Audible and Subaudible Components of the First and Second Heart Sounds

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Cardiovascular disease (CVD) has been a pressing medical issue in the United States for over a century and has been a leading cause of death [1, 2] with a great impact on mortality, morbidity, and healthcare cost. The Centers for Disease Control and Prevention (CDC) [3] reported that CVD is responsible for one death every 34 seconds and approximately 697,000 deaths in 2020 alone. Additionally, between 2017 to 2018, CVD directly and indirectly cost the United States economy approximately 378 billion dollars [2].

New cardiac monitoring techniques can significantly improve patients' quality of life as well as help reduce mortality and cost. Phonocardiography (PCG) is a common reliable technique that relies on auscultation with a stethoscope. This non-invasive method produces an acoustic signal that is widely believed to represent the closing and opening of heart valves [4, 5]. Certain auscultation locations are often used to listen to a particular valve. For example, the second and fourth intercostal spaces (ICS) at the left sternal border are used to listen to the pulmonic and tricuspid valves, respectively. Further, the first heart sound (S1) is known to occur during atrioventricular valve closures and may be best heard at the apex of the heart, which is closer to the tricuspid valve area in this study. The second heart sound (S2), by contrast, occurs during aortic and pulmonary valve closure and may be best heard at the base of the heart [6] which is closer to the pulmonic area in this study. S1 and S2 can provide useful clinical information about cardiac conditions such as valve abnormalities [7]. When listening to heart sounds with a stethoscope, it is important to note that the lower limit of human hearing is approximately 20 Hz [8]. Therefore, cardiac sounds below this frequency may not be audible. Hence, there is limited information in the literature about S1 and S2 in the "sub-audible" frequency range (i.e., <20 Hz).

The goal of this study is to document the audible and subaudible components of the PCG signal as described by the ratio between S1 and S2 amplitudes at two chest surface locations (Figure 1). The ratio was chosen (vs. absolute amplitude values) since it may be less affected by subject variability.

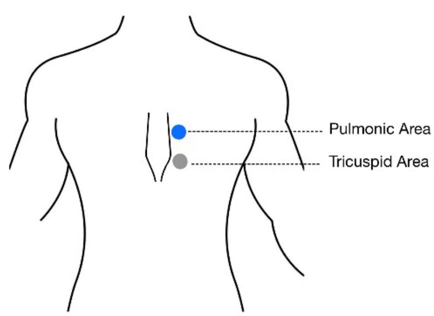
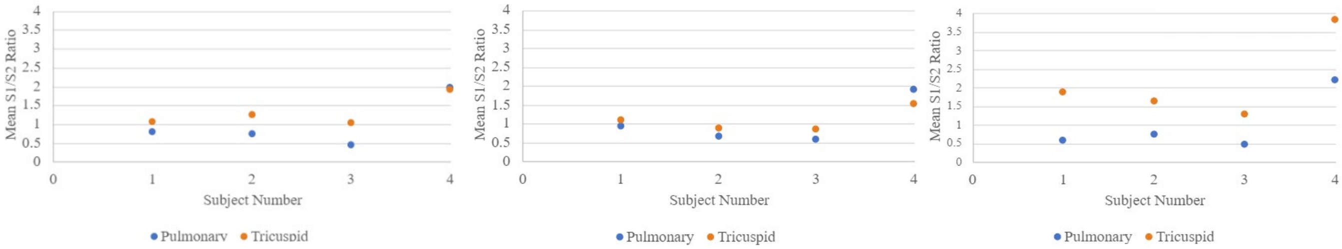


Figure 1. Arrangement on chest surface for the two PCG sensors.

To accomplish the study goals, four healthy female human subjects, aged 19-24 years, were recruited. For each subject, two ECG electrodes were placed at the right clavicle and lower left abdomen [5], whereas a ground electrode was placed at the left clavicle. Two PCG sensors were placed over the chest: one at the pulmonic area and the other at the tricuspid area, as shown in Figure 1. The PCG sensors were attached to the subject's chest surface using double-sided medical tape.

