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Online Estimation of Lower and Upper Bounds for Heart Sound Boundaries in Chest Sound Using Convex-Hull Algorithm

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Abstract— **Heart sound localization in chest sound is an essential part for many heart sound cancellation algorithms. The main difficulty for heart sound localization methods is the precise determination of the onset and offset boundaries of the heart sound segment. This paper presents a novel method to estimate lower and upper bounds for the onset and offset of the heart sound segment, which can be used as anchor points for more precise estimation. For this purpose, first chest sound is divided into frames and then entropy and smoothed entropy features of these frames are extracted, and used in the Convex-hull algorithm to estimate the upper and lower bounds for heart sound boundaries. The Convex-hull algorithm constructs a special type of envelope function for entropy features and if the maximal difference between the envelope function and the entropy is larger than a certain threshold, this point is considered as a heart sound bound. The results of the proposed method are compared with a baseline method which is a modified version of a well-known heart sound localization method. The results show that the proposed method outperforms the baseline method in terms of accuracy and detection error rate. Also, the experimental results show that smoothing entropy features significantly improves the performance of both baseline and proposed methods.**

I. INTRODUCTION

Heart sound localization in chest sound is an essential task for many heart sound cancellation algorithms. For this purpose, a variety of different methods are proposed in the literature. Among them, [1] and [2] use adaptive filtering and non-linear prediction respectively. Multi-resolution decomposition is used in [3, 4]. Recently, [5] shows that entropy based method gives better result than many methods given in the literature, and [4] uses singular spectrum method and denotes that it gives slightly better results than entropy based method with lower computational cost. In heart sound localization, one of the main difficulties comes from precise determination of onset (initial point) and offset (end point) locations of heart sound segment. To overcome this problem, we divide heart sound localization problem into two sub-steps: detection (estimation of upper and lower bounds) and boundary enhancement. In the detection step, the sound waveform is divided into segments so that the onset and offset of the heartbeats are contained in those segments. Segment boundaries of the first stage denote lower and upper bound for onset and offset boundaries of each heartbeat segment respectively. In the boundary enhancement step, the start and end points of each segment are enhanced to find the precise location of onset and offset of heart sound [6]. It is clear that the performance of such two-step heart sound localization algorithm highly depends on the result of the detection step since second stage assumes there exist a heart sound segment within the two consecutive bounds, and localization is finalized by enhancing those boundaries based on this assumption.

For that reasons, the aim of this paper is to develop an accurate and robust detection algorithm, which can be used in the first step of the two-step heart sound localization algorithm. The proposed detection algorithm estimates the upper and lower bounds of heartbeat segment boundaries using the convex-hull algorithm which is originally used in speech segmentation applications [7]. The original convex-hull algorithm described in [7] works offline (use the entire stored data). We modified the algorithm in our implementation to operate online. To compare performance of the proposed algorithm, the heart sound localization algorithm based on entropy-thresholding method [5] is modified to estimate the upper and lower bounds for heart segment boundaries like the proposed algorithm. The experimental results show that the proposed algorithm outperforms the baseline algorithm.

The rest of the paper is structured as follows. In Sec. II the aim of the study is stated. The proposed algorithm to estimate upper and lower bounds for heart sound boundaries described in Sec. III. The experimental results are given in Sec. IV. Discussion and conclusion are given in Sec. V.

II. THE AIM OF THE PROPOSED ALGORITHM

The aim of this study is to segment the chest sound into regions such that the onset and offset boundaries of the heart sound are contained in those regions. The proposed segment boundaries denote the lower and upper bound for onset and offset boundaries of each heartbeat segment respectively. An example of the segmentation results for the proposed algorithm is given in Fig. 1. In this figure, a chest sound data (about one second length) with three heartbeats and the related onset and offset heartbeat boundaries are shown. The highlighted regions (which are lung sound only regions) of this figure denote the time periods, in which the bound estimations should take place. (e.g. the estimated lower bound (LB) and upper bound (UB), which are shown with vertical dashed lines, for the heartbeat located within the period of about [0.5-0.6]s). The existence of more than one bound or absence of any bound in those regions are considered as an error for algorithms. Note also that the lower bound for a heart sound segment can be considered as the upper bound for the earlier heart sound segment and vice versa.

