



## Median-based abnormal heartbeat detection using histogram for arrhythmia reading

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**Abstract:** An abnormal heartbeat caused by the occurrence of arrhythmia in an electrocardiogram signal is very important for arrhythmia reading, and studies on detecting abnormal heartbeats are ongoing. The median absolute deviation method, which is a representative method for detecting abnormal heartbeats, uses the insensitivity of the median value and the median absolute deviation in the feature distribution of the abnormal heartbeat. However, this has a disadvantage in that the processing time is long because the features must be sorted to obtain the median value and median absolute deviation. To improve this, we propose a median-based abnormal heartbeat detection method using a histogram. Unlike the existing median absolute deviation method, the proposed method does not use a sorting process but rather finds the median value and median absolute deviation of the QRS complex's features, which are shape and interval features of the heartbeat, and detects abnormal heartbeats using the standard deviation method. MIT-BIH ADB, a representative arrhythmia database, was used to evaluate the performance of the proposed method. We confirmed that the proposed method reduced the processing time by approximately 81.79% compared with the existing median absolute deviation method and that the efficiency of the proposed method increases as the amount of heartbeat data increases. In addition, in the proposed method, the non-detection rate of an abnormal heartbeat was 0%, and the over-detection rate of a normal heartbeat was found to be 1.8% on average.

**Keywords:** Electrocardiogram signal, Arrhythmia, Abnormal heartbeat, Median absolute deviation, Histogram-based median absolute deviation

### 1. Introduction

The electrocardiogram (ECG) signal represents the electrical activity of the heart through the processes of depolarization and repolarization of the atria and ventricles. To diagnose heart disease, it is necessary to read the ECG signal for longer than 48 h, which burdens the ECG expert [1][2]. In addition, since abnormal heartbeats are more important than normal heartbeats for arrhythmia reading, abnormal heartbeat detection can reduce the burden on the ECG specialist. Specifically, there are approximately 200,000 heartbeats in an ECG signal acquired for 48 h at a sampling frequency of 360 Hz; therefore, so is very difficult to read all of them. Most arrhythmic ECG signals include an abnormal heartbeat of less than 10%. Therefore, if an abnormal heartbeat can be reliably detected, it can considerably help an ECG expert.

Existing abnormal heartbeat detection methods include the standard deviation (STD) method using the characteristics of the

heartbeat [3]-[4] and median absolute deviation (MAD)-based abnormal heartbeat detection for arrhythmia reading [5]. The STD method can be applied in various fields because it effectively detects abnormal data when normal data follow a normal distribution and abnormal data have a distribution far from the average value of normal data [6]. Thus, the STD method detects an abnormal heartbeat using a threshold based on the mean and standard deviation of the heartbeat features.

However, as the number of abnormal heartbeats is included, the mean and standard deviation of the features vary greatly, making it difficult to determine the optimal threshold. The MAD method detects an abnormal heartbeat using the insensitivity of the median value and the median absolute deviation from the characteristic distribution of a normal heartbeat. However, this has a disadvantage in that the processing time is long because it requires a process of sorting the features to obtain the median value and MAD of the feature.

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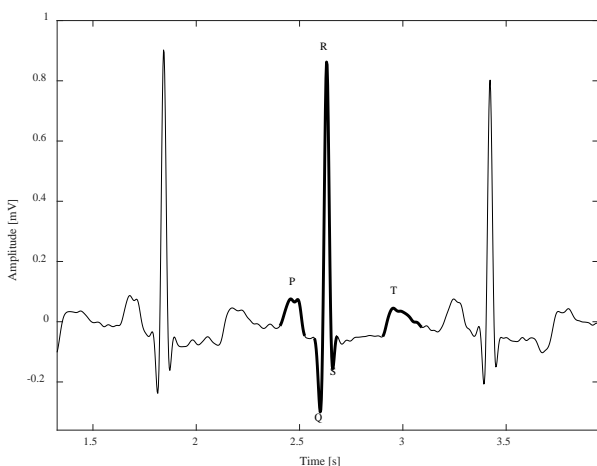
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Herein, we propose a method to obtain the median value and MAD using a histogram that does not require sorting in the process of finding the median value and MAD of a feature. Most arrhythmias are ventricular arrhythmias, and in the case of atrial arrhythmias, early atrial contraction is the most common. They appear as a shape change of the QRS complex, which is a component of the ECG signal, and a change in the interval between the QRS complex. Therefore, in the proposed method, the amplitude and kurtosis representing the shape change of the QRS complex and the RR interval representing the variation of the interval between the QRS complexes are used as the characteristics of the heartbeat. First, using a histogram, the median value and MAD are obtained, and the amplitude and kurtosis of the R wave and the median value and MAD of the RR interval are obtained.

