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A Multimodal Model of ECG and Heart Sound Signal by Considering Normal and Abnormal Heart

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***Abstract*— Analysis of the opening and closing of heart valves and the movement of blood flow in the heart are important in the domain of early detection of heart conditions. To build this correlation model, multimodal signals from electrocardiography and stethoscope are needed. Multimodal signaling was performed using primary data with the same sampling at 10 seconds by recording the PQRST heart signal in the lying position using electrocardiography and the heart sound in the sitting position using an electronic stethoscope. Experimental results showed that the number of R peaks is the same as the number of S1 sound peaks, and also the number of T peaks with the number of S2 sound peaks, so it can be concluded that there is a regular signal pattern relationship between S1-S2 and the RT wave, namely the relationship at the end of the first peak of the QRS wave. The cardiac signal due to ventricular depolarization (ventricular contraction), the appearance of an S1 heart sound, and the association of the end of the next peak of the T wave of cardiac signals indicate ventricular repolarization and the appearance of an S2 heart sound. This is consistent with the fact that electrical events in cardiac activity occur before mechanical events in normal heart conditions. Based on the study of HRV parameters, heart sound signals can be used to determine HRV parameters. The results show the same number of peaks in normal hearts, while in abnormal hearts, there are differences in results because abnormal heart conditions have an erratic rhythmic pattern.**

***Keywords*— Multimodal signal; heart sound; ECG signal; HRV.**

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I. INTRODUCTION

The electrocardiogram (ECG) is an effective and widely used screening tool for heart disease that is comparatively cheap, non-invasive, and simple to use, and the risks associated with ECG are minor and uncommon [1]. The current ECG development is limited to P waves, QRS complexes, and T waves, so a deficiency of the ECG is the trouble in identifying structural heart valve abnormalities and flaws marked by heart murmurs [2]. The mechanical activity of the heart cannot be explained with ECG [3]. Likewise, the sound characteristics of the stethoscope for diagnosing heart, lung, and respiratory sounds and for listening to intestines and blood flow in arteries and veins are limited to S1 and S2 signals. It is critical to understand another weakness of ECG: the ECG cannot record electrical activities produced by the conduction system's specialized cells [4].

Moreover, none of these ECG programs can reliably analyze ECG records without further cardiologist evaluation. As a result, there is an urgent need to create new, extra highly accurate, and strong techniques for processing and evaluating ECG data [5]. The limited stethoscopes using reference ECGs is that the time between electrical and mechanical activity in the cardiovascular system varies for all patients due to various pathological conditions [6].

Heart function can be checked using a variety of methods, including electrical activity (ECG), mechanical activity (echocardiography), and heart sound auscultation (phonocardiogram, PCG) [7]. Several studies have recommended that signals from a stethoscope examination can strengthen the diagnosis of heart conditions with an ECG, such as the development of the devices shown in table 1 [8]–[10]. There are similarities in the location of the sensor position in the ECG and stethoscope measurements, so it is predicted that there would be a relationship between the ECG signal pattern and the stethoscope signal. In general, The ECG signal and the PCG signal occur simultaneously [11], where the former is an electrical signal while the latter is a mechanical signal. ECG and PCG signals are also interrelated because PCG signals are acquired from mechanical heart surgery, namely electrical heart surgery. Consequently, some

research has concentrated on detecting and diagnosing heart defects using the correlation between ECG and PCG signals [11]–[13].

Previous research that merged ECG and PCG analysis was successful in identifying murmurs [14]. This research resulted in a multimodal study of signals from ECG and PCG data. This study aimed to create and test a suitable signal processing to aid component extraction and improve understanding of the fundamental principles of cardiac physiology. We aimed to interpret the correlation of ECG signals and heart sound signals at defined anatomic locations in routine clinical examinations at the same time.

The preliminary investigation stage included frequency domain analysis and time-frequency of the heart signal. This study includes the characteristics of the heart sound signal in normal and abnormal heart conditions. The characteristics of the heart sound signal were analyzed in detail based on the parameters of the S1 and S2 peaks as feature extraction. Likewise, cardiac signals were analyzed based on detecting R and T peaks as feature extraction.

II. Materials and Method

Clinically, the process of auscultating a stethoscope to obtain an accurate diagnosis of heart sounds is a difficult skill and is highly dependent on the ear's sensitivity and the doctor's level of experience. Cardiac signals can provide information about the mechanical activity of the heart but cannot fully illustrate the processes that occur in the heart. For example, damage to the heart that causes a murmur cannot be classified specifically from cardiac signals because the opening and closing of heart valves cause vibrations that cause heart failure.