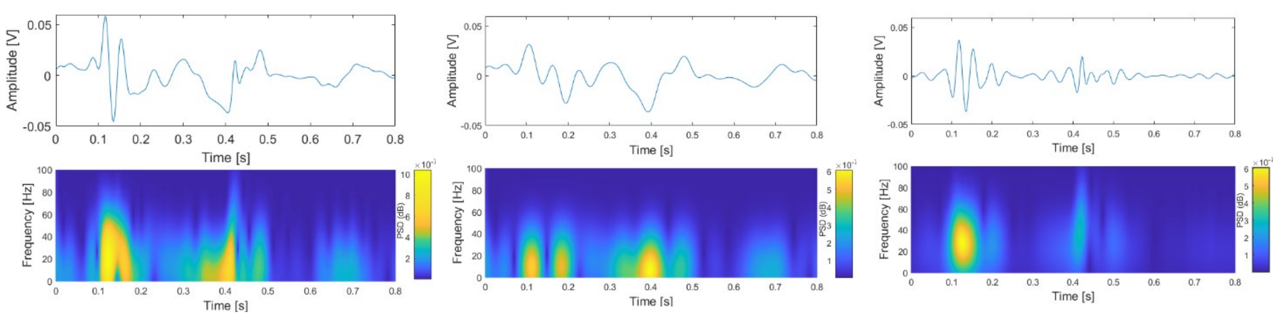
Two minutes of normal breathing was recorded for each subject and signals were processed using MATLAB. Pan-Tompkins algorithm was used to detect ECG R-waves. Subsequently, the PCG signals were segmented using the corresponding ECG R-waves. S1 and S2 were detected as the points of maximum amplitude at certain time windows of each PCG event. The average ratio of S1 to S2 amplitudes (S1/S2 ratio) over all the PCG segments was calculated at each sensor location for each subject. The analysis was performed for 3 frequency bands (0-20 Hz, 20-100 Hz, 0-100 Hz) of the PCG signal corresponding to the subaudible, audible, and full range of heart sounds, respectively.



(a) 0-100 Hz (b) 0-20 Hz (c) 20-100 Hz

Figure 2. The mean S1/S2 ratio at the pulmonic area and tricuspid area for three frequency ranges: (a) 0-100 Hz, (b) 0-20 Hz, (c) 20-100 Hz.

The mean S1/S2 ratio for all subjects for the pulmonic and tricuspid locations is shown in Figure 2 at 0-100 Hz, 0-20 Hz, and 20-100 Hz. The S1/S2 ratios tended to be higher in the tricuspid locations with the exception of subject 4 in Figures 2(a) and 2(b). This suggests that S1 was generally more prominent in the tricuspid than the pulmonic area. This finding of this study is consistent with the literature, which is that a comparatively higher ratio (due to a louder S1 signal) would be heard in inferior locations [6]. This provides confidence in the study methods and results. The trend of decreased S1/S2 ratio for the pulmonic location was clearer for the audible band which may be also interpreted as a higher relative audible S2 amplitude at the pulmonic location where S2 is believed to be generated.



(a) 0-100 Hz (b) 0-20 Hz (c) 20-100 Hz

Figure 3. The top plots illustrate the medoid waveform in three frequency ranges at the tricuspid area of Subject 1: (a) 0-100 Hz, (b) 0-20 Hz, (c) 20-100 Hz. The bottom plots illustrate the TFD for the respective frequency ranges.

This study also investigated the frequency contents of the PCG signal. Figure 3 shows the waveform and time-frequency distribution (TFD) of one PCG beat at the tricuspid area for different frequency bands. Here, TFD was computed using polynomial chirplet transform [9-11]. The left, middle, and right columns of Figure 3 correspond to 0-100, 0-20, and 20-100 Hz frequency bands, respectively. The brighter yellow color represents a higher amplitude while the blue represents lower amplitudes. In Figure 3, the highest amplitude appeared to coincide with the S1 and S2 timing. The figure also shows clear subaudible S1 and S2 energy. This suggests that there is information in PCG beyond what the human ear can hear, which is the second finding of this study. Consequently, these results suggest that investigation of the subaudible

PCG may offer additional insight into the cardiac activity such as heart valve closures or other abnormalities such as those that exist in patients with heart failure. Future studies would involve a larger number of subjects and include subjects with different heart conditions. This can help increase our understanding of acoustic signatures of the cardiac activity and help explore the utility of subaudible PCG in diagnosis and patient monitoring.

