# Effect of the Airway Pressure on the Frequency Domain of Seismocardiographic Signal

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Seismocardiography (SCG) is cardiac-induced chest wall vibration that is often measured non-invasively by accelerometers [1, 2]. SCG is thought to be related to myocardial contractions, valve closures and changes in blood momentum during the cardiac cycle [2-5]. SCG was also reported to assess myocardial contractility [6] and detect valvular heart diseases (e.g., aortic valve stenosis [7]), which would be clinically valuable. The intrathoracic pressure variation during respiration could affect cardiac dynamics and possibly SCG. For example, during inspiration, the low intrathoracic pressure increases the right venous return and right ventricle (RV) preload (i.e., the force that stretches the cardiac muscle prior to contraction) [8] which in turn decreases the left ventricular (LV) preload. This LV preload reduction was attributed to a leftward shift of the interventricular septum that limits LV filling [8]. Besides, during inspiration, the LV afterload was reported to increase due to the increase of the aortic transmural pressure [8]. The frequency domain description of SCG may contain information about blood ejection into the great vessels (in the 0.6-20 Hz band) and heart sounds (for frequencies > 20 Hz) [5]. The objective of the current study is to investigate the effect of the intrathoracic pressure variation on SCG spectral characteristics. This may also increase the understanding of SCG variability.

After IRB approval, twenty healthy subjects (14 Females, 6 Males, 21±2y) were studied. SCG was measured at the 4$^{th}$ intercostal space (ICS) near the left lower sternal border with a tri-axial accelerometer (Model: 356A32, PCB Piezotronics, Depew, NY). Simultaneously, electrocardiography (ECG) and spirometry were acquired. Data was collected during normal breathing (NB) and breath holding (BH). BH was performed at end-inspiration (end INS) and end-expiration (end EXP) with measured airway pressures of 0, ± 2-4 and ± 15-20 cm water. The subject applied the pressure while a face mask covering the mouth and nose was attached to a manometer to monitor the airway pressure. The intrathoracic pressure was not directly measured in the current study (to avoid invasive measurements) but is thought to correlate with the measured airway pressure. Signals were acquired at 1 kHz. To remove background noise, SCG was filtered using a 4$^{th}$ order Chebyshev Type II bandpass filter (0.05-200 Hz Passband). Then, SCG was segmented into beats using the ECG-R waves such that each SCG beat starts 100 ms before the corresponding ECG-R wave. Normal breathing SCG beats were clustered into two groups with

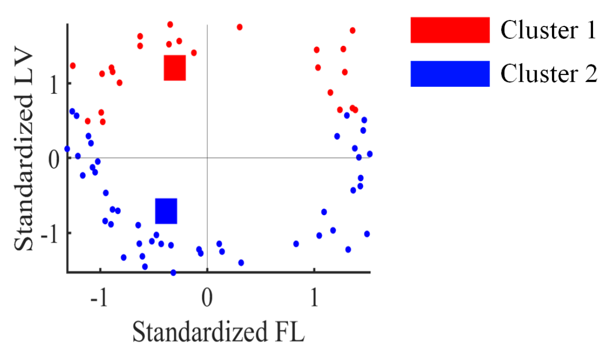


**Figure 1.** A sample of the distribution of SCG events of the two clusters obtained from clustering normal breathing data. Each event was characterized by the standardized lung volume (LV) and respiratory flow rate (FL) evaluated at the ECG-R wave timing. The square marks define the median flow rate and lung volume of each group.

similar waveform morphologies using the "k-medoid" algorithm [9]. SCG spectra were calculated and compared between NB and BH.

Figure 1 shows a sample of the distribution of SCG events of the two clusters obtained from clustering NB data. Each event in Figure 1 is shown at the corresponding "standardized" lung volume and respiratory flow rate evaluated at the ECG-R wave timing [9-11]. The square marks define the median flow rate and lung volume of each group. The median lung volume of cluster 1 was consistently higher than cluster 2 in all subjects. Figure 2 shows the ratio of subaudible to audible energy (SAR) calculated using Equation 1 and averaged over all subjects for the different breathing cases. In Equation 1, $f$ and $PSD$ are the frequency and power spectral density, respectively.

$$SAR = \left(\int_0^{20} PSD(f)df \Big/ \int_{20}^{50} PSD(f)df\right) * 100 \quad (1)$$

