

# AUTOMATIC IDENTIFICATION OF CARDIAC ACTIVATIONS IN THE MULTI-CHANNEL INTRACARDIAC ECGs

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**Abstract:** A novel algorithm is presented in this paper, which can precisely identify the cardiac activations (e.g., A, V, H waves) in the multi-channel intracardiac electrogram (IECG) signals. The aim of this work is to achieve an automatic analysis during the electrophysiological (EP) study. It saves an amount of the time for the physicians compared with manual work, especially for the long-duration diagnosis or operation. The development of the algorithm complies with the various stimulation protocols in the EP lab. The effective digital signal processing techniques and the proper application of the relationship between the surface ECG (SECG) and intracardiac ECG enable the algorithm to achieve the satisfied sensitivity. Finally, 11 patients' data including more than 6000 meaningful cardiac activations are randomly collected from an EP (electrophysiology) lab to evaluate the algorithm. A comparison is made between the manual annotation of the physicians and the result of the algorithm. The sensitivity of the V, A, H wave detection reaches 98.99%, 96.64%, and 97.31% respectively.

**Keywords:** Electrophysiology, EP, ECG, intracardiac ECG, HIS bundle.

## INTRODUCTION

EP study is an invasive procedure on purpose to characterize the electrophysiologic properties of the conduction system, induce and analyze the mechanism of arrhythmias. The multi-electrode catheters are inserted into the heart chambers to record the IECGs or to stimulate a specific region of the heart. According to the different diagnostic programs and the stimulation protocols in the EP study, the interesting cardiac activations, including the atrial potential (A), the ventricular potential (V), and the HIS bundle potential (H), need to be recognized in the IECGs. The sequence and the interval of these waves are used to measure how the cardiac activations are conducted from one area to another in the heart. In most applications, the wave recognition and measurement are done manually in the hospital.

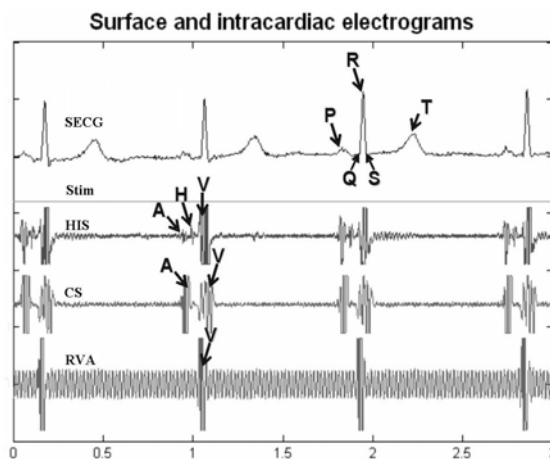
The result of MUSTT (Multicenter Unsustained Tachycardia Trial) presented that the EP-guided therapy can achieve 27% reduction in risk of arrhythmic death and cardiac arrest for patients with coronary artery disease, left ventricular ejection fractions and inducible sustained ventricular tachycardia (VT). The risk is even

reduced by greater than 50% for the patients treated with an ICD (implantable cardioverter-defibrillators) after the EP study [1].

In this paper, an automatic wave identification algorithm is developed using the advanced signal processing technique based on the EP stimulation protocols. The high accuracy of this algorithm is beneficial to the physicians to make the diagnosis less time consuming.

## ALGORITHM DESCRIPTION

An EP lab is normally equipped with radiographic equipment, a recording and monitoring system, a stimulator, and all drugs and equipment required for complete cardiopulmonary resuscitation [2]. The number of the IECG signals are traditionally the HIS (HIS bundle), the HRA (high right atrial), the CS (coronary sinus) and the RVA (right ventricular apex). Standard 12-lead body surface ECGs are recorded simultaneously. Besides, the necessary stimulation information is acquired from the programmable stimulator, that is, whether the electrical pacing is placed, on which catheter the pacing is placed. Fig.1 shows an example of the signals under the normal investigation (no stimulation is applied). In our system, the sample rate of the signals is 2000 Hz. The onsets of the A, H, and V waves in the HIS are most important to the diagnosis. The onsets of the A and V waves in the HRA or CS signal can also provide very valuable information. In the RVA signal, usually only the V wave is useful for the physicians.