The remainder of this paper proceeds as follows. Section 2 introduces the existing STD- and MAD-based abnormal heartbeat detection methods. Section 3 describes the median-based abnormal heartbeat detection method using a histogram. In Section 4, we analyze the performance of the proposed method through experiments, and we conclude the paper in Section 5.

## 2. Existing Abnormal Heartbeat Detection

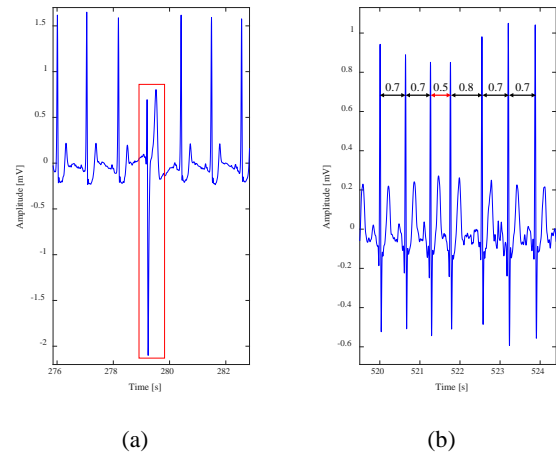
**Figure 1** shows an example of a normal ECG signal, which is periodic, and the heartbeat corresponding to one cycle consists of a P wave caused by atrial depolarization, a QRS complex caused by ventricular depolarization, and a T wave caused by ventricular repolarization [7].



**Figure 1:** Example of ECG signal

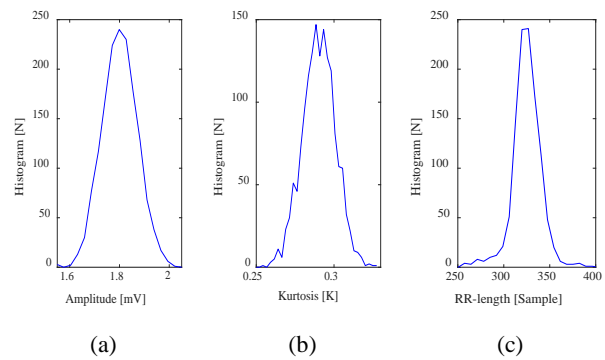
**Figure 2** shows examples of arrhythmic ECG signals. **Figure 2(a)** shows an arrhythmic ECG signal including an abnormal heartbeat with a change in shape from a normal heartbeat, and

**Figure 2(b)** shows an arrhythmic ECG signal including an abnormal heartbeat with a change in the interval from a normal heartbeat.

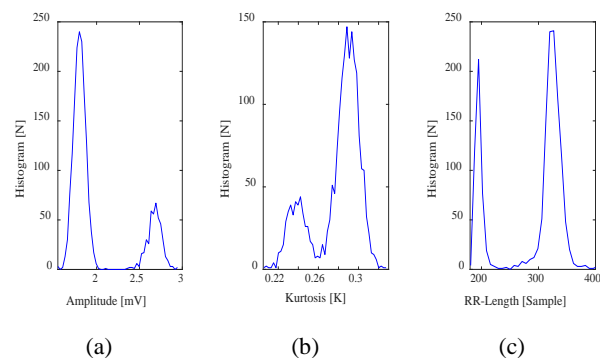


**Figure 2:** Examples of ECG arrhythmia signal:

(a) abnormal shape heartbeat, (b) abnormal interval heartbeat



**Figure 3:** Histograms of normal heartbeats in MIT-BIH ADB 119m record, (a)  $V$ , (b)  $K$ , (c)  $RR$



**Figure 4:** Histograms of total heartbeats in MIT-BIH ADB 119m record, (a)  $V$ , (b)  $K$ , (c)  $RR$

In the existing abnormal heartbeat detection methods, abnormal heartbeats of ventricular arrhythmias and premature atrial contractions are detected. These abnormal heartbeats appear as a

