# Analysis of Unpredictable Intra-QRS Potentials Based on Multi-Step Linear Prediction Modeling for Evaluating the Risk of Ventricular Arrhythmias

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**Abstract**

*The abnormal intra-QRS potentials (AIQP) have been proposed to evaluate the risk of ventricular arrhythmias. However, the extremely low signal-to-noise ratio (AIQP vs. normal QRS) and the overlap between AIQP and normal QRS would limit the accuracy of AIQP estimation. This study proposed a multi-step linear prediction modeling to estimate all of the unpredictable intra-QRS potentials (UIQP) for evaluating the risk of ventricular arrhythmias.*

*The simulation results were showing that the prediction error signal can reflect the variations at slope discontinuities of QRS complex, including onset, offset, sharp R wave and AIQP. The results have also showed that the significant reduction of UIQP in patients with ventricular tachycardia may be new promising evidence of ventricular arrhythmias.*

## 1. Introduction

High-resolution electrocardiogram is an important non-invasive tool to evaluate the risk of ventricular arrhythmias. That ventricular late potentials (VLP) outlast the normal QRS interval has been associated with a reentry substrate for ventricular arrhythmias [1]. Although VLP were initiated from within the normal QRS interval, they are actually characterized by the signal portion that outlasts this interval. Time-domain signal-averaged electrocardiogram (SAECG) parameters have been widely employed to quantify VLP, including the filtered total QRS duration (fQRSD), the root-mean-square voltage of the last 40 ms of the QRS complex (RMS40) and the duration of the low-amplitude signals of the terminal QRS complex below 40 $\mu$V (LAS40) [1]. However, the major limitations of time-domain analysis are an incomplete characterization of reentrant activity [2] and the poor accuracy of positive prediction [1].

Numerous investigations have suggested that the activity of a reentry substrate of ventricular arrhythmias may be completely contained within the normal duration of the QRS [3,4]. Gomis *et al*. [5] proposed an autoregressive moving average model in the discrete cosine transform domain to extract abnormal intra-QRS potentials (AIQP) which represent the transient, unpredictable part of the QRS. However the overlap between extremely low-amplitude AIQP and normal QRS complex would limit the accuracy of AIQP estimation. The estimated AIQP may also involve part of the normal QRS complex. Hence the clinical results remain controversial [5-7].

Instead of estimating the low-amplitude AIQP only, this study proposed a multi-step linear prediction (MLP) model to extract all of the unpredictable intra-QRS potentials (UIQP) for evaluating the risk of ventricular arrhythmias.

## 2. Methods

### 2.1. Materials and data acquisitions

A total of 72 patients, 30 patients with VT and 42 control subjects, at institution from Taiwan were recruited for the study. Two study groups were aged-matched. High-resolution electrocardiograms were recorded using a commercially available Simens-Elema Megacart® machine with a bipolar, orthogonal X, Y and Z, lead system. The ECG signals were amplified about 300 times so that they reached a signal level suitable for the analog to digital converter. A sample of 10 min raw ECG with 12-bit resolution at 2 kHz was stored on computer hard disk for subsequent analysis. Signal averaging was performed to lower the effects of the random noise [1].The final noise level of SAECG measured with a 40–250 Hz bidirectional Butterworth filter was less than 0.7μV. The onset and offset of the QRS complex were obtained from vector magnitude analysis [1].

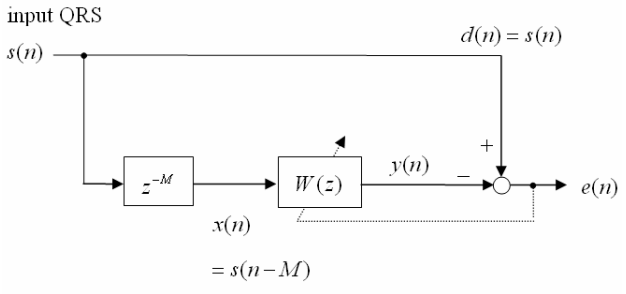


Figure 1. Block diagram of the multi-step linear prediction modelling.

## 2.2. Multi-step linear prediction modeling

The MLP modeling used the linear combination of some past input samples determined by the prediction depth and filter length to estimate the next sample data. The prediction error signal was considered as the linearly unpredictable part. Figure 1 is the block diagram of MLP modeling, where $s(n)$ is the input QRS signal, $M$ is the time-delay length or prediction depth, and $W(z)$ denotes the system function of an finite-impulse-response (FIR) Wiener filter. The design of an FIR Wiener filter is to produce the minimum mean-square estimate of a given desired input $d(n)$ by filtering a set of observations of a related reference input $x(n)$. The output of this FIR prediction filter of order $q$–1 has the form

$$y(n) = x(n) \otimes w(n) = \sum_{i=0}^{q-1} w(i)x(n-i) \tag{1}$$

where $\otimes$ denotes the convolution operation, $w(i)$ for $i = 0,\cdots,q$ are the coefficients of the prediction filter. The Wiener filter design problem requires to find the filter coefficients, $w(i)$, that minimize the mean-square error

$$\xi = E\{|e(n)|^2\} = E\{|d(n) - y(n)|^2\} \tag{2}$$

The optimal filter coefficients can be derived from the Wiener-Hopf equations [8] as follows.