**Fig. 1** Waves on surface and intracardiac ECGs.

However, the sequence and morphologies of the waves will change significantly during the different stimulation scenarios. Furthermore, the electrical interference can distort the IECGs and make the detection of the waves more difficult. In order to improve the quality of the detection, the following strategies are applied in our algorithm:

1) The electronic interferences in the IECGs are analyzed and reduced as much as possible in the pre-processing stage;

2) A highly accurate QRS detection method is used to find the onset of the V wave in the IECGs;

3) The positions and the number of the pacing pulses are checked in each V-V interval, which indicates the type of the study being performed. It leads the algorithm to different branches to accurately detect the A, H waves.

Fig. 2 illustrates the structure of the algorithm.

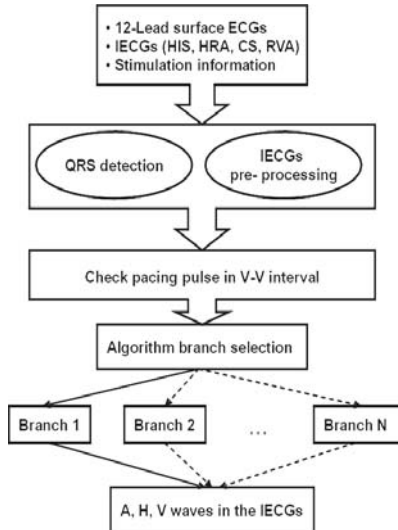


Fig. 2 Algorithm structure.

### Pre-processing stage of the IECGs

There are two goals in this phase: one is to reduce the interferences, the other one is to calculate the envelope signals of the IECGs to simplify the wave detection. The whole processing is shown in Fig. 3.



Fig. 3 Pre-processing stage of the IECGs.

Pacing pulse is sent to one electrode of a catheter by the stimulator, however, the influence of the pacing pulse can cause distortion on other signals, which is called 'pacing artefact'. It has random amplitude in different IECGs and similar morphologies as other useful waves. In our system, the artefact is largely

eliminated by the estimation of its position and width from the stimulator.

Another main interference is the signal ripples caused by the catheter insertion (Fig. 4). The frequency components of the signal ripples are analyzed by calculating its power spectrum density (PSD). It occupies 40~60 Hz. Therefore, a digital band-stop Butterworth filter is designed to restrict these ripples.

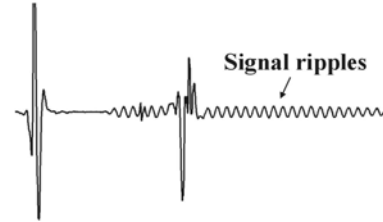


Fig. 4 Signal ripples in the IECGs.

After the band-stop filter, an absolute operation is firstly performed; then a non-linear transform based on Hilbert transform is applied. Assume the input signal is  $x(n)$ .

$$x(n) = b(n) \cos(\omega_m n + \Phi) \quad (1)$$

The envelope  $b(n)$  can be extracted from  $x(n)$  without any knowledge of the modulation frequency  $\omega_m(n)$  or the phase shift  $\Phi$ . Its analytic signal  $z(n)$  can be expressed as

$$z(n) = x(n) + j\hat{x}(n). \quad (2)$$

The envelope  $b(n)$  is calculated as:

$$b(n) = |z(n)| = \sqrt{x^2(n) + \hat{x}^2(n)}. \quad (3)$$

The equation (3) can be replaced here by an experienced approximation to reduce the calculation:

$$\hat{b}(n) = |x(n)| + \frac{2}{\pi} |x(n+1) - x(n-1)|. \quad (4)$$

The last step in the pre-processing phase is a linear low-pass filter. The output  $y(n)$  of the low-pass filter is the smoothed envelope of the input signal  $x(n)$ .

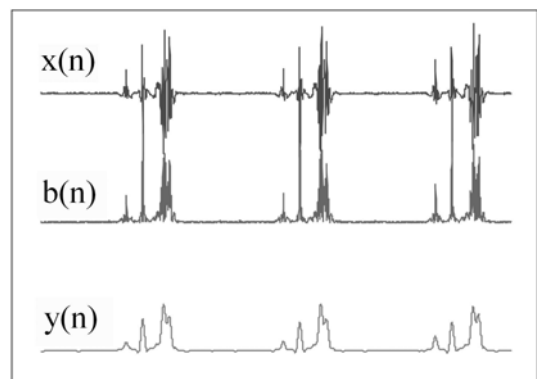


Fig. 5 Envelope signal of the IECGs:  $x(n)$  - signal after the band-stop filter;  $b(n)$  - signal after the non-linear transform  $y(n)$  - signal after the low-pass filter.