shape change in the QRS complex and an interval change between the QRS complex. First, it is assumed that the histograms of the amplitude ( $V$ ) and kurtosis ( $K$ ) of the R-peak in the QRS complex and the RR interval ( $RR$ ) between the QRS complexes for a normal ECG signal follow a normal distribution. **Figure 3** shows an example of a histogram of a normal heartbeat in the 119m record of the MIT-BIH ADB [8], a standard arrhythmia database.

**Figure 4** shows an example of a histogram of arrhythmic ECG signals. **Figure 4** shows that the histogram of the arrhythmic ECG signal does not follow a normal distribution. This is due to the abnormal heartbeat in the arrhythmic ECG signal.

### 2.1 STD-based abnormal heartbeat detection

The STD-based abnormal heartbeat detection method ensures that the histogram of arrhythmic ECG signals has a normal distribution. The STD method consists of a feature extraction process to obtain the features of a heartbeat and an abnormal heartbeat detection process using these features.

The feature extraction process is as follows: the R-peak is detected by the R-peak detection method [4] using the refractory period. Then, from the detected R-peak, the amplitude and kurtosis corresponding to the height and curvature at the R-peak are obtained. In addition, the RR interval between the QRS complexes is calculated as the time difference between the current R-peak and the previous R-peak.

The abnormal heartbeat detection process is as follows. It leverages the fact that, as the difference between the feature values from the mean of the normal heartbeat distribution increase, so does the probability of an abnormal heartbeat. Specifically, a heartbeat including an R-peak that satisfies all of the conditions of **Equation (1)** is detected as a normal heartbeat, and a heartbeat including an R-peak that does not satisfy any of the conditions of **Equation (1)** is detected as an abnormal heartbeat.

$$\begin{aligned} m_V - \omega_V \sigma_V < V < m_V + \omega_V \sigma_V, \\ m_K - \omega_K \sigma_K < K < m_K + \omega_K \sigma_K, \\ m_{RR} - \omega_{RR} \sigma_{RR} < RR < m_{RR} + \omega_{RR} \sigma_{RR} \end{aligned} \quad (1)$$

Here,  $(m_V, m_K, m_{RR})$  and  $(\sigma_V, \sigma_K, \sigma_{RR})$  denote the mean and standard deviation of  $(V, K, RR)$ , respectively, and  $(\omega_V, \omega_K, \omega_{RR})$  denotes the weights for determining the threshold values of  $(V, K, RR)$ .

In this method, the abnormal heartbeat detection result varies depending on the value, and it is difficult to determine the optimal value. In addition, as the number of abnormal heartbeats is included, the mean and standard deviation of the features vary greatly, making it difficult to determine the optimal threshold value.

### 2.2 MAD-based abnormal heartbeat detection

In the STD-based abnormal heartbeat detection method, it is difficult to determine the optimal threshold value because the mean and standard deviation of the features vary greatly as the number of abnormal heartbeats increases. In the MAD method, reliable abnormal heartbeats are detected, even if the number of abnormal heartbeats is large, using the median value and the median absolute deviation, which are insensitive to the feature values of the abnormal heartbeats.

**Equation (2)** is an expression showing the median value ( $M_V$ ) and the median absolute deviation ( $MAD_V$ ) for  $V$ , and the same can be obtained for  $K$  and  $RR$ .

$$\begin{aligned} M_V &= \text{median}(V), \\ MAD_V &= b_M \times \text{median}(V - M_V) \end{aligned} \quad (2)$$

Here,  $b_M$  is a constant that causes the standard deviation and the MAD to coincide with the normal distribution.