In Figure 2, the mean SAR for NB was around 150% which is comparable to reported values of 100% [12]. As can be seen in Figure 2, BH end INS at zero airway pressure had a lower SAR than clusters 1 and 2 of NB ($p < 0.05$, paired t-test) while SAR for BH end EXP at zero airway pressure was significantly lower SAR than cluster 1 of NB only ($p < 0.05$, paired t-test). SAR increased (for BH end INS and end EXP cases) as the airway pressure decreased ($p < 0.05$, paired t-test) but did not significantly increase when the airway pressure increased ($p > 0.05$) compared to BH at zero pressure.

Two physiological mechanisms might help interpret the relationship (observed in Figure 2) between the intrathoracic pressure and the low frequency components of SCG during BH. First, low intrathoracic pressures are known to be associated with high LV afterload [8]. This high afterload would require a higher cardiac muscle contraction force generation and may also affect blood ejection, which is known to be related to the low SCG frequency components (i.e., < 20 Hz) [5]. Second, cardiac muscle fibers contraction velocity decreases when the afterload increases [13], which might increase the energy associated with the low SCG frequency components. As a result, SAR might be a useful feature to monitor weakened cardiac muscles especially under pressure maneuvers that can further increase the cardiac afterload.

In conclusion, the intrathoracic pressure appears to affect cardiac dynamics and cause SCG energy redistribution between audible and subaudible frequency bands. Future studies may utilize time-frequency analysis to locate the timing of spectral changes due to intrathoracic pressure changes. More subjects are also needed to confirm the study findings. The autonomic nervous system (ANS) regulates circulation through the activity of sympathetic and parasympathetic nervous systems by controlling the heart rate and contractility [14]. However, the specific mechanism of the ANS response to intrathoracic pressure variation needs more investigation, which would be performed in future studies.

## ACKNOWLEDGMENTS

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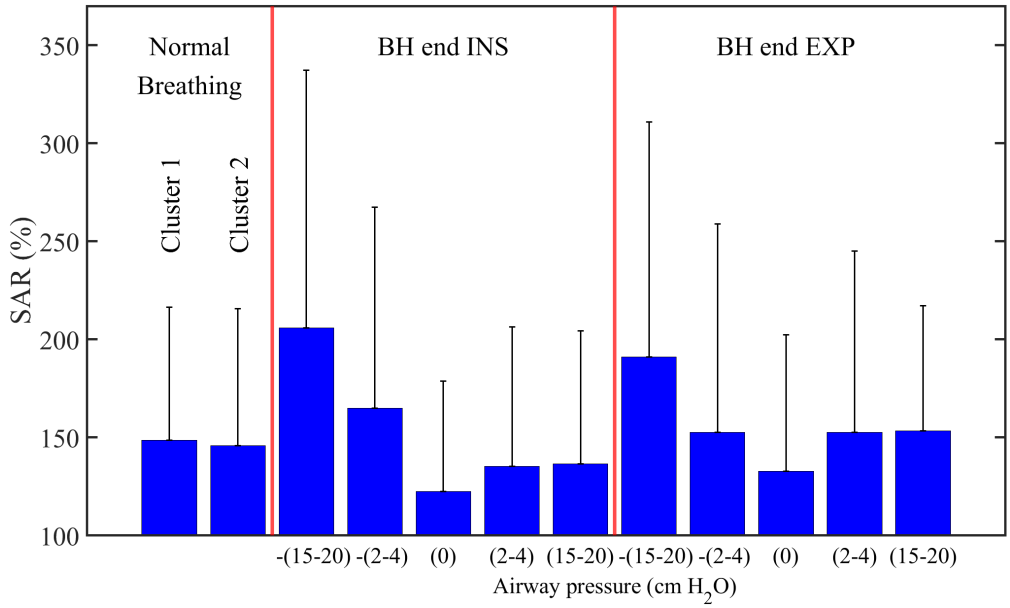


**Figure 2.** Subaudible to audible energy ratio (SAR) for NB clusters and BH cases at different airway pressures. The values in the figure represent the mean+std of SAR over all subjects.

