Autoregressive Whitening Filtering of Phonocardiography Signals for Detection of Coronary Artery Disease

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Abstract

Background: Narrowing of the coronary arteries, which defines coronary artery disease (CAD), can be discovered through phonocardiography (PCG) analysis. Increased power of frequencies below 200 Hz in the diastole has been associated with CAD, and can be used to distinguish CAD from NonCAD patients. However, spectral roll off is steep (~40 dB/dec), and spectral leakage might mask the weak CAD-related signal.

Methods: PCGs from 1168 subjects, 213 CAD and 955 NonCAD, were pooled from three studies. The average power spectral density (PSD) of diastole segments for NonCAD subjects was found, and an auto-regressive (AR) model of this PSD was constructed. The inverse of the corresponding filter was used for whitening.

Results: A single iteration of whitening filtering was insufficient to make the PSD white for 5-1000 Hz. Two iterations of whitening filtering with an order of 6-10 were required to reach a plateau of maximal whitening with a spectral flatness measure close to 1 in the frequency band 5-1000 Hz. The whitening process revealed additional PSD differences between CAD and NonCAD subjects for the mid-diastole segment.

Conclusion: Whitening of diastole PCG segments emphasized the difference between CAD and NonCAD patients.

1. Introduction

Cardiovascular disease is the most common cause of death world-wide, accounting for nearly 18 million (31%) deaths in 2016. More than half of these deaths can be categorized as coronary artery disease (CAD) – a growing cause of death; 13% in 2000 to 17% in 2016 [1].

Early detection of coronary artery disease will enable patients to seek life style changes and/or medical prophylaxes, and thus avoid or slow progression of the disease. Phonocardiography provides the potential of a cheap and non-invasive method for early detection of CAD. The technology has already been developed for exclusion of patients who are suspected of CAD early in the diagnostic process. Further improvements would increase the efficacy of this method, and possibly allow for screening of CAD using PCG.

Earlier studies have found differences in average power spectral densities (PSD) between subjects with CAD and subjects not afflicted by this disease (NonCAD) [2–4]. This difference is replicated in our available data set, as shown in Figure 1 and 2. However, due to the steep roll-off, spectral leakage makes potential, and relatively weaker, differences at higher frequencies difficult to determine.

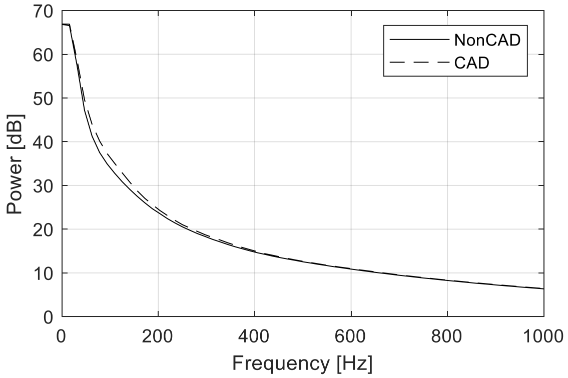

Figure 1. Shows the average diastole PSD for CAD and NonCAD subjects. A fourth order bandpass filter with cut-off frequencies of 5 Hz and 1 kHz has been applied.

The diastole has a short duration, and thus there is a limit to increasing segment length to reduce the problem of spectral leakage.

Using a non-rectangular window can reduce the problem of spectral leakage at frequencies further away from source frequencies. PSD estimates shown in Figures 1 and 2 were created using a Hamming window.

To further reduce the influence of spectral leakage on the comparatively weak CAD-related signal, we will investigate the possibility of using whitening filtering.

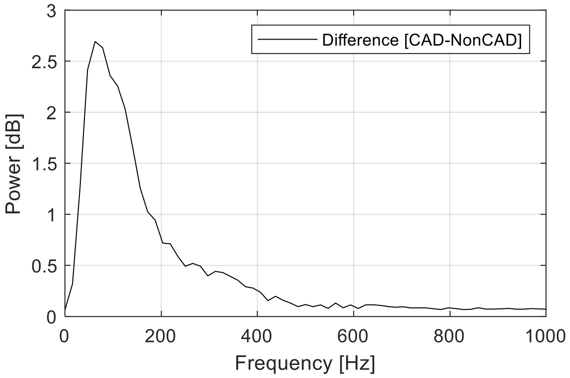

Figure 2. The PSD difference between average CAD and NonCAD patients are most pronounced for frequencies 20-200 Hz, and no difference is apparent at frequencies above 400 Hz. Potential differences at these frequencies could be masked by spectral leakage.

1.1. Hypothesis

Whitening filtering can be used to emphasize the diastole PSD differences between CAD and NonCAD subjects, and thus useful when using PCG for diagnosing patients suspected of having CAD.