$$\mathbf{R}_x \mathbf{w}_o = \mathbf{r}_{dx} \tag{3}$$

where $\mathbf{R}_x$ is the $q \times q$ autocorrelation matrix of the reference input $x(n)$, $\mathbf{w}_o$ is the $q \times 1$ vector of the optimal filter coefficients, and $\mathbf{r}_{dx}$ is the $q \times 1$ vector of cross-correlations between the desired input $d(n)$ and the reference input $x(n)$. This study introduced the General Levinson Recursion [8] to recursively solve the Wiener-Hopf equation which is a set of Hermitian Toeplitz equations of the form given in Eq. (3). The prediction error signal $e(n)$ representing the unpredictable signals can be used to approximate the slop variations at slope discontinuities of QRS complex as shown in section 2.3. The root-mean-square value of the prediction error signal within entire QRS duration was adopted to quantify the UIQP and to evaluate the risk of ventricular arrhythmias. The UIQP indexes are defined as follows,

$$\text{UIQP\_}l\ (\mu\text{V}) = \sqrt{\frac{1}{\text{fQRSD}} \sum_{n=n_1}^{n_2} e^2(n)} \tag{4}$$

where $l$ denotes lead X, Y or Z, $n_1$ and $n_2$ are the onset and offset of the QRS complex respectively.

## 2.3. Simulation studies for the analysis of the unpredictable intra-QRS potentials

Two simulation studies were performed to demonstrate the analysis of the UIQP. The first simulation adopted a positive triangle wave to simulate the input QRS complex as depicted in Fig. 2(a) (solid line). The slops $m_1$ and $m_2$ ($\mu$V/ms) of straight lines $L_1$ and $L_2$ were 30 and –15 respectively. The linear prediction output with prediction depth $M$ = 4 (2ms) and filter length $q$ = 10 was shown in Fig 2(a) (dotted line). Figure 2(b) shows that the prediction errors mainly arose from the slop discontinuities. For the prediction depth $M$ = 4, there were $M$ = 4 points having significant prediction errors at each slop discontinuity. When the slop was suddenly changed from $m_1$ to $m_2$, the $M$th-point prediction error is about ($M$/2) × ($m_2$–$m_1$). For example, the prediction errors were about –22.5$\mu$V, –45$\mu$V, –67.5$\mu$V and –90$\mu$V at time 100ms in Fig. 2(b).

The second simulation adopted a positive sinusoidal wave and a low-amplitude (30$\mu$V peak value), transient (only 5 ms sustained) triangle wave to simulate the input QRS complex and the AIQP respectively. They were combined as the input QRS signal shown in Fig. 3(a) (solid line). The linear prediction output with prediction depth $M$ = 6 and filter length $q$ = 10 was shown in Fig 3(a) (dotted line). The prediction errors also mainly arose from the slop discontinuities, including onset and offset of the positive sinusoidal wave and the transient triangular wave.

The two simulation results demonstrated that the signals with constant slop (e.g. the straight lines) or continuously variable slop (e.g. the sinusoidal wave) can be approximately predicted by the output of the prediction filter. The prediction error signal reflected the slop variations at slop discontinuities of the input signal. Hence the prediction error can be used to detect the slop variations at onset, offset, sharp R wave and AIQP within entire QRS complex.

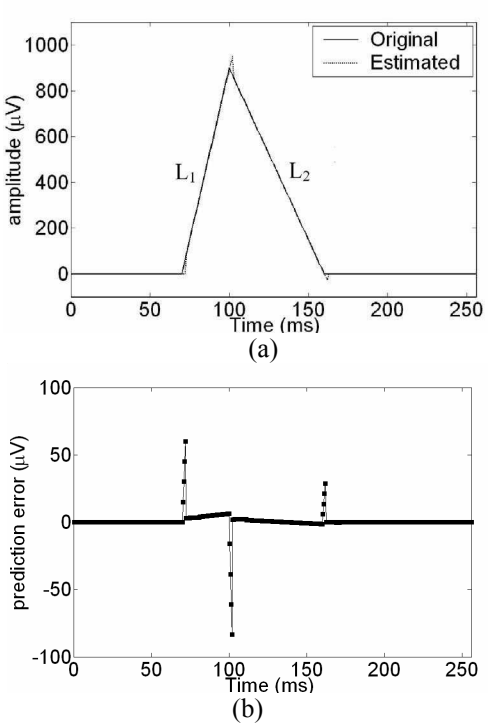


Figure 2. Simulation results for a positive triangular wave (a) the input triangular wave (solid line) and the prediction output (dotted line), (b) the prediction error signal.

