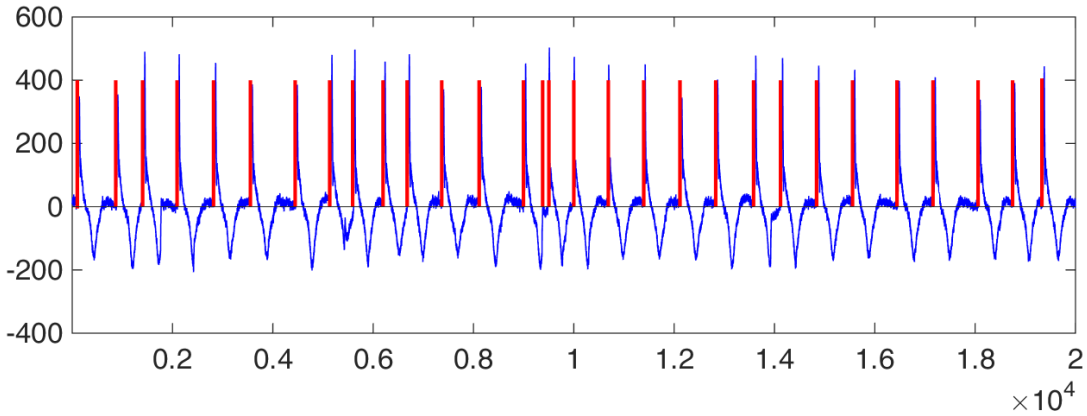

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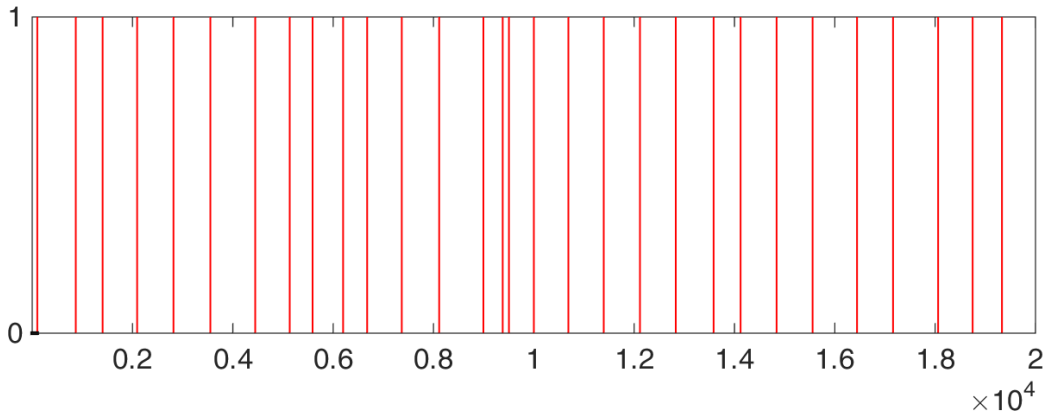
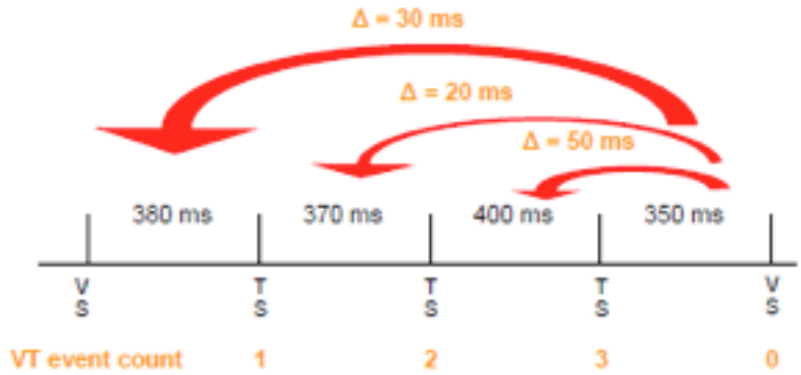


Figure: Monitor. Sudden Onset Detection

3. Stability?

- Used to prevent inappropriate therapy for AF with a rapid ventricular rate, which is usually irregular, whereas it is usually regular during VT.



Example:
Stability programmed at 40 ms : the difference between 4th and 3rd intervals is 50 ms :

=>Unstable rhythm and VT event count reset to 0.

PROGRAMMING RECOMMENDATION :

Nominal value : 40 ms

- STL-specification

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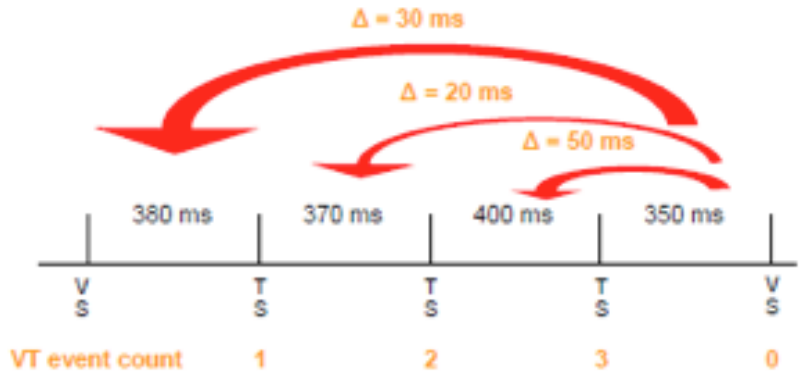

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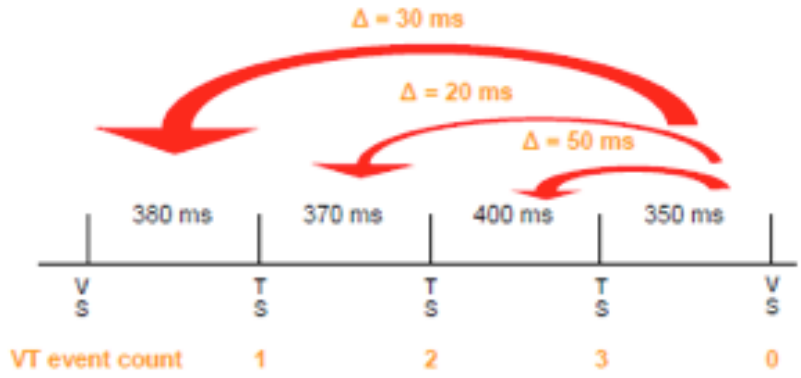

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$$(\xi, t) \models \text{“Unstable”} \iff (\xi, t) \models \mu_0 \wedge (\mu_1 \vee \mu_2 \vee \mu_3)$$

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