2. Methods

2.1. Data

Phonocardiography recordings were pooled from three different studies: AdoptCAD [5], BIO-CAC (NCT02913144), and Dan-NICAD [6, 7] as shown in Table 1. Only one recording for each subject was included; in cases where more than one recording were available, the first recording was selected. Some subjects did not have any recording associated to them, and thus the number of available recordings in Table 1 is lower than the full number of subjects included in the studies.

Recordings in the three studies followed the same procedure: subjects were in supine position, and recording commenced after five minutes rest. PCG signals were recorded at the 4th intercostal space on the left side using a CADScor device with a sampling frequency of 8000 Hz. Subjects were instructed to hold their breaths four times of eight seconds each during the recording.

Only subjects with a clear diagnostic outcome of CAD or no indication of CAD were included in this study. CAD is defined as patients with a coronary angiographic identified stenosis with at least 50% diameter reduction. NonCAD patients had a coronary artery calcium (CAC) score of 0 and no coronary artery stenosis discovered through coronary computed tomography angiography (CCTA). Further details of classification method are described in [8].

Table 1. Number of recordings as distributed between the three studies and diagnosis.

		Diagnosis		
Study	Available Recordings	CAD	Non-CAD	Included Recordings
AdoptCAD	298	95	84	179
Dan-NICAD	1563	161	739	900
BIO-CAC	661	2	275	277
Total	2522	258	1098	(a) 1356
Excluded		45	143	
Final Total		213	955	(b) 1168

Recordings (a) were checked for quality using Acarix CADScor heart sound processing framework, and 131 recordings were excluded on this basis.

Furthermore, heart beats with a diastole duration outside the 95% confidence interval (CI) of the mean – as calculated on (a) – were excluded. Lastly, any recordings containing less than 8 heart beats (after removal of diastoles outside CI) were also excluded – 57 recordings. The final total of recordings included in the further analysis is shown in Table 1 as (b) – 1168 recordings.

2.2. Analysis

Breath-hold periods of phonocardiograms were first segmented into heartbeats using a duration dependent hidden Markov model developed by Schmidt et al. [9]. Next, an adaptive filter was used to reduce background noise present in the room using a simultaneous recording of room noise. A fourth order bandpass Butterworth filter with cut-off frequencies of 5 Hz and 1000 Hz was applied to each heartbeat. To avoid influence from S1 and S2 sounds, diastoles of breath-hold periods were annotated as the segment between S3 and S4 using the CADScor algorithm framework.

Welch's power spectral density (PSD) estimate was calculated for each diastole using the Matlab function, pwelch, with a segment length of 512 samples (64 ms) and 256 samples overlap. Each segment was windowed with a Hamming window. The average diastole PSD for each subject was calculated, and then the average of the NonCAD subjects was taken. Using inverse Fourier transformation, this NonCAD average PSD was then used to retrieve the corresponding auto-correlation function.

Finally, Levinson-Durbin recursion was used to find the AR coefficients using the Matlab function levinson. The coefficients were calculated for AR filter orders 1-30.

The inverse of these coefficients was then used as a whitening filter, and applied to the original PCG signals.

As this process was insufficient to provide a white spectrum at 5-1000 Hz, the whitening process was repeated twice more, and evaluated at each iteration.

2.3. Spectral Flatness

To evaluate the efficacy of the whitening filter, a spectral flatness measure was calculated using the Wiener Entropy:

$$S_f = \frac{\exp\left[\frac{1}{n}\sum_{k=1}^{n}\ln(x_k)\right]}{\frac{1}{n}\sum_{k=1}^{n}x_k} = \frac{\sqrt[n]{\prod_{k=1}^{n}x_n}}{\frac{1}{n}\sum_{k=1}^{n}x_k}$$

x_k is the power spectrum magnitude of bin number k, $0 \leq S_f \leq 1$ is the spectral flatness measure, and $S_f = 1$ is the PSD that describes a white noise process.

Spectral flatness was evaluated for the frequency band 5-1000 Hz.

3. Results

As shown in Figure 1, whitening filtering improves the spectral flatness score for all orders and all number of applications. A single iteration of whitening filtering is not enough to reach a high level of spectral flatness for the frequency range 5-1000 Hz even at higher filter orders. Figure 1 also shows that a high degree of flatness is reached with 2 iterations of whitening filtering at orders of 6-10. Note that the second iteration of whitening filtering is different, as each iteration calculates new AR coefficients based on the residual mean PSD of the NonCAD diastole.