Similar to the STD-based abnormal heartbeat detection method, MAD abnormal heartbeat detection uses the fact that as the difference between the features from the median value increase, the more likely it is to be an abnormal heartbeat. Specifically, a heartbeat including an R-peak that satisfies all of the conditions of **Equation (3)** is detected as a normal heartbeat, and a heartbeat including an R-peak that does not satisfy any of the conditions of **Equation (3)** is detected as an abnormal heartbeat.

$$\begin{aligned} M_V - \omega_V MAD_V < V < M_V + \omega_V MAD_V, \\ M_K - \omega_K MAD_K < K < M_K + \omega_K MAD_K, \\ M_{RR} - \omega_{RR} MAD_{RR} < RR < M_{RR} + \omega_{RR} MAD_{RR} \end{aligned} \quad (3)$$

Here,  $(M_V, M_K, M_{RR})$  and  $(MAD_V, MAD_K, MAD_{RR})$  denote the median and MAD of  $(V, K, RR)$ , respectively, and  $(\omega_V, \omega_K, \omega_{RR})$  denotes the weights for determining the threshold values of  $(V, K, RR)$ . Although the MAD method includes a large

number of abnormal heartbeats, the median value and the median absolute deviation show only slight changes, so it can reliably detect abnormal heartbeats.

### 3. Proposed Abnormal Heartbeat Detection

The disadvantage of the MAD method is that the calculation time is long because a sorting process is required to obtain the median value and the median absolute deviation. We propose a histogram-based MAD method (HMAD) that calculates the median value and median absolute deviation without a sorting process.

First, when a histogram with an amplitude value of  $k$  for a given amplitude data  $V = \{v_1, \dots, v_N\}$  is expressed as  $H(V, k)$ , the median value ( $\mu_M$ ) can be obtained as in **Equation (4)**.

$$\mu_M(V) = \underset{v_{min} \leq i \leq v_{max}}{\operatorname{argmin}} \left\{ CH(V, i) \geq \frac{N}{2} \right\},$$

$$CH(V, i) = \sum_{k=0}^i H(V, k) \quad (4)$$

Here,  $CH(V, i)$  denotes the number of heartbeats with an amplitude value less than or equal to  $i$ , the amplitude data  $V$  given as a cumulative histogram.  $\mu_M(V)$  represents the amplitude value at the moment over half of the total heartbeats ( $N$ ) in the cumulative histogram, which is the median value.

Using the median value  $\mu_M$  and the histogram, the MAD ( $\sigma_M$ ) is calculated as in **Equation (5)**.

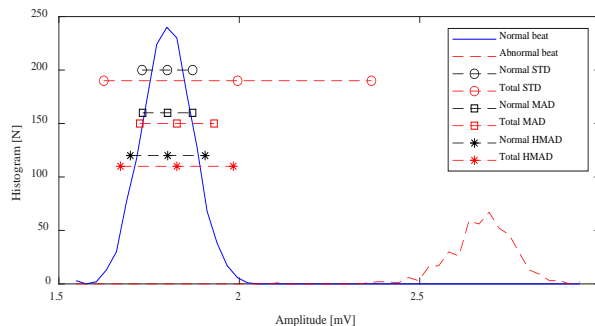
$$\sigma_M(V) = \underset{v_{min} \leq i \leq v_{max}}{\operatorname{argmin}} \left\{ CH'(V, i) \geq \frac{N}{2} \right\},$$

$$CH'(V, i) = \sum_{k=\mu_M-i}^{\mu_M+i} H(V, k) \quad (5)$$

Here,  $CH'(V, i)$  denotes the number of heartbeats with an amplitude difference of less than or equal to  $i$ .  $\sigma_M(V)$  represents the amplitude value at the moment over half of the total heartbeats in the cumulative histogram, which is the MAD.

**Figure 5** shows the mean and median values, standard deviation, and MAD of the histogram for the normal heartbeat, and the mean and median values, standard deviation, and MAD of the histogram, including the abnormal heartbeat in the 119m record of the MIT-BIH ADB.