## REFERENCES

[1] A. Taebi, B. E. Solar, A. J. Bomar, R. H. Sandler, and H. A. Mansy, "Recent Advances in Seismocardiography," *Vibration,* vol. 2, no. 1, pp. 64-86, January 14, 2019.

[2] R. S. Crow, P. Hannan, D. Jacobs, L. Hedquist, and D. M. Salerno, "Relationship between Seismocardiogram and Echocardiogram for Events in the Cardiac Cycle," *American Journal of Noninvasive Cardiology,* vol. 8, pp. 39-46, 1994.

[3] D. M. Salerno and J. Zanetti, "Seismocardiography for monitoring changes in left ventricular function during ischemia," (in eng), *CHEST,* vol. 100, no. 4, pp. 991-3, October 1991.

[4] D. M. Salerno, J. M. Zanetti, L. A. Green, M. R. Mooney, J. D. Madison, and R. A. Van Tassel, "Seismocardiographic changes associated with obstruction of coronary blood flow during balloon angioplasty," *The American Journal of Cardiology,* vol. 68, no. 2, pp. 201-207, July 15, 1991.

[5] P. Castiglioni, A. Faini, G. Parati, and M. D. Rienzo, "Wearable Seismocardiography," in *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, August 2007, pp. 3954-3957.

[6] K. Tavakolian *et al.*, "Myocardial contractility: A seismocardiography approach," in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, September 2012, pp. 3801-3804.

[7] C. Yang, N. D. Aranoff, P. Green, and N. Tavassolian, "Classification of Aortic Stenosis Using Time–Frequency Features From Chest Cardio-Mechanical Signals," *IEEE Transactions on Biomedical Engineering,* vol. 67, no. 6, pp. 1672-1683, June 2020.

[8] S. Lara and B. Desmond, "Cardiovascular Effects of Mechanical Ventilation," *Archives of Disease in Childhood,* vol. 80, no. 5, p. 475, May 1, 1999.

[9] S. Ahdy, M. K. Azad, R. H. Sandler, N. Raval, and H. A. Mansy, "Spatial Distribution of Seismocardiographic Signal Clustering," in *Signal Processing in Medicine and Biology:*

*Innovations in Big Data Processing*, I. Obeid, J. Picone, and I. Selesnick Eds. Cham: Springer International Publishing, 2023, pp. 87-119.

[10] R. H. Sandler, S. Ahdy, M. K. Azad, N. Raval, R. Mentz, and H. Mansy, "Comparison Of Two Different Methods For Clustering SCG Signals," *Journal of Cardiac Failure,* vol. 29, no. 4, p. 597, April 1, 2023.

[11] R. Sandler, S. Farahat, M. K. Azad, N. Raval, R. Mentz, and H. Mansy, "Dependence Of SCG Clustering On SCG Measurement Location," *Journal of Cardiac Failure,* vol. 28, no. 5, Supplement, p. S76, April 1, 2022.

[12] M. K. Azad, "Seismocardiographic Signal Variability and Pulmonary Phase Detection in Adults," Ph.D., Department of Mechanical and Aerospace Engineering, University of Central Florida, 2020.

[13] R. Klabunde, *Cardiovascular Physiology Concepts*. Lippincott Williams & Wilkins, 2011.

[14] J. E. Hall and M. E. Hall, *Guyton and Hall Textbook of Medical Physiology*. Elsevier Health Sciences, 2020.

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## Introcution

- Seismocardiography (SCG) is cardiac-induced chest wall vibration that is often measured non-invasively by accelerometers.
- SCG is thought to be related to myocardial contractions, valve closures and changes in blood momentum during the cardiac cycle.
- SCG is clinically valuable; it was reported to assess myocardial contractility and detect valvular heart diseases.
- The intrathoracic pressure variation during respiration could affect cardiac dynamics and possibly SCG.
- For example, during inspiration, the low intrathoracic pressure increases the right venous return and right ventricle (RV) preload, decreases the left ventricle preload and increases its afterload.
- The frequency domain description of SCG may contain information about blood ejection into the great vessels (in the 0.6-20 Hz band) and heart sounds (for frequencies > 20 Hz).
- The effect of the intrathoracic pressure on SCG spectral energy distribution has not been investigated yet.

## Objectives

- Investigate the effect of the intrathoracic pressure variation on SCG spectral characteristics. This may increase the understanding of SCG variability.