This situation provides information that the mechanical activity of the heart associated with abnormal heart sounds is sufficient to explain using one variable. A synchronous and simultaneous characteristic between heart sounds and heart signals is needed to classify and explain the mechanical activity of the heart. In this study, two variables in the dynamics of the heart were used, namely heart sounds and heart signals that are displayed simultaneously, to obtain information about the occurrence of S1 and S2 heart sounds on the cycle that occurs in heart signals. This multimodal signal is analyzed using R peaks and T waves to determine the location of the heart sound, recording the heart signal and the heart sound signal simultaneously. This method has strong advantages in computational performance and efficiency [15]. The first heart sound (S1) occurs at the beginning of ventricular contraction and corresponds to the QRS complex in cardiac signals [11], [16]–[18], and the S2 heart sound caused by semilunar valve closure occurs after the formation of a T wave in cardiac signals [19], [20]. S1 onset is traditionally thought to occur after R peak in previous ECG-based PCG segmentation studies [21]–[23].

In a normal heart, S1 has concentrated energy in the 100-150 Hz range with a single frequency spectral component of 0.04-0.15 s duration [24], and S2 has concentrated energy in the 50-250 Hz range is evenly distributed throughout 0.03-0.15 s. 0.12 s [25], [26]. Whereas in abnormal heart conditions, S1 shows more than one frequency energy spectrum, and its duration is wider than normal S1 conditions [27], [28], while S2 shows a frequency energy spectrum that is not uniformly distributed and has a longer duration [29], [30]. Under normal conditions, the energy magnitude of the S1 signal is higher than that of S2, while under abnormal conditions, the S2 signal has a wider magnitude than S1 [31], [32].

TABLE I
Overview of several stethoscope and ECG signal modalities technologies on the market

Device	Research related to stethoscope and ECG modalities
Rijuven CardioSleeve [10], [33].	Combined portable 3-lead ECG and digital heart sounds.
Eko duo [9], [10], [33].	Combined single lead ECG and digital/electronic stethoscope
Ekoscope [10], [33]	Combined 8 ECG electrodes and electronic stethoscope.

The aortic valve is sited in the center of the chest between the aorta and the left ventricle. The sound of aortic valve movement can be most clearly heard in the second intercostal space (between the 2nd and 3rd ribs) to the right of the sternum (the bone in the middle of the chest). The second intercostal space to the left of the sternum is where the pulmonary valve, which is situated between the pulmonary artery and right ventricle, can be heard best. The intercostal space is the best place to hear the tricuspid valve, which is located between the right atrium and right ventricle. The fifth intercostal space, which is located between the fifth and sixth ribs, is just to the left of the sternum. The mitral valve, which divides the left atrium and ventricle, is also most clearly heard in the fifth intercostal space but more to the left of the sternum. Usually, the position of the ECG recording, as shown in Figure 1 was in sync with the position of the heart valve sound produced by the activity of the heart.

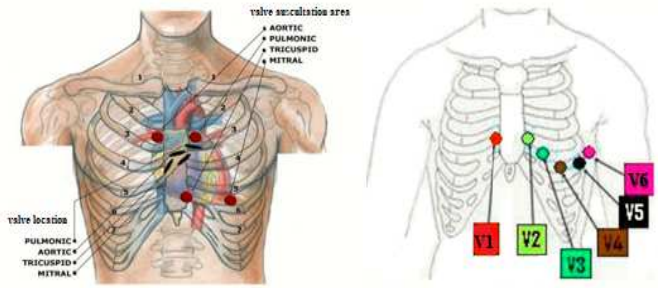

Fig. 1 Interpretation the position of the heart valves coincides with the auscultatory position, and the position of the ECG electrode [34][35].

The first process carried out in signal merging is to determine the peaks of the normal S1 and S2 signals in the heart sound signal and the R peak in the PQRST cardiac signal. Based on measurement peak S1-S2 and peak R, can be calculated parameters HRV.