## QRS complex detection

The first step of the wave identification in the IECGs is to find the V-V interval. Normally the potential of the V wave is much larger than the other waves in the HIS signal, however, it becomes sometimes comparable to the A wave or coincides with the A wave due to various placements of the catheters.

Therefore the Q wave in the surface ECG signal II is detected as the reference of the V wave onset because the Q wave indicates the onset of the ventricular activation. A wavelet based QRS complex detection algorithm is applied and it is proved that this algorithm can achieve around 99% sensitivity and positive predictivity by testing the MIT arrhythmia database and the QT database from the Physionet [3] (the online research resource for complex physiologic signals). The frequency components of the QRS complex is between 12~25 Hz. In order to reduce the computational load, the signal II is downsampled to 250 Hz.

The detection becomes more difficult if the stimulation is placed in the right ventricular apex, which leads to an inversed cardiac conduction. Such stimulation is called 'retrograde pacing', in contrast to 'antegrade pacing'. Hence the window to search the retrograde beat is defined as 200 ms after each retrograde pacing pulse.

Once a new QRS complex is detected, the time window between the last two QRS complexes will be focused to perform the wave identification in the IECGs and their enveloped signals.

### Algorithm branches of the wave identification

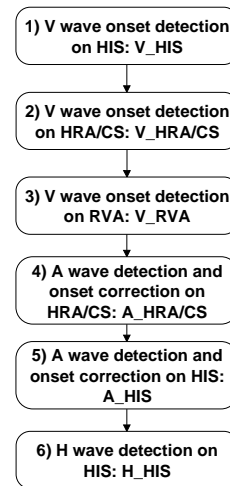
Referring to the different diagnostic programs and the stimulation protocols in the EP lab, the following algorithm branches are defined to detect the A, H, V waves. The classification of the branch is according to the number of the pacing pulses within the V-V interval (Table 1). Such structure makes it easier to modify or extend the functions of the algorithm.

Branch	Number of pacing pulses in V-V interval	Diagnosis mode	HRA/CS existence
1	0	-	Yes
2	1	Antegrade	Yes
3	2	Antegrade	Yes
4	1	Retrograde	Yes
5	0	-	No

**Table 1:** Branches of the wave detection in the IECGs.

The main criterion to identify the waves is based on the sequence of the wave appearance under different conditions and their amplitude relationships. Therefore, empirical searching windows together with the adaptive thresholds are considered for each branch. The adaptive thresholds mean that the thresholds are adapted by the estimated baseline in each V-V interval.

*Branch 1* – No pacing pulse in the V-V interval, catheters are placed at HIS bundle, HRA or CS, RVA to investigate the conduction system of the patient. This is the most usual case in the EP study. Fig. 6 illustrates the common procedure of the wave identification. 1) V wave onset in the HIS signal derived from the Q wave. If the mapping point in the HIS envelope is over the threshold of the V wave, the onset of the V wave is backward searched within a 30 ms window. Otherwise, the onset of the V wave is forward searched in the filtered HIS signal. The forward correction can avoid detecting the V wave onset too early. 2) The detected V wave onset detection in the HIS signal is further mapped to the HRA or CS. Different threshold levels are defined to search the V wave onset in the HRA and CS. 3) If there is catheter in the RVA, the V wave can be also detected around the detected V wave onset in the HIS signal. 4) Normally the A wave has larger potential in the HRA or CS than that in the HIS, so it can be easier discovered. Hence the A wave is firstly identified in the HRA or CS. The maximal peak in the V-V interval, which is over the threshold, is considered as the A wave. 5) The A wave in the HIS signal is further searched in the window around that in HRA or CS. Its onset is further backward corrected in a 20 ms window. 6) The last step is the H wave detection in the HIS signal. Different windows are applied to search the H wave according to whether there is an A wave and how large the distance between the A and the V wave is in the HIS signal.