From **Figure 5**, the mean and median values of normal heartbeats, as well as the standard deviation and MAD, are similar. However, when an abnormal heartbeat is included, the mean and standard deviation change significantly, while the median and



**Figure 5:** Comparison of STD, MAD, and HMAD according to the distribution of abnormal heartbeats in the MIT-BIH ADB 119m record

MAD show little change. This is similar to the cases of  $K$  and  $RR$ . Therefore, it is difficult to determine the optimal weight in **Equation (1)** for STD-abnormal heartbeat detection using the mean and standard deviation.

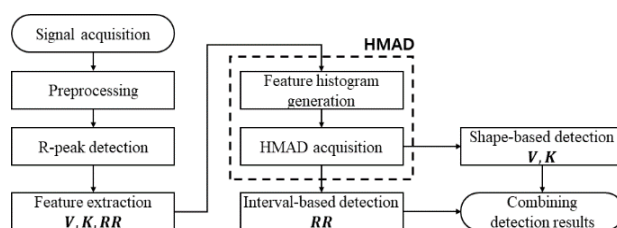
If the median value and MAD are calculated using the histogram, as in **Equations (4)-(5)**, the amount of calculation can be reduced because the sorting process is not required. This can solve one problem associated with the MAD method, in which the sorting time increases in proportion to the total number of heartbeats.

Histogram-based abnormal heartbeat detection uses the fact that as the difference between the feature value and the median value increases, the more likely it is to be an abnormal heartbeat. Specifically, a heartbeat including an R-peak that satisfies all of the conditions of **Equation (6)** is detected as a normal heartbeat, and a heartbeat including an R-peak that does not satisfy any of the conditions of **Equation (6)** is detected as an abnormal heartbeat.

$$\mu_M(V) - \omega_V \sigma_M(V) < V < \mu_M(V) + \omega_V \sigma_M(V),$$

$$\mu_M(K) - \omega_K \sigma_M(K) < K < \mu_M(K) + \omega_K \sigma_M(K),$$

$$\mu_M(RR) - \omega_{RR} \sigma_M(RR) < RR < \mu_M(RR) + \omega_{RR} \sigma_M(RR) \quad (6)$$



**Figure 6:** Algorithm flowchart of the proposed method

Here,  $(\mu_M(V), \mu_M(K), \mu_M(RR))$  and  $(\sigma_M(V), \sigma_M(K), \sigma_M(RR))$  denote the median and MAD of  $(V, K, RR)$ , respectively, and  $(\omega_V, \omega_K, \omega_{RR})$  denotes the weights for determining the threshold values of  $(V, K, RR)$ . The MAD method can reliably detect an abnormal heartbeat because there is little change in the transient, even if many abnormal heartbeats are included.

Figure 6 is a flowchart of the proposed method.

### 4. Experiments and Results

MIT-BIH ADB, an electrocardiogram database including arrhythmias, was used to evaluate the performance of the proposed method. MIT-BIH ADB consists of 48 records of approximately 30 min with a sampling frequency of 360 Hz. A 1- to 25-Hz 3rd-order Butterworth band-pass filter was used for preprocessing to reduce baseline fluctuations and power supply noise.

Next, to confirm the superiority of the computational amount of the proposed method, the time required to obtain the median value and MAD according to heartbeat was measured. The test environment used an Intel i5-10400 2.9-GHz CPU, with 32 GB of RAM, and MATLAB 2021.

Table 1 shows the results of the time taken to obtain the median value and MAD according to the heartbeat. After measuring the processing time for the 30-min length of the experiment, the processing time was measured up to 50-h data in 10-h increments in consideration of the long-term measurement of 48 h or more.

Figure 7 is a graphical representation of Table 1.

Table 1: Comparison of processing time according to data length

Data length (Hour)		0.5	10	20	30	40	50
Processing time (ms)	Median method	0.15	1.05	1.48	2.37	4.14	5.93
	Proposed method	0.12	0.25	0.42	0.55	0.88	1.08

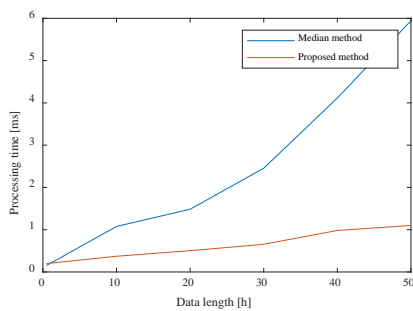


Figure 7: Graph of Table 1

As shown in Table 1 and Figure 7, the proposed method does not require a sorting process, so the processing time is reduced

compared to the median method. When the data length increases, the processing time of the median method increases more rapidly than that of the proposed method.