Signal merging is done by recording data for 10 seconds for heart sound signals and ECG signals. The next step is to determine the signal peak to calculate how many beats as the basis for HRV parameters. The process of determining the peak in the voice signal goes through the stages of the Hilbert transformation process and smoothing, which is then shown only the peak of the signal. Meanwhile, the determination of the peaks in the ECG signal does not require the Hilbert transformation process because the peaks in the ECG signal can be read properly. The next step is to compare the results of the ECG signal and heart sound signal simultaneously for

normal and abnormal heart conditions by analyzing the relationship between the S1-S2 time interval, the R-T time interval, the S1-R time interval, and the S2-T time interval.

A. Determine the Peaks of the Normal S1 and S2 Signals in the Heart Sound Signal

Normal and abnormal heart sound signals from stethoscope measurement electronics are decomposed at levels 5 and 12. Heart sound signals normal at level 5 decomposition are already very visible in signal positions S1 and S2, while those with abnormal heart sound signals are only visible in a level 12 decomposition position. Abnormal signals need additional steps in the software to remove the recorded noise. In this stage, the thresholding method is used to obtain a better signal pattern, to estimate the signal from the signal contaminated with additional noise.

B. Determine the R and T Peak in the PQRST Wave Cardiac Signal

Identifying R peaks is critical because they identify the heartbeats; the accuracy of all subsequent observations is reliant on this. Before interpreting the R peaks on the PQRST wave of the ECG signal, it is necessary to interpret the wave using the 12-level symlet 8 wavelets. All Normal heart signals, the measurement results of a 3-lead heart recorder show P, QRS, and T wave patterns clearly when decomposed at level 12.

The wavelet transform is used to extract characteristic points PQRST heart signal and to find sharp points of variation. The steps involved include detecting the QRS complex, T wave, and P wave.

C. Determine the Number of Beats

This process aims to measure the number of beats as a basis HRV parameters with 10-second signal sampling. The calculation of the number of peaks for S1, S2, and R, T wave peaks is performed automatically and simultaneously takes data for heart sound and heart signal data in the same respondents. The stethoscope measurement treatment was carried out in a sitting position, while the ECG measurements were carried out in a supine position, clean of metal.

D. Determine Intervals: S1-S2, S1-R, R-T, and S2-T

The process of determining the peak in the voice signal through the stages of the Hilbert transformation and smoothing process is then shown only the peak of the signal. While the determination of the peak on the ECG signal is not Hilbert transformation process is needed because the peak in the ECG signal is already able to read well. The next step is to compare the results ECG signal and heart sound signal simultaneously for heart conditions, normal and abnormal, by analyzing the relationship of the S1-S2 time interval, time interval R-T, time interval S1-R, and time interval S2-T. This is done by merging signals which are done by plotting 2 signals in the same frame so that intervals S1-S2, R-T, S1-R, and S2-T can be calculated.

III. Result and Discussion

The measurement of respondents using an electronic stethoscope in the sitting position to make the heart sound more audible compared to the sitting position sleep. The detection of normal heart sounds can be seen in Fig. 2.

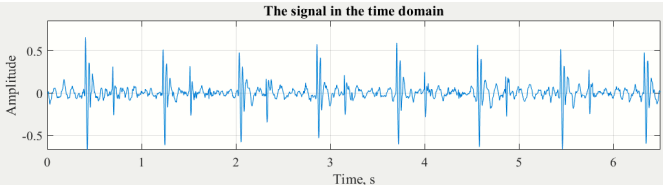

Fig. 2 Interpretation of S1-S2 signal on heart sound signal

PQRST cardiac signals were analyzed using the detrending method because it can efficiently eliminate baseline wandering without distorting any morphological characteristics of the ECG signal without a time delay [36], as shown in Fig. 3.

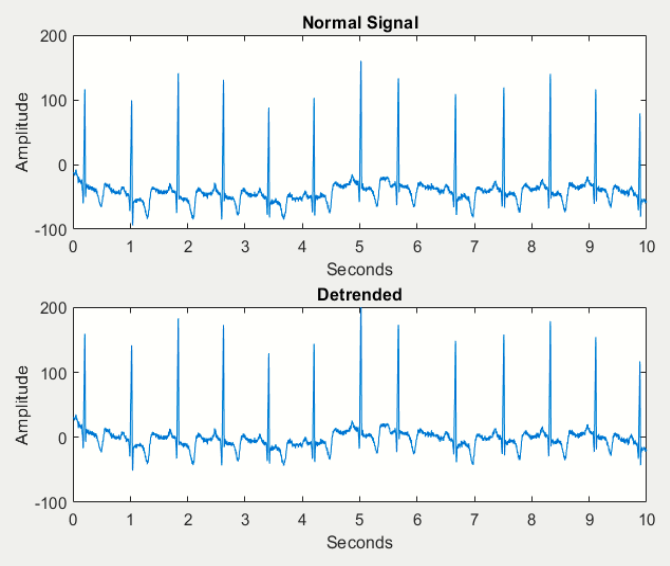

Fig. 3 Normal heart signals and detrended signal.

