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# Automatic moment segmentation and peak detection analysis of heart sound pattern via short-time modified Hilbert transform

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ABSTRACT

This paper proposes a novel automatic method for the moment segmentation and peak detection analysis of heart sound (HS) pattern, with special attention to the characteristics of the envelopes of HS and considering the properties of the Hilbert transform (HT). The moment segmentation and peak location are accomplished in two steps. First, by applying the Viola integral waveform method in the time domain, the envelope ($E_T$) of the HS signal is obtained with an emphasis on the first heart sound (S1) and the second heart sound (S2). Then, based on the characteristics of the $E_T$ and the properties of the HT of the convex and concave functions, a novel method, the short-time modified Hilbert transform (STMHT), is proposed to automatically locate the moment segmentation and peak points for the HS by the zero crossing points of the STMHT. A fast algorithm for calculating the STMHT of $E_T$ can be expressed by multiplying the $E_T$ by an equivalent window ($W_E$). According to the range of heart beats and based on the numerical experiments and the important parameters of the STMHT, a moving window width of $N = 1$ s is validated for locating the moment segmentation and peak points for HS. The proposed moment segmentation and peak location procedure method is validated by sounds from Michigan HS database and sounds from clinical heart diseases, such as a ventricular septal defect (VSD), an aortic septal defect (ASD), Tetralogy of Fallot (TOF), rheumatic heart disease (RHD), and so on. As a result, for the sounds where S2 can be separated from S1, the average accuracies achieved for the peak of S1 ($AP_1$), the peak of S2 ($AP_2$), the moment segmentation points from S1 to S2 ($AT_{12}$) and the cardiac cycle ($ACC$) are 98.53%, 98.31% and 98.36% and 97.37%, respectively. For the sounds where S1 cannot be separated from S2, the average accuracies achieved for the peak of S1 and S2 ($AP_{12}$) and the cardiac cycle $ACC$ are 100% and 96.69%.



## 1. Introduction

HS auscultation is a noninvasive, easy, and efficient method to evaluate heart function. Because of its ease of operation and economical cost, It is widely used in medical check-ups for adults and children, such as a VSD Diagnosis [1], testing of foetal heart rate extraction algorithms [2], fetal examinations

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[3], diagnosis of valvular heart disease [4], identification of heart valve diseases [5], screening of children congenital heart diseases [6], etc. Basic heart sound signals are mostly composed of four sound types: two outstanding sounds (S1 and S2), and two weak sounds called the third sound (S3) and the fourth sound (S4). Although these four sounds may be audible by the auscultation of the heart and occur in the frequency range of 20–2000 Hz, the unitary murmurs such as a systolic ejection murmur (e.g., aortic stenosis) and a pan systolic murmur (e.g., mitral regurgitation) mostly appear between S1 and S2 with different noise patterns such as the diamond and rectangular shapes [7]. However, S3 and S4 appear at very low amplitudes with low frequency components and are difficult to detect in usual auscultation. Therefore, the analysis of S1 and S2 plays an important role in heart sound analysis. In other words, to obtain more information about S1 and S2, the moment segmentation of the HS might be an important pre-processing step for automatic HS analysis.

In recent years, the studies of segmenting heart sound that have been reported can be summarized into three categories as follows:

(i) With the reference ECG, the performance of the heart sound segmentation is quite good [8,9]. However, the ECG, another signal source, may not be convenient for use in a medical check-up. Furthermore, in cases of infants or newborn children, placing the leads on a newborn is difficult because of the limited space on the torso and the noncooperation of the baby. Furthermore, in children with left or right hypertrophic ventricle, axis deviation of heart causes an abnormality on ECG signal which complicates the heart sound segmentation [10].

(ii) The frequency domain based segmentation algorithm was proposed by tracking of the heart sound spectrum [11–14]. With the aid of frequency domain analysis, certain frequency components are first extracted according to the time domain characteristics, and the start and end points of each cycle are determined by using the time domain search method at a given threshold value. However, the selection of the threshold and the filtering of the unexpected noise are still difficult problems in this type of method, and few studies mention this issue.

(iii) The envelope based moment segmentation method was studied by many researchers [7,15]. Our previous study [16] reported that the cardiac sound characteristic waveform (CSCW) method provided sufficient performance compared to the conventional Shannon envelope and Hilbert envelope algorithms, which were used as the empirical or manual way and the automatically selecting way to estimate cardiac sound segmentation, respectively. However, the selection of the threshold and the filtering of the unexpected noise are still difficult problems in this method. To overcome these points, one researcher [17] proposed a novel method for the segmentation of the HS. In this paper, the envelope CW (denoted by $E_T$) of the HS in time domain and the center moment character (CMW) of $E_T$ based on the Viola integral method were proposed first. Then, each heart sound cycle could be quickly found by the local peak points of the CMW. This paper showed that $E_T$ was effective against not only amplitude variation but also complex noise. Moreover, using CMW local peak point method for locating the segmentation not only avoided the difficulty of setting multiple thresholds to detect S1 or S2, but also overcame the detections of the start and end points of the sounds (S1 or S2) drowned in the murmurs. However, this paper showed that how to locate the local peaks is still very difficult because the CMW local peaks are very different due to the complexity of $E_T$, as shown in Fig. 7.

Thus, in conclusion, the researchers [17] proposed the efficient envelope $E_T$ and developed moment segmentation of HS. Unfortunately, locating the CMW local peaks is very difficult, especially for clinical heart sounds (Fig. 7). However, by experimental analysis, the characteristics of the $E_T$ can be summarized as follows (Fig. 2):

(a) The local region from S1 to S2 is basically considered as an even convex function symmetrical with respect to the vertical line crossing the symmetrical point considered as the transmission point of this local region from S1 to S2 (named $T_{12}$, and marked by ∗). S1 is causes by turbulence created when the mitral and tricuspid values close and S2 is produced by the closing of the aortic and pulmonic valve leaflets. Moreover, the envelop $E_T$ based S3 and S4 is almost not detected (Fig. 2), and this study focus on S1 and S2. Therefore, the transmission point $T_{12}$ may reflect a relative balance point from one heart motion producing S1 to another heart motion producing S2 without considering S3 and S4.

(b) The local region from S2 to S1, is also basically considered as an even concave function symmetrical with respect to the vertical line crossing the symmetrical point considered as the transmission point of this local region from S2 and S1 (named $T_{21}$, and marked by ▼). Therefore, the transmission point $T_{21}$ may reflect a relative balance point from one heart motion producing S2 to another heart motion producing S1 without considering S3 and S4.

(c) The local parts around the peaks of S1 and S2 can all be considered as symmetrical concave curves.

Because the $E_T$ (note: here $E_T$ is the same as CW defined in study [17]) is proved to be a periodic signal with the same period that the heart sound signal has, which is Theorem 1 proved in Section 2.2.3, using the difference between two adjacent points $T_{21}$ on the $E_T$ can compute a heart sound period, which is proved in Section 2.2.3. Therefore, the difference between two adjacent points is considered as HS moment segmentation including S1 and S2. Therefore, the HS moment segmentation and peak location will be realized by locating the local symmetrical points $T_{21}$ considered as the moment segmentation point of the symmetrical convex curves and the peak of the concave curves. To locate the peak of an even curve automatically, one study [18] used a HT of an even function $r(t) = 1/(1 + t^2)$ considered as an R-wave envelope model to detect the peak of the R-wave automatically and showed that this approach not only does not require any amplitude threshold and prior knowledge of the past detected R-peaks, but also achieves much higher detection rates than those produced by the other existing methods. Although there are