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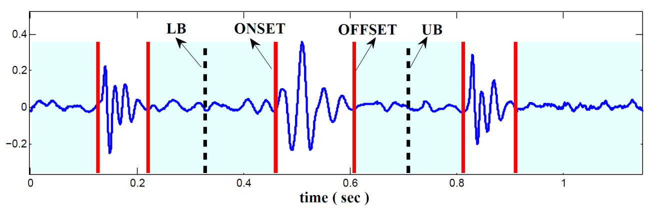

Figure 1. Definition of lower and upper bounds for heartbeat boundaries

III. THE PROPOSED ALGORITHM

The proposed algorithm works online and defined as follows: Chest sound is gathered for one second, the algorithm processes data to estimate upper and lower bounds for heart sound boundaries. After this process, additional data for one second is taken for further processing, and so on. The main block diagram of the proposed method is given in Fig. 2. There are three main stages of the proposed method: feature extraction, feature smoothing and detection. These stages are explained in detail as follows.

A. Feature Extraction from Chest Sound

Among the different types of acoustic features, entropy based features are considered as more accurate and robust features than others for detection and localization of heart sound [5, 6]. Hence, in this work, we used entropy feature for heart sound bound estimation. In calculation of the entropy for each of chest sound frame (with 20 ms window length and with 50% overlap), the approach of [6] is followed.

B. The Smoothing Process of Extracted Features

One of the main advantages of using one second delayed signal, it allows applying the smoothing process within the delayed time. In this work, the smoothed version of the entropy features is estimated as follows. The smoothing stage is handled by using zero-phase low-pass filter with cutoff frequency of 12 Hz. A second order Butterworth IIR filter is used as a low-pass filter. For zero-phase the filtering is performed in the forward direction, the filtered sequence is then reversed and run back through the same filter; and the time reverse of the output of this second filtering gives result having precisely zero phase distortion. An example for smoothed version of the entropy features of the chest sound can be seen in Fig. 2.

C. Heart Sound Detection (Bound Estimation)

In this work, the convex-hull algorithm is used to detect heart sound segments in chest sound. The convex hull algorithm, initially described by Mermelstein, has been used in speech segmentation into syllabic units [7]. For the sake of completeness, we briefly describe it in here. A small entropy segment is selected for explanation, as can be seen in Fig. 3. The convex-hull of the selected entropy segment is the non-decreasing from the start of the segment to its point of maximum point and monotonically non-increasing thereafter. The main convex-hull of the entropy segment is

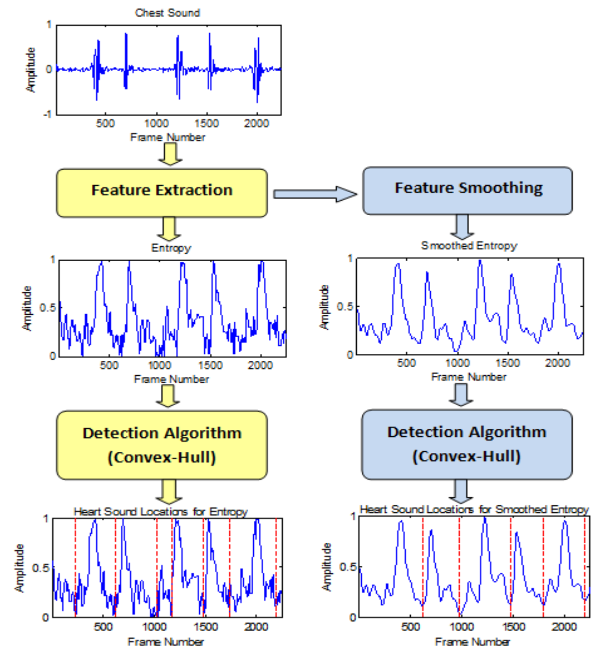

Figure 2. Main block diagram of the proposed algorithm

shown in Fig. 3 with a black dotted line, also called as h(t). Within the segment, the maximal difference point between the convex-hull and the entropy function is defined as a potential boundary. If the difference exceeds the certain threshold value, (here, mean plus standard deviation of entropy) then the segment is divided into two sub-segments. Assuming that maximum difference d_1 at point c' exceeds the certain threshold value; the algorithm divides segment (a-c) in to two sub-segments (a-c') and (c'-c). Then convex-hull algorithm is performed for each new segment. The corresponding convex-hull for these two segments, $h_1(t)$ and $h_2(t)$ are also shown in Fig. 3. If the maximum difference between $h_1(t)$, $h_2(t)$ and entropy function are called d_2 and d_3 respectively and if they are smaller than the threshold value, there will be no further segmentation. Segmentation is carried out recursively until the difference within the segment is below the threshold value. For the example given in Fig. 3, the convex-hull algorithm states that there are two heart sound segments between point a and c, and the point c' is the boundary between these heart sound segments. This boundary is considered as the lower bound for the second heart sound segment and upper bound for the first heart sound segment. The original algorithm assumes that entire data is stored before processing commences. However, heart sound detection can also be used in online operation. Hence, the convex hull algorithm has been modified in our implementation to operate online with certain time delay which is no shorter than one heart beat duration. We implement the algorithm with one second delay. Moreover, this modification requires careful implementation. In the first step, the algorithm takes one second chest sound data and processes it to detect heart sound segments. After first step, the algorithm takes next one second data for segmentation, the segment which starts from the last heart segment boundary until the starting point of the second step