The process of detecting the peak of each heart signal wave (Fig. 4) was used to determine the perform the PQRST signal characteristics, especially for the R peak and the peak T, which was used in multimodal signals. Fig. 4 can show the peak characteristics of each wave.

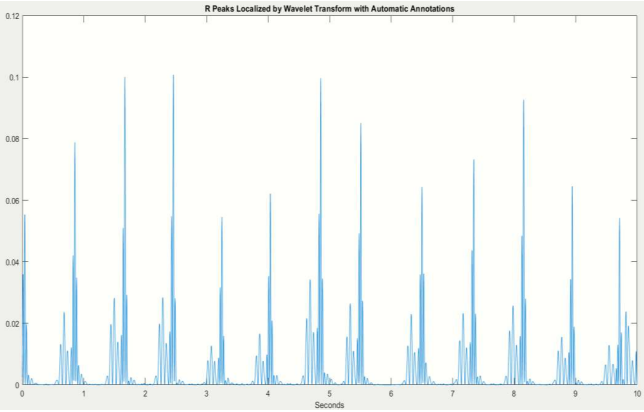

Fig. 4 Interpretation of peak on PQRST wave

It can be seen from the pattern recorded in Fig. 5 that the number of the same peak for peak R and peak S1 sound in 10 sampling seconds, which is as many as 13 peaks, so it can be

concluded that the stethoscope is electronically capable of replacing the ECG in the measurement of HRV parameters in the time domain with a success rate of nearly 100%.

The correlation between heart sound signals and heart signals is illustrated in Fig. 5-8.

A. Normal Heart

Fig 5 appears that a normal heart condition shows the relationship between the end of the first peak of the heart signal (QRS wave) in the heart signal indicating energy due to ventricular depolarization (ventricular contraction) and the emergence of the first heart sound (S1). The end of the next peak of the cardiac signal (T wave) indicates ventricular repolarization and the appearance of a second heart sound (S2). This situation results from the fact that the electrical events in the heart's action occur before the mechanical events [11], [37]. Mechanical events pump blood in the heart, carried out by contractile cells formed from cardiac muscle cells. Under normal circumstances, contractile cells do not generate their action potentials but through electrical events resulting from autorhythmic cells triggering and transmitting action potentials that cause contraction of the cardiac contractile cells.

In addition, it is also seen that the second heart sound is shorter in duration and has a higher frequency than the first heart sound. Based on observations in Fig. 5, it is shown that there is a minimal difference between the time interval when the peak of S1 is to peak of S2, and the time interval when the peak of R is to the peak of T. It is also seen that the time interval of the peak of S1-S2 is always higher than the time interval of the peak of R-T. Likewise, based on the results in Fig. 5, there is a minimal difference between the time interval of the S1 peak to the R peak, and the S2 peak to the T peak. The highest peak achieved by the S1-S2 time interval difference is the 1st peak data (Table II), the highest peak R-T time interval is the 9th peak data, and the 11th peak data (Table III) is the highest for the peak time intervals S1-R and S2-T. There is a match between the position of the S1 sound with the R wave, and S2 sound with a T wave. The blue dotted line 1, shows the appearance of the S1 sound faster than the R wave but still in the region of the QRS complex. However, on the data to 8, S1 peak appears shortly after the R wave. This is because heart sound is a non-stationary signal.

Fig. 5 Interpretation of a combination of heart sound signals and PQRST heart signals for normal heart responders, with the measurement position sitting for a stethoscope, and lying supine for a heart recorder.