ACKNOWLEDGEMENTS

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Abstract

- As cardiovascular disease continues to be a pressing medical issue in the United States, new cardiac monitoring techniques may significantly improve patients' quality of life and help reduce mortality and healthcare cost.
- Phonocardiography (PCG) is a common reliable technique that relies on auscultation with a stethoscope and is believed to represent the closing and opening of heart valves [1, 2].
- First (S1) and second (S2) heart sounds may be best heard at particular chest locations and provide useful clinical information [3, 4].
- The lower limit of human hearing is approximately 20 Hz, which may limit heart sound information heard with a stethoscope.
- This abstract presents information about the "sub-audible" (<20 Hz) frequency range of S1 and S2.
- Results are described in terms of a ratio between the S1 and S2 (S1/S2 ratio), rather than absolute amplitude values, as the ratio may be less affected by subject variability.

Objectives

- The goal of this study is to document the audible and subaudible components of the PCG signal as described by the ratio between S1 and S2 amplitudes at two chest surface locations (Figure 1).

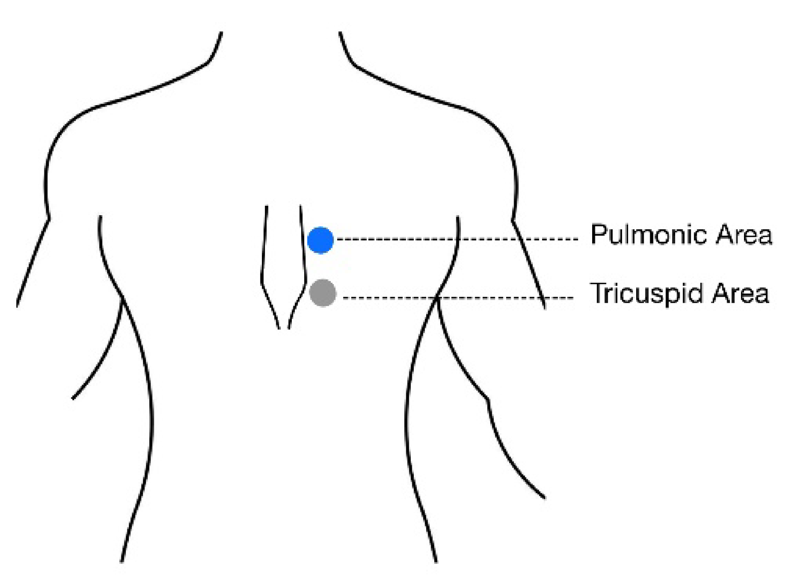

Figure 1. Arrangement on chest surface for the two PCG sensors.

Methodology and Experimental Setup

- Four healthy female human subjects, aged 19-24 years, were recruited.
- 2 PCG sensors placed on the chest and 3 ECG electrodes placed using double-sided medical tape [2].
- 2 minutes of normal breathing was recorded.
- Signals processed using MATLAB.
- Pan-Tompkins algorithm used to detect ECG R-wave peaks and segment PCG signals.
- S1 and S2 detected as points of maximum amplitude within certain time windows of each PCG event.

S1/S2 Ratio Relative to Chest Location

- The average ratio of S1 to S2 amplitudes (S1/S2 ratio) over all the PCG segments was calculated at each sensor location for each subject.
- Analysis performed for 3 frequency bands of PCG signal (0-20Hz, 20-100Hz, 0-100Hz) corresponding to subaudible, audible, and full range of heart sounds, respectively.