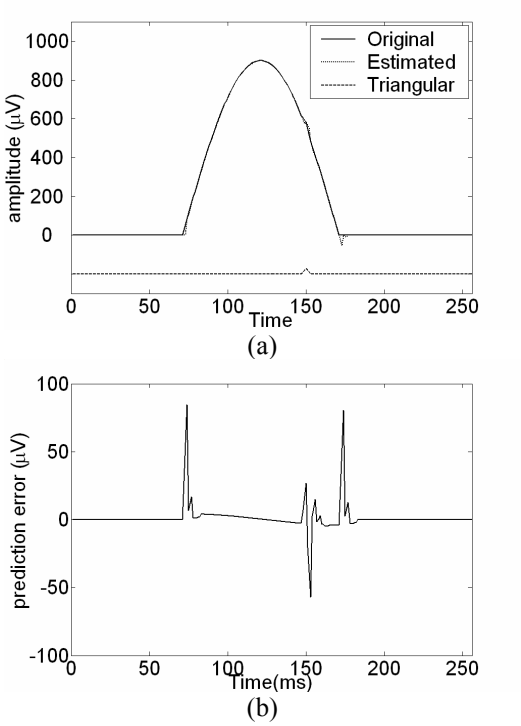


Figure 3. Simulation results for a positive sinusoidal wave (a) the input signal (solid line) composed of a positive sinusoidal wave and a low-amplitude, transient triangular wave (dashed line), and the prediction output (dotted line), (b) the prediction error signal.

## 2.4. Statistical analysis

All statistical analyses were undertaken using Statistical Package for the Social Sciences®. The F test was utilized to compare the variances of different variables, and the Student's t test with two tails was adopted to compare the means of two independent variables. Statistical significance was defined as $p < 0.05$. The area under the receiver operating characteristic curve (AUC) was applied to evaluate the global diagnostic performance.

## 3. Results

This study selected a 10th-order filter for analyzing the UIQP of all SAECGs. The different prediction depth, $M$, ranged from 1 to 20 was used to evaluate the diagnostic performance of UIQP. The optimal prediction depth maximized the global diagnostic performance for the risk of ventricular arrhythmias. Figure 4 demonstrates the UIQP analysis results for a lead-Y SAECG of a normal subject using a MLP model with the prediction depth $M$ = 8 and the filter length $q$ = 10. Figure 4(a) and (b) are the input QRS signal and the prediction error signal respectively. The prediction error distributed over entire QRS complex. The UIQP_Y index is 90.9$\mu$V.

Table 1 shows the summary results of UIQP analysis. The mean UIQPs from leads Y and Z of the VT group were significantly lower those of the normal group ($p <$ 0.05). The optimum prediction depth was 8 and 6 in lead Y and Z respectively. Although the mean UIQP ($M$ = 8) from lead X of the VT group was lower than that of the normal group, the difference was not statistically significant. The global performance was 86.1% and 71.5% of AUC in leads Y and Z respectively.

## 4. Discussion and conclusions

This study proposed a new index, UIQP, extracted by a linear MLP model to evaluate the risk of ventricular arrhythmias. The VT patients enrolled in this study survived clinically documented myocardial infarction (MI). The study results showed that the VT patients have a significant reduction of UIQP in leads Y and Z. Several previous studies have reported that MI [9,10] reduced high-frequency components within the QRS complex. The loss of myocardial generator units would be expected to attenuate both low and high QRS frequencies [11]. Hence MI may also cause the reduction of UIQP in VT patients.

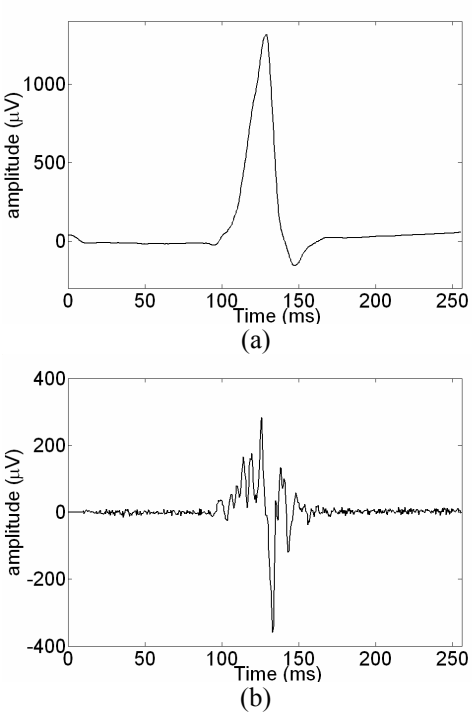


Figure 4. The UIQP analysis of a real QRS wave (a) the input QRS wave in lead Y from a normal subject, (b) the prediction error signal using a prediction depth $M = 8$ and filter length $q = 10$, UIQP_Y = 90.9$\mu$V.

Table 1: Summary of the UIQP analyses

| | UIQP parameters ($\mu$V) | | |
|---|---|---|---|
| Subjects | UIQP_X | UIQP_Y | UIQP_Z |
| VT | 58.4±29.2 | 60.2±19.0 | 50.3±19.6 |
| Normal | 61.7±14.0 | 92.4±24.2** | 64.8±16.5* |

NS, not significant ($p > 0.05$); *, $p < 0.01$; **, $p < 0.001$

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