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Carotid Sound Signal Artifact Detection based on Discrete Wavelet Transform Decomposition

Abstract: Auscultation methods allow a non-invasive diagnosis of cardiovascular diseases like atherosclerosis based on blood flow sounds of the carotid arteries. Since this process is highly dependent on the clinician's experience, it is of great interest to develop automated data processing techniques for objective assessment. We have recently proposed a computer-assisted auscultation system that we use to acquire carotid blood flow sounds. In this work, we present an approach for detecting artifacts within the blood flow sound caused by swallowing or coughing events. For this purpose, we first decompose the signal using a discrete wavelet transform (DTW). Then, we compute an energy ratio between the DWT scales associated with the signal information with and without artifacts using a sliding window of 1 s length. Evaluation based on Kruskal-Wallis and Wilcoxon rank-sum tests shows a statistically significant difference ($p\text{-value} < .0001$) between the signal with and without artifact. Therefore, the proposed method allows the identification of the studied signal artifacts.

Keywords: Carotid sound, Discrete Wavelet Transform

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1 Introduction

Diagnostic tools based on auscultation allow a non-invasive identification of several cardiovascular diseases such as atherosclerosis. This methodology, called phonoangiography, was initially proposed by Lees and Dewey in 1970 [1]. Using a stethoscope, clinicians can perform a non-imaging assessment of the carotid based on the artery flow sound [2]. Unfortunately, this operation is highly dependent on the clinician's experience, and involves a slow learning curve. Therefore, it is of great interest to develop data processing systems for automatic assessment. Recently, we have presented a new approach for acquiring carotid audio signals with a portable device [3], [4]. Although this approach has shown to acquire stable and significant carotid sound dynamics [5], [6], for an accurate extraction of these dynamics it is crucial to process an adequate stable signal segment. Signal artifacts produced by swallowing or coughing are inevitable during the signal acquisition, affecting its assessment. Unlike episodes of normal breathing, these episodes involve characteristics that can hide essential information used for the analysis, such as vascular sounds resulting from the propagation of the main normal heart sounds S1 and S2. The main idea behind this work is to automatically identify these types of signal artifacts, paving the way to select informative and stable data for reliable processing automatically. For this purpose, we have created a dataset of carotid sound data, including normal breathing, where additional events of coughing and swallowing were generated. As a first processing step, the signal is decomposed by a discrete wavelet transform (DWT). Then, using a sliding window of 1 s length, we compute the energy ratio between the DWT scales associated with the signal information and those associated with swallowing and coughing artifacts. Finally, we perform a statistical evaluation of the data based on Kruskal-Wallis [7] and a Wilcoxon rank-sum test [8] to study the discriminating capability of the computed energy ratio statistically.

2 Materials and Methods

This section presents the hardware design of the auscultation system that was used for the carotid sound recording, the procedure for the data acquisition, and the proposed methodology for the signal analysis.

2.1 Hardware design

The carotid sound signals used in this work were acquired using a custom-built auscultation system. This system comprises an auscultation device and a desktop application. The device consists of an audio sensor and a processing unit powered by a lipo battery. All these components are together encased in a 3D printed mechanical structure. This device is connected to a desktop application via a self-generated Wi-Fi network. The desktop application allows the user to visualize the signals in real-time and record the signals on a host system like a personal computer. The files are then stored on the computer in the form of audio files. The software also allows the user to input manual information such as personal activity, comorbidities, medication, etc. For a more in-depth explanation of the described system, please refer to [5].

2.2 Data acquisition

For the proposed approach, we use real carotid sound data consisting of a dataset with 160 recordings of 36 s length with a sampling frequency $f_s = 16$ kHz. These recordings were obtained from four different users (forty recordings per user), up to our knowledge, without vascular diseases. The signal acquisition was performed according to a protocol that includes segments of normal breathing, swallowing, and coughing, each segment with a length of 12 s. It is important to note that the last two segments involve two swallowing and two coughing events. A representation of this acquisition protocol is shown in Fig. 1, where the signal is plotted in blue

with its values normalized between 0 and 1. The black benchmarks delimit the mentioned segments. In summary, the dataset involves 320 swallowing and 320 coughing events.

2.3 Manual localization of swallowing and coughing events

As explained above, the acquired recordings involve two events of swallowing (time interval between 12-24 s) and two events of coughing (time interval between 24-36 s). Considering that the primary goal of this work is to characterize these events and analyze the difference between these events and segments during normal breathing, we first localize them manually to study their signal dynamics independently. In this context, for the 160 recordings, we perform a visual identification of the swallowing and coughing events by manually labeling their starting and ending times. A representation of these episodes is shown in Fig. 1, where these events are delimited by the lines in red. This preliminary identification is used to study the difference between these events and the carotid sound during normal breathing.

As shown in Fig. 1, sometimes these events can be easily detected. However, frequently their detection is more complex. Therefore, a robust processing is required for an automatic signal artifact identification.