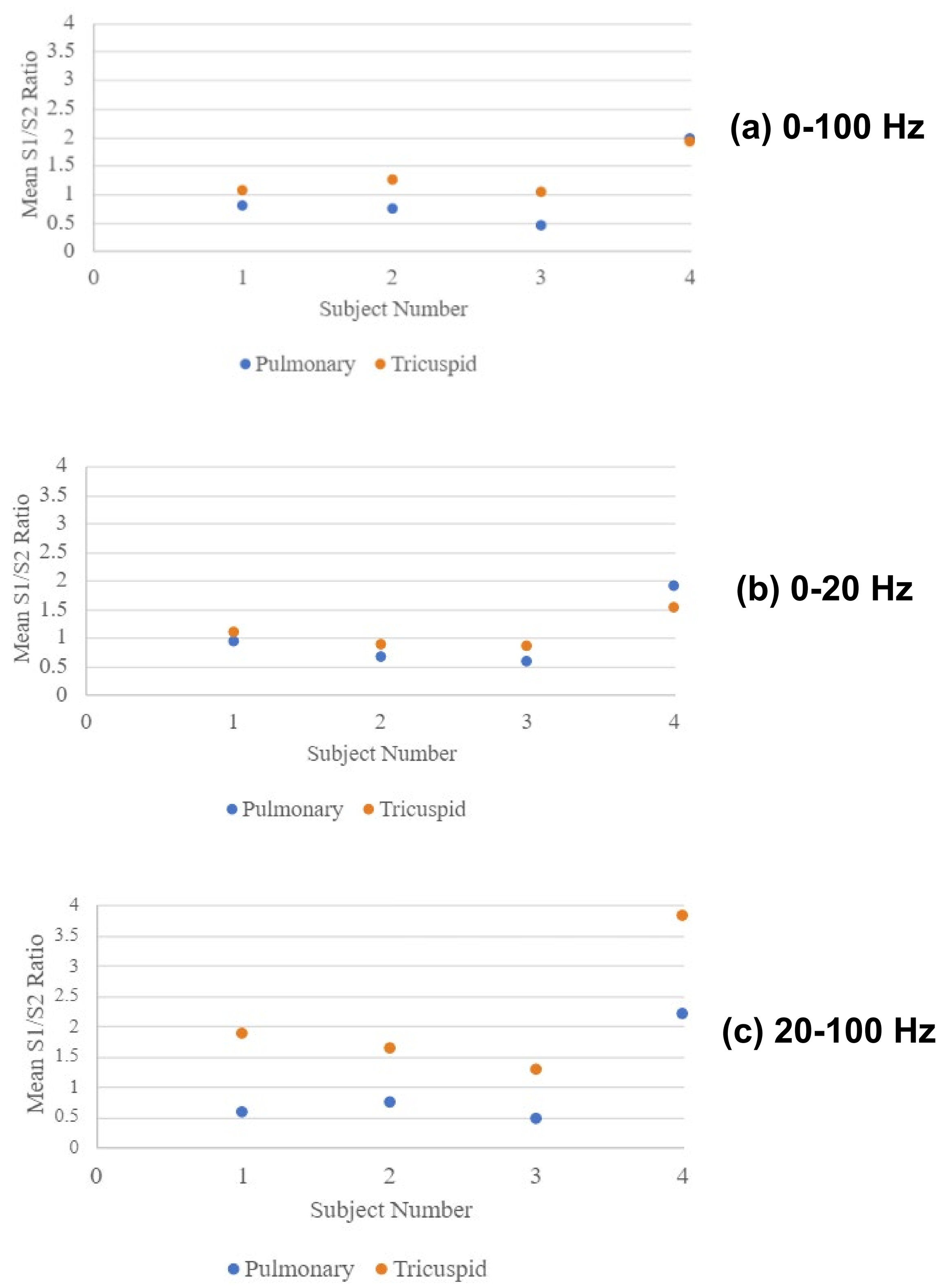

Figure 2. The mean S1/S2 ratio at the pulmonic area and tricuspid area for three frequency ranges: (a) 0-100 Hz, (b) 0-20 Hz, (c) 20-100 Hz.

- S1/S2 ratios tended to be higher in the tricuspid locations with the exception of subject 4 in Figures 2(a) and 2(b).
- This suggests that S1 was generally more prominent in the tricuspid than the pulmonic area.
- This finding of this study is consistent with the literature, which is that a comparatively higher ratio (due to a louder S1 signal) would be heard in inferior locations [3].
- The trend of decreased S1/S2 ratio for the pulmonic location is most clear for the audible band. This may be also interpreted as a higher relative audible S2 amplitude at the pulmonic location, where S2 is believed to be generated.

Frequency Contents of PCG Signal

- The frequency contents of the PCG signal were investigated using the medoid waveform and time-frequency distribution (TFD) generated by MATLAB.
- TFD was computed using polynomial chirplet transform [5-7].