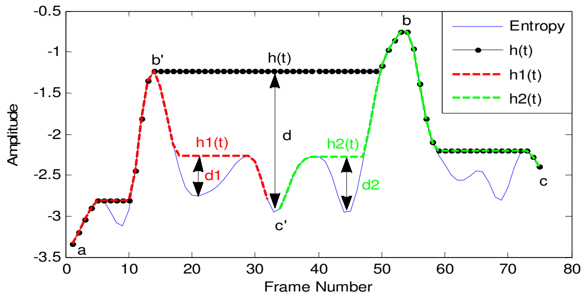

Figure 3. A small part of the entropy of chest sound and the corresponding convex-hull envelopes

is added to the second step data and this extends the data slightly more than one second. This small modification guarantees that starting point of the second segment coincide with a minimum in the entropy function.

IV. Experimental Work

The experimental studies carried out in this work are explained in this section as follows.

A. Database

The database used in this study is five-healthy-person database, which is the same database used in [5] except one person[1]. The detail description of the database can be found in [5]. The database contains chest sound measured from the third intercostal space anteriorly on the right upper lung lobe. The sampling frequency of the database is 10240 Hz. In this work, the experimental results are tested under three respiratory flow rates: low, medium and high. To measure the performance of the proposed algorithm, the localization of the heart sound is determined by hand.

B. Performance Measures

To measure the accuracy of the proposed method, two performance measures are used in this work: detection error rate (DER) and Accuracy (ACC). These performance measures can be calculated using following formulas.

$$DER = \frac{FP + FN}{TP} x100\%, \qquad ACC = \frac{TP}{TP + FN + FP} x100\%,$$

where TP, FN, and FP denote, respectively, the number of true-positives when a heart sound segment is correctly detected by the algorithm, false-negatives when a heart sound segment is missed, false-positives when a lung sound is detected as heart sound.

C. Baseline Method

The proposed algorithm is compared to the baseline algorithm which is based on entropy-thresholding method explained in [5]. Originally, this algorithm is proposed to estimate localization of the heart sound segment in chest sound. We modified this algorithm such that it detects heart sound segments and estimate lower and upper bounds for them. The baseline algorithm decides that the current segment is a heart sound segment if the entropy of the data exceed a certain threshold value (which is mean plus standard deviation of entropy: μ+σ). The onset and offset boundaries of the estimated heart sound segment are then used to estimate the upper and lower bounds for those boundaries. The middle point of offset and onset boundaries of two consecutive heartbeat segments is considered as upper bound for the offset of the first heartbeat and lower bound for the onset of the second heartbeat. As an example, the estimated heart sound segments using entropy-thresholding method are shown by horizontal red stripes numbered from one to six in Fig. 4.b. The onset and offset boundaries of the last two heart sound segments (numbered five and six) are between at (154-160) and (204-208) frames, respectively. Using the segment locations, the boundary location for these two heart sound segments is found to be 182 calculated as (160+204) /2. In other words, 182th frame is the upper bound for offset of heart segment numbered five while it is the lower bound for the onset of the heart sound segment numbered six.

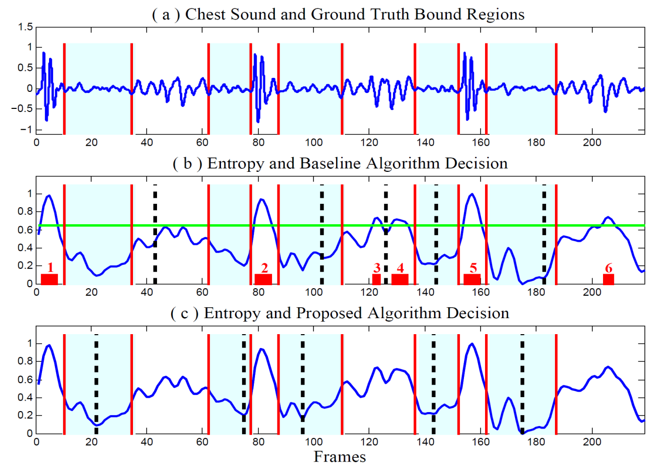

Figure 4. An example of chest sound signal and related entropy features with hand labeled heart sound boundaries (vertical red solid lines). The highlighted regions are the allowed places for the correct estimation bounds. Chest sound waveform (a). The corresponding entropy data with threshold value: λ=μ+σ (horizontal solid green line. According to this treshold value, the estimated locations of the heart sound segments are denoted by horizontal red stripes numbered from one to six. The upper and lower bounds (vertical dashed black lines) estimated by baseline algorithm (b). The upper and lower bounds (vertical dashed black lines) estimated by the proposed algorithm. (c)