TABLE II
INTERVAL OF S1 AND S2 SOUND SIGNAL IN NORMAL HEART

Peak	S1		S2		Time interval S1 and S2
	Time (s)	time difference (s)	Time (s)	time difference (s)	
1	0.1605	0	0.4735	0	0.313
2	0.8715	0.711	1.166	0.6925	0.2945
3	1.6763	0.80475	1.945	0.765	0.2687
4	2.509	0.83275	2.805	0.86	0.296
5	3.4573	0.94825	3.72	0.905	0.2627
6	4.1738	0.7165	4.478	0.768	0.3042
7	4.9135	0.73975	5.223	0..745	0.3095
8	5.761	0.8475	6.057	1.033	0.296
9	6.5023	0.74125	6.809	0.752	0.3067
10	7.136	0.63375	7.443	0.634	0.307
11	7.875	0.739	8.171	0.728	0.296
12	8.7225	0.8475	9.017	0.846	0.2945
13	9.4638	0.74125	9.763	0.746	0.2992

TABLE III
INTERVAL OF R AND T WAVES IN A NORMAL HEART

Peak	R Wave		T Wave		Time Interval R and T wave
	Time (s)	Time Different (s)	Time (s)	Time different (s)	
1	0.2083	0	0.4944	0	0.2861
2	1.022	0.8137	1.297	0.8026	0.275
3	1.836	0.814	2.094	0.8	0.261
4	2.625	0.789	2.878	0.781	0.253
5	3.414	0.789	3.678	0.8	0.264
6	4.203	0.789	4.478	0.8	0.275
7	5.022	0.819	5.308	0.83	0.286
8	5.675	0.653	5.944	0.636	0.269
9	6.669	1.102	6.978	1.0344	0.309
10	7.511	0.842	7.792	0.814	0.281
11	8.322	0.811	8.578	0.786	0.256
12	9.114	0.792	9.378	0.8	0.264
13	9.883	0.769	10.175	0.797	0.292

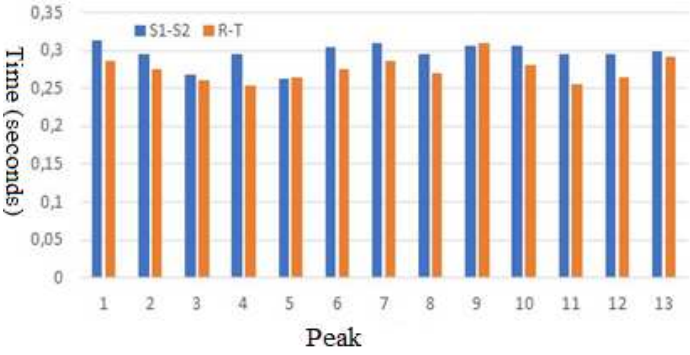

Fig. 6 A Comparison of Time Intervals between S1-S2 and R-T

TABLE IV
INTERVAL OF S1-R AND S2-T WAVES IN A NORMAL HEART

Peak	S1-R Interval (s)	S2-T Interval (s)
1	0.0478	0.0209
2	0.1505	0.131
3	0.1597	0.149
4	0.116	0.073
5	0.0433	0.042
6	0.0292	0
7	0.0185	0.085
8	0.086	0.113
9	0.1667	0.169
10	0.375	0.349
11	0.447	0.407
12	0.3915	0.361
13	0.4192	0.412

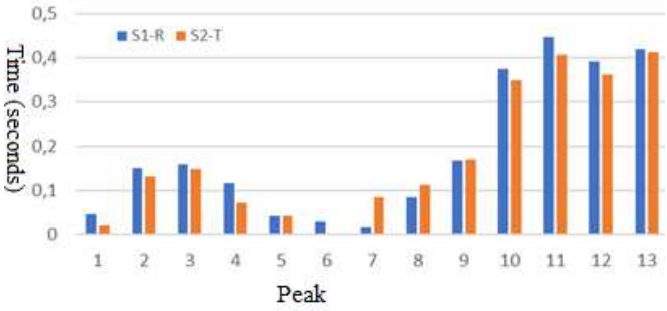

Fig. 7 A Comparison of Time Intervals between S1-R and S2-T.

Fig. 7 shows differences in the S1-R and S2-T intervals, but the patterns formed are random, depending on the type of abnormality. This is because only certain patterns are shorter or longer and may only occur in For a certain second, as shown in Fig. 6, the difference between the S1-S1 sound signals is very noticeable and more visible on signals 4 and 5 as well as signals 6 and 7, as well as for the S1-S2 interval, there is a very significant difference between the intervals. As for the ECG signal formed, there is a different rhythm pattern at the ST elevation, occurring only in certain seconds. Therefore, to form a pattern of cardiac abnormalities through the relationship of the S1-R and S2-T time intervals, large data is needed to create an intelligent system of time interval modeling. It is also very necessary for a doctor's diagnosis to read the recording results for the validity of the recorded signal data according to the medical record.