## Methodology

- After IRB approval, 20 healthy subjects (14 Females, 6 Males, 21±2y) were studied.
- SCG (at 4th ICS), ECG, and spirometry were simultaneously acquired.
- Data was collected during normal breathing (NB) and breath holding (BH).
- BH was performed at end-inspiration (end INS) and end-expiration (end EXP) with measured airway pressures of 0, ± 2-4 and ± 15-20 cm water.
- The subject applied the pressure while a face mask covering the mouth and nose was attached to a manometer to monitor the airway pressure.
- The intrathoracic pressure was not directly measured in the current study but is thought to correlate with the measured airway pressure.
- Signals were acquired at 1 kHz.
- To remove background noise, SCG was filtered using a 4th order Chebyshev Type II bandpass filter (0.05-200 Hz Passband).
- Then, SCG was segmented into beats using the ECG-R waves such that each SCG beat starts 100 ms before the corresponding ECG-R wave.
- Normal breathing SCG beats were clustered into two groups with similar waveform morphologies using the "k-medoid" algorithm.
- SCG spectra were calculated and compared between NB and BH.

## Results

- Figure 1 shows a sample of the distribution of the two clusters obtained from clustering NB data. Figure 2 shows ratio of subaudible to audible energy (SAR) calculated using Equation 1.
- $$SAR = \left(\int_0^{20} PSD(f)\,df \Big/ \int_{20}^{50} PSD(f)\,df\right) * 100 \quad (1)$$

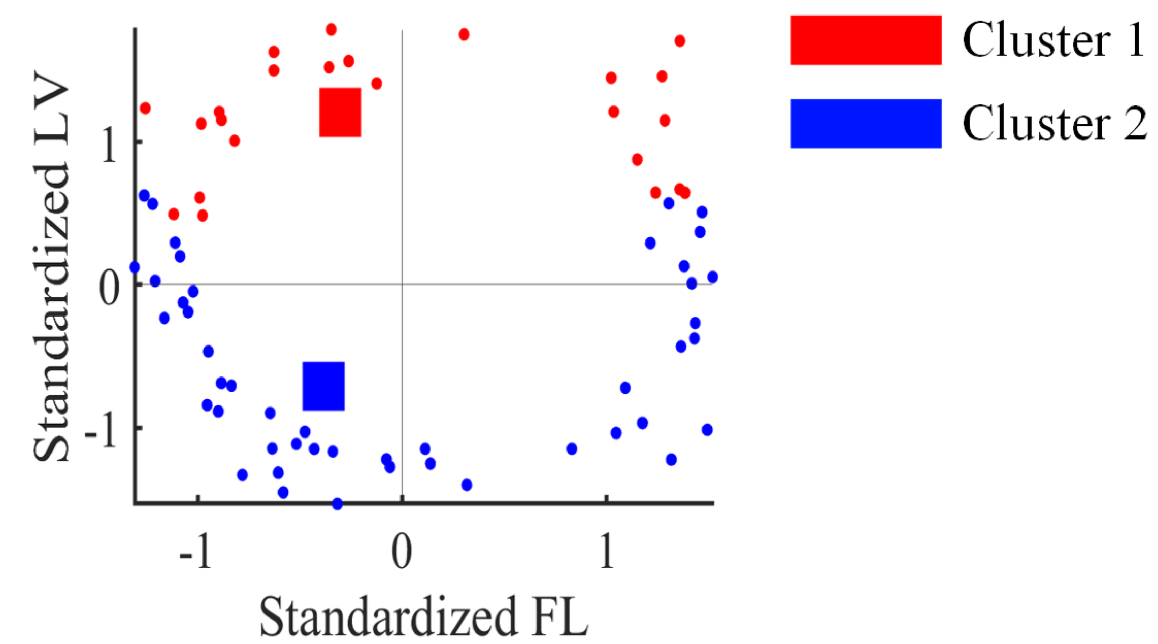


Figure 1. A sample of the distribution of SCG events of the two clusters obtained from clustering normal breathing data. Each event was characterized by the standardized lung volume (LV) and respiratory flow rate (FL) evaluated at the ECG-R wave timing. The square marks define the median flow rate and lung volume of each group.