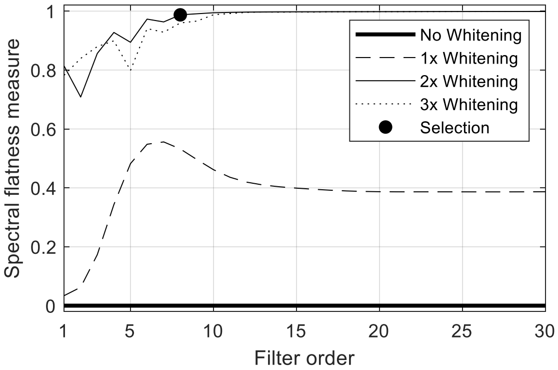

Figure 3. Spectral flatness measure of the mean PSD of the diastole segments of NonCAD subjects after various whitening attempts. The x-axis represents the different orders of AR filters, and the y-axis is the spectral flatness measure introduced in section 2.3. The three lines show the spectral flatness measure for three levels of repeated whitening filtering. The dot shows the selected filtering for further comparison of CAD and NonCAD PSD.

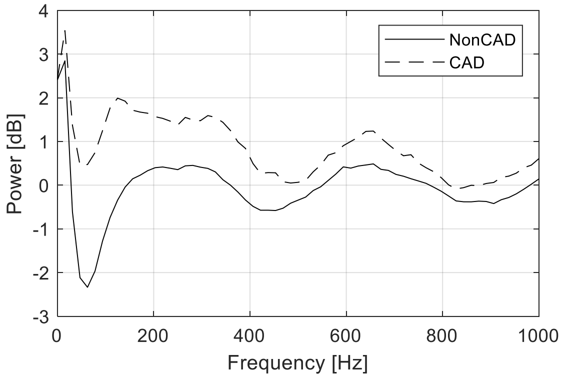

Figure 4. The average diastole PSD for CAD and NonCAD subjects after 2x whitening filtering using filter order of 8, which is the selected dot in Figure 2. The differences are more apparent than before whitening as shown in Figur 1 – especially at frequencies above 200 Hz.

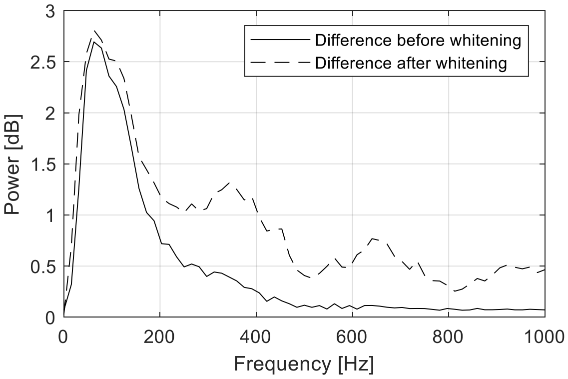

Figure 5. While PSD differences between CAD and NonCAD subjects for frequencies below 200 Hz remained largely unchanged, there was a markedly improvement at frequencies >200 after whitening filtering.

4. Discussion

Whitening of diastolic heart sounds using an inverse AR-filter did emphasize differences in PSD between CAD and NonCAD subjects. How this will translate into improved performance of CAD classification algorithms must be investigated in further work.

Acknowledgements

We would like to thank Acarix A/S for providing access to heart sound recordings used in this study.

Conflict of Interest

Bjarke Skogstad Larsen is an industrial PhD fellow at Acarix A/S and Aalborg University, and is also a minor shareholder in Acarix A/S.

Samuel Emil Schmidt is a minor shareholder in Acarix A/S, and is also employed at this company as a part-time consultant.

References

[1] World Health Organisation. *Global Health Estimates 2016: Disease burden by Cause, Age, Sex, by Country and by Region, 2000-2016*. 2018.

[2] Semmlow J, Rahalkar K. Acoustic Detection of Coronary Artery Disease. *Annu Rev Biomed Eng* 2007; 9: 449–469.

[3] Tateishi O. Clinical significance of the acoustic detection of coronary artery stenosis. *J Cardiol* 2001; 38: 255–62.

[4] Schmidt SE, Hansen J, Zimmermann H, et al. Coronary artery disease and low frequency heart sound signatures. In: Murray A (ed) *2011 Computing in Cardiology*. Hangzhou, China: IEEE, pp. 481–484.

[5] Winther S, Schmidt SE, Holm NR, et al. Diagnosing coronary artery disease by sound analysis from coronary stenosis induced turbulent blood flow: diagnostic performance in patients with stable angina pectoris. *Int J Cardiovasc Imaging* 2016; 32: 235–245.

[6] Winther S, Nissen L, Schmidt SE, et al. Diagnostic performance of an acoustic-based system for coronary artery disease risk stratification. *Heart* 2018; 928–935.

[7] Nissen L, Winther S, Isaksen C, et al. Danish study of Non-Invasive testing in Coronary Artery Disease (Dan-NICAD): study protocol for a randomised controlled trial. *Trials* 2016; 17: 262.

[8] Schmidt SE, Winther S, Larsen BS, et al. Coronary artery disease risk reclassification by a new acoustic-based score. *Int J Cardiovasc Imaging* 2019; 1–10.

[9] Schmidt SE, Holst-Hansen C, Graff C, et al. Segmentation of heart sound recordings by a duration-dependent hidden Markov model. *Physiol Meas* 2010; 31: 513–529.

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