2.4 Carotid sound signal artifact characteristics

For the proposed analysis, we employ DWT-based decomposition. We assume that the carotid sounds, including the swallowing and coughing events, comprehend very complex characteristics, involving not only oscillatory dynamics but also transient behavior. Therefore, considering these transient dynamics, DWT is better suited than other traditional methods such as Fourier transform [9]. Also, DWT allows the analysis of the oscillatory characteristics. For the

Fig. 1: Carotid sound recording belonging to the user U4. This recording was acquired according to the following protocol: (0-12 s) normal breathing; (12-24 s) swallowing; (24-36 s) coughing. These segments are delimited by benchmarks in black. The benchmarks in red correspond to the starting and ending time of the swallowing and coughing events set manually for the proposed analysis.

proposed analysis, we apply a 12-level DWT-based decomposition considering a Wavelet Daubechies 4. An example of the performed decomposition is presented in Fig 2, where we show the scales 3, 5, 6, 7, 8, and 10 selected strategically to visualize their contribution to the information of interest.

As we can observe, the examined artifacts are presented in most of the scales (see the segments between the red lines), represented by the transient dynamics of higher amplitude. Nevertheless, the vascular sounds originated from the main normal heart sounds S1 and S2 appear clearly only from the scale 7 upwards. Based on this preliminary analysis, we investigate if these observations are reflected in the complete dataset by studying the energy ratio between the scales of lower frequency (scales 7 to 12) and higher frequency (scales 1 to 6), determining if this information can help to identify the investigated signal artifacts. For this purpose, we compute the described energy ratio based on a sliding window of 1 s length. This ratio is shown in Fig. 3, whose values are scaled between 0 and 1. Here, we can observe that the energy ratio during swallowing and coughing events is considerably lower than the ratio computed during normal breathing, which can help detect the mentioned events.

Fig. 2: Scales obtained by the decomposition based on discrete wavelet transform applied to the recording presented in Fig. 1.

Fig 3: Ratio computed between the energy of scales of lower frequency (scales 7 to 12) and higher frequency (scales 1 to 6).

Since this ratio considers all the DWT scales (scales 1 to 12), it results in a standardized value, i.e., the ratio can be compared among the recordings independently of their amplitude.

3 Results

This section presents the results obtained by a statistical analysis applied to the energy ratio computed from the carotid sound during normal breathing, swallowing, and coughing. It is performed to determine if the computed ratio can help to identify the investigated events based on a statistical analysis based on Kruskal-Wallis and Wilcoxon rank-sum tests.

On the one hand, considering that the analysis involves only one independent variable and three categorical groups, we selected the Kruskal-Wallis test as a suitable analysis for comparing the three groups. This test is the analogous non-parametric version of the one-way analysis of variance (ANOVA) [10], which, unlike ANOVA, can also be used for non-normally distributed data [11]. This analysis is performed under the null hypothesis that the observations are from identical distributions, which is expressed by the estimated p -value. On the other hand, the Wilcoxon rank-sum test is employed as a post hoc analysis to examine each pair of groups separately to determine their statistically significant difference (p -value < .0001). The Wilcoxon rank-sum test's main advantage is that it does not require a preliminary assumption of data normality, as in the case of a t -test [8].

Fig. 4 shows the boxplots for the energy ratios computed during normal breathing, swallowing, and coughing. The vertical borders of the box correspond to the 25th and 75th percentiles of the data; the median values are represented by the red line, and red crosses correspond to the outliers.

The obtained statistical results are presented in Table 1, which shows the obtained p -values for the performed analyzes. Results based on the Kruskal-Wallis indicate a significant difference between the mean of the three groups. In addition, based on the Wilcoxon rank-sum test, each pair of data involves a statistically significant difference (p -value < .0001), indicating that the computed energy ratio can help to identify the signal artifacts.

Fig. 4: Boxplots of the energy ratio during normal breathing, swallowing, and coughing. The vertical borders of the box correspond to the 25th and 75th percentiles of the data. The median of the data is represented by the red line, and red crosses are the outliers. For the normal breathing group, there are five outliers higher than 3.5×10^4 that are omitted for better visualization.

Table 1: Results of the statistical tests applied to the energy ratio during normal breathing, swallowing, and coughing.

	<i>p</i> -value
Kruskal-Wallis test	<.0001
Post hoc - Wilcoxon rank-sum test	
Normal breathing vs. swallowing	<.0001
Normal breathing vs. coughing	<.0001
Swallowing vs. coughing	<.0001

4 Conclusion

This work has presented an approach to detect signal artifacts associated with swallowing and coughing events that can potentially be present during carotid sound acquisition. The applied statistical tests such as Kruskal-Wallis and Wilcoxon rank-sum show a statistically significant difference between the studied signal segments during normal breathing, swallowing, and coughing. Therefore, the obtained results indicate that the energy ratio between the DWT scales of lower and higher frequencies can help identify the studied signal artifacts and pave the way for the automatic selection of stable carotid sound segments. Also, they indicate that it is even possible to differentiate between the artifacts produced by the swallowing and produced by the coughing events.

Note that this approach has only been tested on 160 measurements from four users. Therefore, to validate our results, it would be necessary to include a higher number of both recordings and users into the proposed analysis.

As a future step, we propose to examine more types of signal events, such as controlled respiration and abrupt sensor movements. We also propose to extract signal features from stable segments and to study their performance in predicting specific cardiovascular pathologies such as atherosclerosis.

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