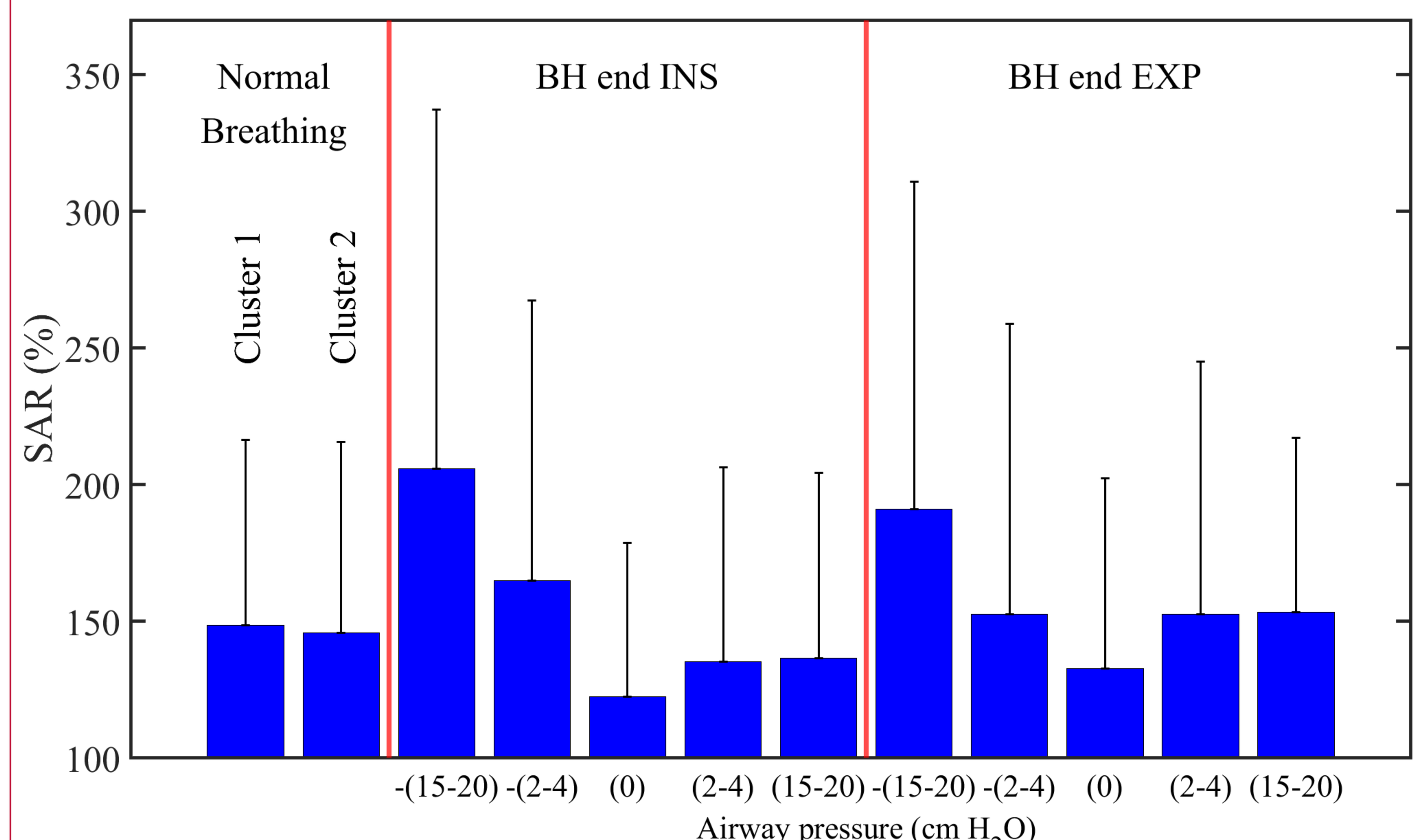


Figure 2. Subaudible to audible energy ratio (SAR) for NB clusters and BH cases at different airway pressures. The values in the figure represent the mean+std of SAR over all subjects.