A confusion matrix was used as an indicator for the performance evaluation. True Positive (TP) denotes the number of detections of an abnormal heartbeat as an abnormal heartbeat, and False Negative (FN) denotes the number of detections of abnormal heartbeats as normal heartbeats. TN (true negative) represents the number of normal heartbeats detected as normal heartbeats, and False Positive (FP) represents the number of normal heartbeats detected as abnormal heartbeats. The false-negative ratio (FNR), indicating the non-detection rate of an abnormal heartbeat, and the false-positive ratio (FPR), indicating the over-detection rate of a normal heartbeat, were used. The FNR and FPR are shown in Equation (7).

$$FNR(\%) = \frac{FN}{TP+FN} \times 100,$$

$$FPR(\%) = \frac{FP}{TN+FP} \times 100 \tag{7}$$

The results of the STD-based, MAD-based, and proposed methods were compared with respect to shape, interval, and signals in which both shape and interval deformation occurred. The 214m, 209m, and 119m data are records containing a large number of abnormal heartbeats corresponding to each type of deformation, and the detailed detection results are analyzed as follows.

The 214m data includes 256 premature ventricular contraction (PVC) abnormal heartbeats with shape deformation, as shown in Figure 8.

The detection results of Figure 8 are shown in Table 2.

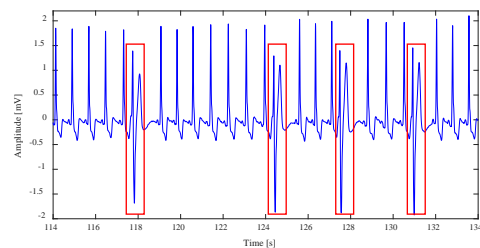
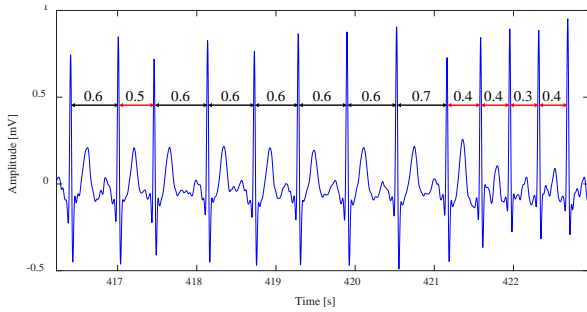


Figure 8: Abnormal heartbeats in 214m record

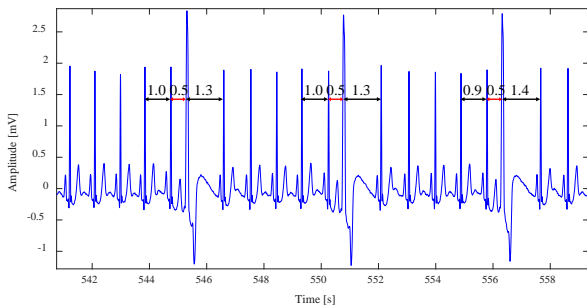
Table 2: Detection results for 214m record.

Method	Total beat	Abnormal beat	De-ctected beat	TP	TN	FP	FN	FNR (%)	FPR (%)
STD	2261	259	52	44	1994	8	215	83.01	0.40
MAD			265	256	1993	9	3	1.16	0.45
Proposed			265	256	1993	9	3	1.16	0.45

In **Table 2**, the STD-abnormal heartbeat detection method over-detected the normal heartbeat and a large number of non-detections of abnormal heartbeats. Conversely, the proposed method for detecting an abnormal heartbeat greatly reduced non-detections and over-detections.