**Fig.6** The common procedure of the wave's identification.

*Branch 2* – One antegrade pacing pulse is placed in the V-V interval in the HRA or CS signal. It leads to a random appearance of the A wave, therefore it is difficult to find the A wave. In the normal case, the A wave occurs within 60 ms after the pacing pulse. However, if the antegrade pacing pulse is placed a short time before the V wave onset, there may be no atrial activation after the pacing pulse for the atrium can be still in its effective refractory period (ERP). Moreover, another condition called AV-node ERP can occur, that

is, the conduction is broken in the AV-node. In consequence, there are two A waves in the V-V interval.

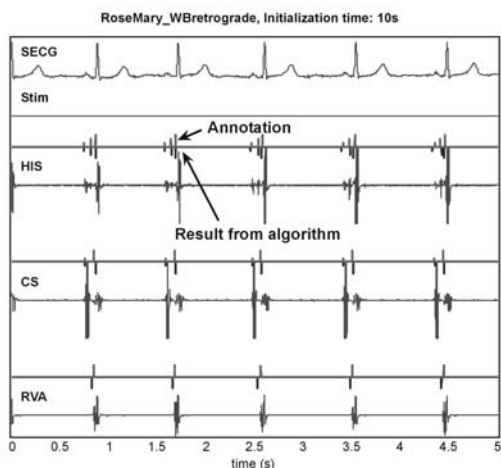
*Branch 3* – Two antegrade pacing pulses exist in the V-V interval during the fast continuous pacing or gradual decrease of the pacing interval (e.g., Wenckebach point analysis). The possible A wave after the first pacing pulse is searched as the largest peak between both pacing pulses. The A wave after the second pacing pulse is searched using the same rules as branch 2.

*Branch 4* – One retrograde pacing pulse is placed in the V-V interval in the RVA signal. The retrograde pacing causes inversed cardiac conduction from ventricular to atrium. So the wave sequence after the pacing pulse is first a V wave and then an A wave under the normal condition. However, the V wave and A wave can often coincide, which enhances the difficulty to detect the A wave in the HIS signal.

*Branch 5* – A normal investigation as in branch 1, however, no catheter is placed at HRA or CS. It is not easy to separate the A and H wave only using the HIS signal. As a solution, the detection of the P wave in the signal II is applied as a reference to define the window of the A wave detection in the HIS signal.

## TEST METHOD

The algorithm is developed in Matlab and is validated using the patient's data from an EP lab, which are collected from 11 patients including more than 6000 meaningful cardiac activations. These data are digitally annotated by the physicians using the coding format: '1' indicates the A wave, '2' indicates the H wave, '3' indicates the V wave. The output of the algorithm uses also the same codes. The figures in Matlab are plotted to analyze the results. Fig. 7 shows an example of the figure that compares the manual annotation and the result yielded by the algorithm. The manual annotation is plotted above the annotation line; the result from the algorithm is plotted below the annotation line.



**Fig. 7** Example of the plotted test result.

## RESULT AND CONCLUSION

The following tables conclude the test result. Table 2 shows the results of the all annotated waves, the sensitivities of the V, A, and H wave detections are 98.99%, 96.64% and 97.31% respectively. Then the noise signal is removed in the statistics of Table 3 so that the results are slightly improved. Table 4 and Table 5 extract the results under the conditions of antegrade pacing and retrograde pacing. As to the retrograde pacing, the H wave is often invisible in the HIS signal and the detection is clinically less useful.

	Number of the annotation	Number of the detection	Sensitivity (%)
V wave	2483	2458	98.99
A wave	2708	2617	96.64
H wave	967	941	97.31

**Table 2:** Results of all annotated waves.

	Number of the annotation	Number of the detection	Sensitivity (%)
V wave	2479	2458	99.15
A wave	2689	2617	97.36
H wave	966	941	97.41

**Table 3:** Results excluded the noised signal.

	Number of the annotation	Number of the detection	Sensitivity (%)
V wave	757	756	99.87
A wave	761	744	97.77
H wave	322	307	95.34

**Table 4:** Results of all the antegrade pacing beats.

	Number of the annotation	Number of the detection	Sensitivity (%)
V wave	182	180	98.90
A wave	221	200	90.50

**Table 5:** Results of all the retrograde pacing beats.

The results show that the performance of the algorithm is comparable to the manual recognition. The implementation of the algorithm can be expected to help the physicians largely improve the efficiency during the EP study.

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