- BH end INS at zero airway pressure had a lower SAR than clusters 1 and 2 of NB ($p < 0.05$, paired t-test)
- SAR for BH end EXP at zero airway pressure was significantly lower SAR than cluster 1 of NB only ($p < 0.05$, paired t-test).
- SAR increased (for BH end INS and end EXP cases) as the airway pressure decreased ($p < 0.05$, paired t-test) but did not significantly increase when the airway pressure increased ($p > 0.05$) compared to BH at zero pressure.
- Based on the literature, the high left ventricular afterload associated with low intrathoracic pressure can reduce the cardiac muscle fibers contraction velocity. This might explain the observed relationship between the intrathoracic pressure and low frequency components of SCG during breath holding.

## Conclusions

- The intrathoracic pressure appears to affect cardiac dynamics and cause SCG energy redistribution between audible and subaudible frequency bands.
- SAR might be a useful feature to monitor weakened cardiac muscles especially under pressure maneuvers that can further increase the cardiac afterload.
- Future studies may utilize time-frequency analysis to locate the timing of spectral changes due to intrathoracic pressure changes. More subjects are needed to confirm the study findings. The specific mechanism of the autonomic nervous system response to intrathoracic pressure variation needs to be investigated.

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## References

[1] A. Taebi, B. E. Solar, A. J. Bomar, R. H. Sandler, and H. A. Mansy, "Recent Advances in Seismocardiography," *Vibration,* vol. 2, no. 1, pp. 64-86, January 14, 2019.

[2] R. S. Crow, P. Hannan, D. Jacobs, L. Hedquist, and D. M. Salerno, "Relationship between Seismocardiogram and Echocardiogram for Events in the Cardiac Cycle," *American Journal of Noninvasive Cardiology,* vol. 8, pp. 39-46, 1994.

[3] D. M. Salerno and J. Zanetti, "Seismocardiography for monitoring changes in left ventricular function during ischemia," (in eng), *CHEST,* vol. 100, no. 4, pp. 991-3, October 1991.

[4] D. M. Salerno, J. M. Zanetti, L. A. Green, M. R. Mooney, J. D. Madison, and R. A. Van Tassel, "Seismocardiographic changes associated with obstruction of coronary blood flow during balloon angioplasty," *The American Journal of Cardiology,* vol. 68, no. 2, pp. 201-207, July 15, 1991.

[5] P. Castiglioni, A. Faini, G. Parati, and M. D. Rienzo, "Wearable Seismocardiography," in *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, August 2007, pp. 3954-3957.

[6] K. Tavakolian *et al.*, "Myocardial contractility: A seismocardiography approach," in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, September 2012, pp. 3801-3804.

[7] C. Yang, N. D. Aranoff, P. Green, and N. Tavassolian, "Classification of Aortic Stenosis Using Time–Frequency Features From Chest Cardio-Mechanical Signals," *IEEE Transactions on Biomedical Engineering,* vol. 67, no. 6, pp. 1672-1683, June 2020.

[8] S. Lara and B. Desmond, "Cardiovascular Effects of Mechanical Ventilation," *Archives of Disease in Childhood,* vol. 80, no. 5, p. 475, May 1, 1999.

[9] S. Ahdy, M. K. Azad, R. H. Sandler, N. Raval, and H. A. Mansy, "Spatial Distribution of Seismocardiographic Signal Clustering," in *Signal Processing in Medicine and Biology: Innovations in Big Data Processing*, I. Obeid, J. Picone, and I. Selesnick Eds. Cham: Springer International Publishing, 2023, pp. 87-119.

[10] R. H. Sandler, S. Ahdy, M. K. Azad, N. Raval, R. Mentz, and H. Mansy, "Comparison Of Two Different Methods For Clustering SCG Signals," *Journal of Cardiac Failure,* vol. 29, no. 4, p. 597, April 1, 2023.

[11] R. Sandler, S. Farahat, M. K. Azad, N. Raval, R. Mentz, and H. Mansy, "Dependence Of SCG Clustering On SCG Measurement Location," *Journal of Cardiac Failure,* vol. 28, no. 5, Supplement, p. S76, April 1, 2022.

[12] M. K. Azad, "Seismocardiographic Signal Variability and Pulmonary Phase Detection in Adults," Ph.D., Department of Mechanical and Aerospace Engineering, University of Central Florida, 2020.

[13] R. Klabunde, *Cardiovascular Physiology Concepts*. Lippincott Williams & Wilkins, 2011.

[14] J. E. Hall and M. E. Hall, *Guyton and Hall Textbook of Medical Physiology*. Elsevier Health Sciences, 2020.