**Figure 9:** Abnormal heartbeats in 209m record



**Figure 10:** Abnormal heartbeats in 119m record

**Table 3:** Detection results for 209m record.

Method	Total beat	Abnormal beat	Detected beat	TP	TN	FP	FN	FNR (%)	FPR (%)
STD	3004	384	49	28	2599	21	356	92.71	0.80
MAD			429	377	2568	52	7	1.82	1.98
Proposed			430	377	2567	53	7	1.82	2.02

**Table 4:** Detection results for 119m record.

Method	Total beat	Abnormal beat	Detected beat	TP	TN	FP	FN	FNR (%)	FPR (%)
STD	1986	444	1	1	1542	0	443	99.77	0
MAD			444	444	1542	0	0	0	0
Proposed			444	444	1542	0	0	0	0

The 209m data includes 383 premature atrial contraction abnormal heartbeats with RR interval deformation, as shown in **Figure 9**.

In datum 209m, as shown in **Figure 9**, in the case of a normal heartbeat, the RR interval is 0.6–0.7 s, but when an abnormal beat

occurs, it is reduced to 0.3–0.5 s. The abnormal beat detection results from **Figure 9** are shown in **Table 3**.

In **Table 3**, the STD method has a large number of non-detections because the distortion of the standard deviation according to the ratio of the abnormal heartbeat is large. Conversely, the non-detection rate was greatly reduced in the proposed method.

As shown in **Figure 10**, the 119m data includes 444 PVC abnormal heartbeats in which shape and RR interval changes occur simultaneously.

**Table 4** shows the detection results of **Figure 10**. From **Table 4**, the proposed method has excellent performance, while the non-detection and over-detection performance of the STD method are not as good.

**Table 5:** FNR and FPR of proposed algorithm for MIT-BIH ADB records.

Method	Record	100	101	103	105	107	111	112	117	123	228	230	Average (%)
STD	FNR (%)	26.54	40.0	0	2.17	8.47	0	0	0	0	4.38	0	7.41
	FPR (%)	1.88	1.34	1.87	3.56	2.94	2.54	1.38	2.35	0.59	1.84	0.40	1.88
MAD	FNR (%)	0	0	0	0	0	0	0	0	0	0	0	0
	FPR (%)	1.21	3.34	2.11	2.34	0.39	0.71	1.18	2.48	3.76	1.66	0.35	1.78
Proposed	FNR (%)	0	0	0	0	0	0	0	0	0	0	0	0
	FPR (%)	1.21	3.34	2.11	2.34	0.39	0.71	1.18	2.48	3.76	1.66	0.35	1.78

**Table 5** shows the non-detection and over-detection rates of the proposed method for the MIT-BIH ADB records.

From **Table 5**, the non-detection rate of the abnormal heartbeat for the MIT-BIH ADB of MAD and the proposed method was 0%, and the over-detection rate was 1.8% on average. Thus, we can confirm that the proposed method preserves the performance of the MAD well. Therefore, we can conclude that the proposed method has excellent abnormal heartbeat detection performance in terms of the calculation amount, non-detection rate, and over-detection rate.

## 5. Conclusion

We proposed a median-based abnormal heartbeat detection method using a histogram. Unlike the existing MAD method, the proposed method does not use a sorting process but rather finds the median value and median absolute deviation of the shape and

RR interval of the QRS complex, which are features of heartbeats, and detects an abnormal heartbeat using the STD method. Through the experiment, we confirmed that the processing time was reduced by approximately 81.79% compared with that of the MAD method. We confirmed that the efficiency of the proposed method increases as the amount of data increases. In addition, through experiments, the proposed method detected all of the non-detection rates of the abnormal heartbeat as 0% and minimized the over-detection rate of the normal heartbeat to 1.8%. Therefore, the proposed abnormal heartbeat detection method can be effectively utilized for expert arrhythmia readings.

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### Author Contributions

Conceptualization, S. Lee and K. Park; Methodology, K. Park; Software, S. Lee; Validation, S. Lee; Formal Analysis, K. Park; Investigation, K. Park; Resources, S. Lee; Data Curation, S. Lee; Writing—Original Draft Preparation, S. Lee; Writing—Review & Editing, K. Park; Visualization, S. Lee; Supervision, K. Park; Project Administration, K. Park; Funding Acquisition, K. Park.

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