D. Experimental Results

In order to test and compare the results of the proposed method with the baseline method in upper and lower bound estimation task, the methods are evaluated on the same database described above. The experimental results are given as follows. Bound estimation results for the chest sound given in Fig. 4.a using baseline and the proposed method can be seen in Fig. 4.b and Fig. 4.c respectively. Since baseline method misses the heart sound segment between (40-60) frames and divide the heart sound segment between (110-140) frames into two heart segments, two of the five bounds are estimated incorrectly, which are in non-highlighted regions On the other hand, the proposed algorithm estimates all bounds correctly, all of which are located within the highlighted regions. Table.1 and Table.2 show DER and

[1] Only five persons' data is provided to us for this study by corresponding author of [5]

TABLE I. LOWER AND UPPER BOUNDS ESTIMATION RESULTS OF PROPOSED AND THE BASELINE METHODS (MEAN ± STD.)

Flow Rate	Method	DER (%) (Normal)	DER (%) (Smooth)	ACC (%) (Normal)	ACC (%) (Smooth)
Low	Baseline	83.6±32	5.1± 13.3	55.6 ±8.6	94.1 ± 10
	Proposed	20.6±15.4	4.6± 6.4	85 ± 11.4	95.2 ±5.6
Med.	Baseline	82.4±36.2	9.8± 10.5	55.9±10.6	91.2 ±8.3
	Proposed	36.9±41.0	2.1± 2.5	74.8±21.7	97.3 ±2.4
High	Baseline	75.4±43.8	13.6±12	55.3 ±13	87.3 ±8.5
	Proposed	28.7±30.8	6.8± 7.3	77± 15.3	94.4 ±6.5

ACC results for the baseline and the proposed method under three respiration flow rates: low, medium and high with normal and smoothed entropy feature. The values given in these tables are averaged for five subjects and the corresponding standard deviations are calculated. From Table.1, it can be stated that the baseline algorithm is not suitable for bound estimation task with normal entropy features due to its high DER and low ACC results. On the other hand, from Table.1, it can also be seen that, smoothing entropy feature highly improves the performance of the baseline algorithm and make it suitable for bound estimation. The results for the proposed algorithm are also shown in this table. It can be observed that the proposed algorithm outperforms the baseline algorithm in terms of DER and ACC for the both normal and smoothed entropy features under all-three respiration rates. Table-2 gives overall experimental results for three respiration flow rates. First three columns indicate the total number of TP, FN and FP bounds for the database. The baseline algorithm estimates 695 bounds correctly with two missed bounds from a total of 697 bounds and it produces 553 wrong bounds (incorrectly inserted) for normal entropy features. Under the same conditions, the proposed algorithm finds 679 bounds correctly and it misses 16 bounds and inserts 176 wrong bounds from a total of 697 bounds. Note that the numbers FN and FP are equally bad for bound estimation since our final aim will be to search the correct onset and offset boundaries of heart sound using these estimated bounds. Therefore, it is necessary to use DER or ACC for a fair comparison of the algorithms instead of looking at the numbers FN or FP errors separately. Comparing the proposed and baseline algorithm in terms of DER and ACC measurement, we can conclude that proposed algorithm gives better results than the baseline algorithm. Moreover, the usefulness of the smoothing entropy features can also be seen from this table.

TABLE II. OVERALL EXPERIMETAL RESULTS (MEAN ± STD.)

Methods	Number of TP	Number of FN	Number of FP	DER (%)	ACC. (%)
Baseline (N*)	695	2	553	79.8±37	55.6±11
Proposed (N)	679	16	176	28.3±12	77.9±8.9
Baseline (S*)	674	23	43	9.5±4.3	91.4±7.0
Proposed (S)	695	2	32	4.5±2.4	95.6±4.6

* (N) and (S) denote normal and smoothed entropy features used in the method

V. CONCLUSION

In this work, we introduce a new method based on convex-hull algorithm to estimate upper and lower bounds of onset and offset boundaries of heart sound segment in chest sound. These bounds will be used as anchor points for precise determination of onset and offset boundaries. The performance of the proposed method is compared with the baseline method which is modified version of the entropy-thresholding method, a well-known method used in the literature [5]. The experimental work is performed with the database used in the literature [5]. The experimental results show that the proposed algorithm estimate heart sound location bounds better than baseline method in terms of DER and ACC Experimental results also show that smoothing entropy feature significantly improves the performance of the proposed and baseline method. Moreover, the proposed algorithm is more robust than baseline method since it produces lower standard deviation

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