B. Abnormal Heart

The results of combining heart sound signals and heart signals from the ECG can be seen in Fig. 8. Based on the results obtained, there is a very visible random pattern, so to determine HRV parameters in abnormal heart conditions, big data is needed. Each patient's disorder must be different depending on the characteristics of the disease because several types of diseases affect heart conditions, such as diabetes, high blood pressure, and even individual stress levels.

Fig. 8 shows that there are differences in the S1-R and S2-T intervals, but the pattern of randomly formed, depending on the type of abnormality. This is because only certain patterns are shorter or longer and also may only occur at certain seconds. As in Fig. 7, the sound signal interval S1-S1 looks very striking, and more seen in signals 4 and 5 and signals 6 and 7. As well as for the S1-S2 interval, there are very significant differences in the intervals. Whereas ECG signal is formed, there is a different rhythm pattern at ST elevation, occurring only at certain seconds. Therefore, it can be concluded to form an abnormal pattern heart through the relationship between the S1-R and S2-T time intervals. It is necessary to have accurate data great to be able to create intelligent systems of time interval modeling, and also, it is very necessary for a doctor's diagnosis in reading the recordings to determine the validity of the recorded signal data under the medical track record.

Based on the study of HRV parameters, the heart sound signal can be used to determine HRV parameters in the normal heart. The results obtained with the pattern of the same number of peaks, while in the abnormal heart, there are differences in results due to heart conditions abnormal has an indeterminate rhythmic pattern.

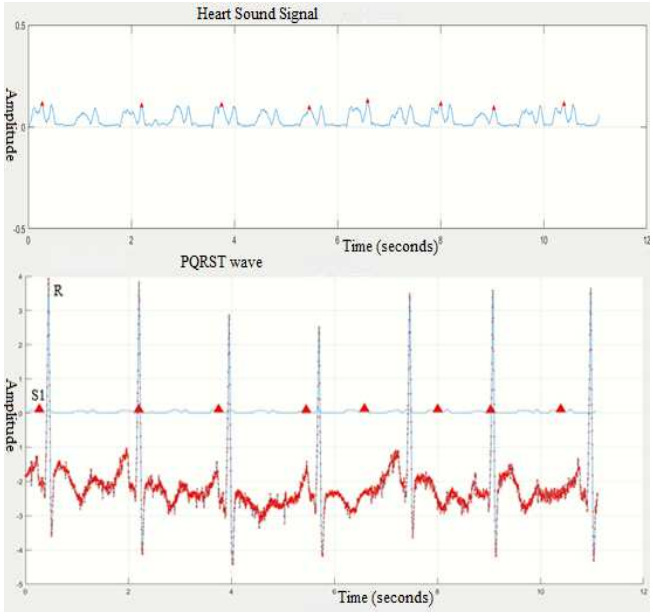

Fig. 8 Interpretation of (a) Combination of heart sound signals and PQRST heart signals, (b) electronic stethoscope sound signals in abnormal heart responders with measurement positions sitting for a stethoscope and supine lying down for a heart recorder.

IV. Conclusion

The merging of two signals in a multimodal system was analyzed concerning the characteristics of the heart sound signal and the PQRST heart signal, and the fusion was carried out on the signal pattern. Multimodal signaling was performed using a database with the same sampling at 10 seconds by recording the PQRST heart signal in the lying position and the heart sound in the sitting position. Experimental results show that the number of R peaks is the same as the number of S1 sound peaks, and also the number of T peaks with the number of S2 sound peaks, so it can be concluded that there is a regular signal pattern relationship between S1-S2 and the R-T wave, namely the relationship at the end of the first peak of the QRS wave. The cardiac signal due to ventricular depolarization-contraction and the appearance of an S1 heart sound and the association of the end of the next peak of the T wave cardiac signal indicates ventricular repolarization and the appearance of an S2 heart sound. This is consistent with the fact that electrical events in cardiac activity occur before mechanical events, with heart sound signals obtained from cardiac surgery electrically. Based on the study of HRV parameters, heart sound signals can be used to determine HRV parameters. In normal hearts, the results are obtained with the same peak number pattern, while in abnormal hearts, there are differences in results because abnormal heart conditions have an indeterminate rhythmic pattern. Further research and development of a database of ECG and PCG signals can be measured simultaneously for heart conditions in Indonesia.

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