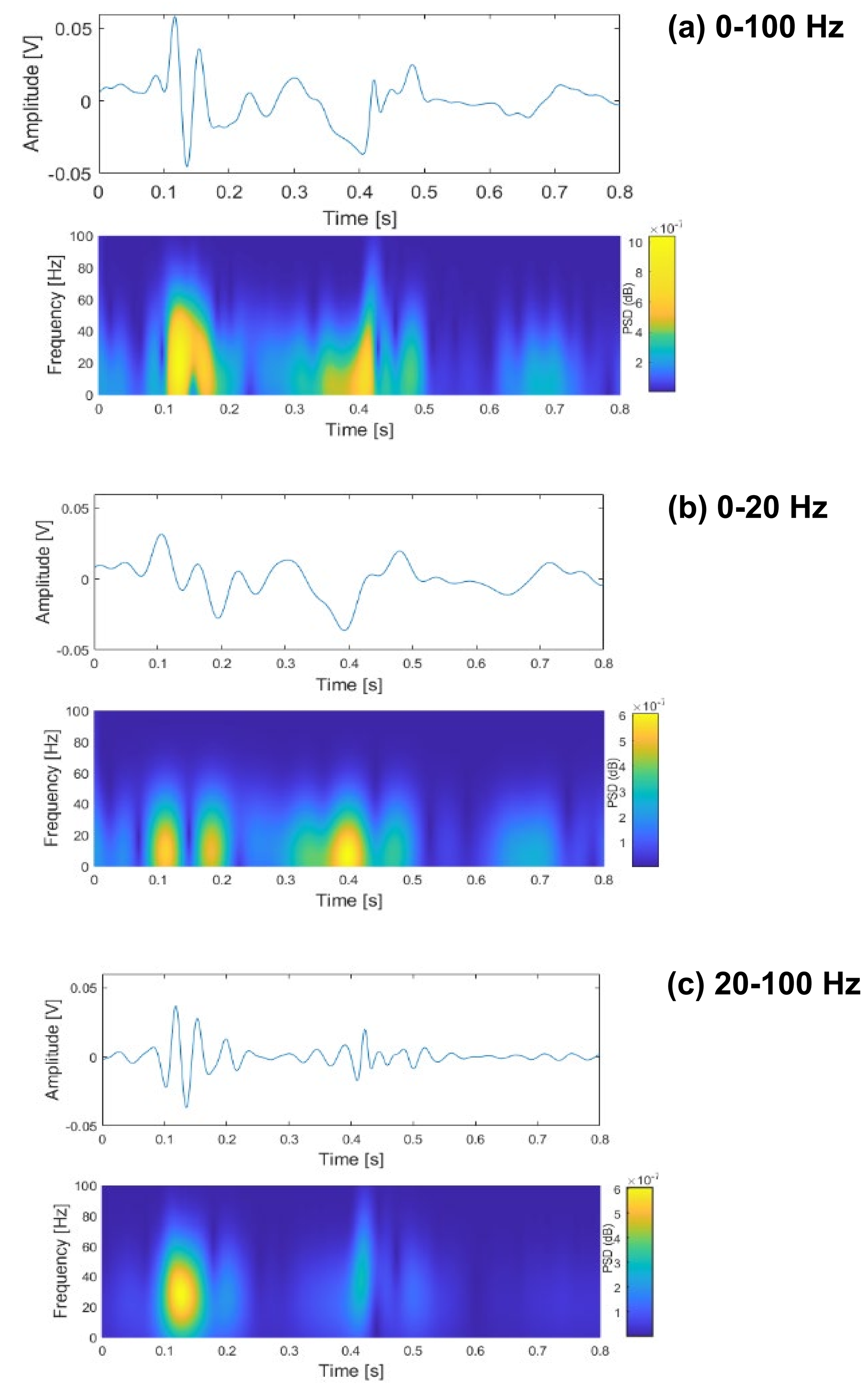

Figure 3. The top plots illustrate the medoid waveform in three frequency ranges at the tricuspid area of Subject 1: (a) 0-100 Hz, (b) 0-20 Hz, (c) 20-100 Hz. The bottom plots illustrate the TFD for the respective frequency ranges.

- The brighter yellow color represents a higher energy while the blue represents lower amplitudes.
- In Figure 3, the highest energy appeared to coincide with the S1 and S2 timing.
- Figure 3 also shows clear subaudible S1 and S2 energy.
- This suggests that there is information in PCG beyond what the human ear can hear, which is the second finding of this study.

Conclusions

- Figure 2 shows a trend of higher S1/S2 ratios for the tricuspid location in comparison to the pulmonic area.
- Therefore, Figure 2 provides confidence in the study methods and results due to results being consistent with the literature.
- Figure 3 shows significant energy in the subaudible frequency range during the S1 and S2 events, as demonstrated by the yellow bands.
- Regarding Figure 3, this data suggests that investigation of the subaudible PCG may offer additional insight into the cardiac activity such as heart valve closures or other abnormalities such as those that exist in patients with heart failure.
- Future studies would involve a larger number of subjects and additional PCG sensors at different locations. They would include subjects with different heart conditions.

Acknowledgments

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