Impact of Biological Sex on Radar-Measured Heart Sound Quality

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Abstract— **Radar based contact-free technology has number of potential applications for monitoring the cardiopulmonary functions of patients. However, no study has evaluated the effect of gender on the quality of the recordings. This study makes an attempt to distinguish radar based recording of male and female subjects. The study analysed a publicly available dataset of radar-recorded heart sound signals from both male and female subjects. Here, we exploit the reference signal-to-noise ratio (RSNR) to quantify the signal's quality. The results indicate that there is a significant difference in the signal quality between males and females, with males having a higher RSNR value compared to females. This could be a limitation in the widespread use of the current radar based cardiopulmonary recording techniques and overcoming this should be considered for future research.**

Clinical relevance— **This work has highlighted the gender based difference. By considering this, the radar based cardiopulmonary device has the potential for being used for patients requiring long-term monitoring.**

I. INTRODUCTION

Continuous monitoring of cardiac and pulmonary activity is essential, especially for the critical and high-risk patients during hospitalisation. These are often the basis for determining the treatment protocol [1]. Electrocardiogram (ECG), Photoplethysmography (PPG), and Phonocardiograph (PCG) are some of the modalities used for this purpose. PPG measures the blood oxygenation, PCG is the sound of the heart, whereas the ECG is based on the recording electrical activity of the heart. The each of these are of utmost importance and routinely used in clinical practice, there is one shortcoming in each of these; the need for physical contact with the body. Long-term monitoring often leads to discomfort, and the presence of artifacts due to motion, and placing of electrodes on patients with extensive injuries or burns may not even be feasible [2]. Thus, there is an urgent need for non-contact methods for monitoring the cardiac and pulmonary activity of patients [3].

The majority of the current non-contact vital sign monitoring systems rely on imaging, radar, and laser technologies [4]–[7]. While each of these has unique advantages, radar-based techniques promise to be compact, inexpensive and less sensitive to patient movement.

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The radar system, also referred to as Doppler system [8] detects the motions on the chest skin's surface to get the information about the cardiorespiratory activity. Several techniques for sensing cardiopulmonary activity were developed using microwave Doppler radar. When a microwave signal is sent towards a person's chest, it undergoes modulation due to small chest surface displacement. Subsequently, the signal that bounces back from the person's chest carries information about the chest displacement caused by cardiopulmonary activity such as breathing and heartbeat.

The displacements caused by cardiopulmonary activity can differ from one individual to another. To accurately measure the overall movement of the chest wall, various quantitative methods have been used in the past. These include the techniques that use structured lights and the Moire effect [9], a single point laser displacement system [10], impulse cardiogram [11], a magnetic displacement sensor [12], a capacitance transducer [13], and a microphone that records heart sounds [14]. Due to differences such as age and body shape, these values corresponding to each heartbeat can vary between individuals.

The impact of the left ventricle on the chest results in the most significant movement of the chest wall, which is observed at the fourth and fifth intercostal spaces. When clinicians are effectively listening to the mitral valve for women, they place their stethoscope under the fold of the breast tissues. Thus, breast tissue may limit radar's ability to detect chest wall movement.

In women, breasts are typically located on the chest wall between the second and sixth ribs, which may result in less overall displacement of the chest surface compared to men. The highest level of movement detected at the point of maximum contraction using non-contact sensors is typically around 0.6mm [15], and this value can vary greatly among individuals due to factors such as physiology, health, fitness, and age. Can the breast tissues have a significant impact on the recordings using the Doppler radar system? This question is important if the Doppler radar system has to be used by clinicians in the healthcare to monitor their female patients.

There is no published work where this question has been explored. This study aims to examine the impact of human gender on the heart sound signal measured using radar technology.

II. MATERIAL AND METHODS

In 2018, Will et al. [16] published a pioneering study in the field of measuring heart sounds using radar technology. They used a six-port radar system placed 20 cm away from

2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340554

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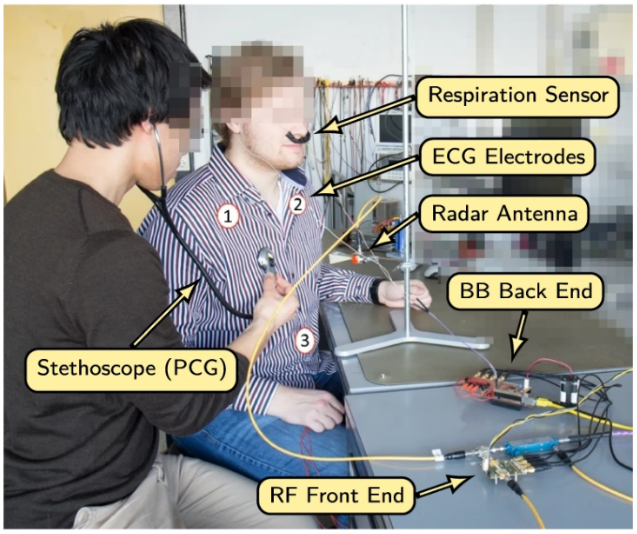

Fig. 1. Experimental Setup (image was taken from [17])

TABLE I
DATABASE DESCRIPTION

Descriptors	Public Dataset
No of Subjects	11 (7M, 4F)
Recording Length	60s
Sampling Rate	2000 Hz
Distance	20cm
Radar	six port radar

the subjects to record chest surface displacement, along with synchronized ECG and PCG data. The recorded data were analyzed to demonstrate the feasibility of measuring heart sounds using radar.

The impact of gender on the radar-recorded heart sounds quality was examined in this study, utilizing a comprehensive database published by Shi et al. [17] in 2020. This database included recordings of radar heart sounds, ECG, PCG, and respiration.

A. Details of the radar heart sound dataset

The study utilized a dataset consisting of synchronized data collected using a 24 GHz six-port radar system, an ECG, a respiration sensor, and a digital stethoscope. figure 1 depicts the experimental setup. The dataset includes measurements from 11 test subjects in various scenarios and positions, including various frontal positions on the thorax, carotid, and back. The study comprised 11 participants, with 7 males and 4 females. The average age of the participants was 34.73±15.94 years, and their average BMI was 23.19±3.61kg/cm2. Most of the measurements were taken in a default scenario where the subject was in a relaxed sitting position and breathing freely. The ROIs on the thorax, where heart sounds have high signal quality, were identified and used for placing both the radar and PCG.

The dataset included a excel sheet with information of signal quality for the radar and PCG recordings of the two heart sounds (S1 and S2), the ECG signal, and the respiration

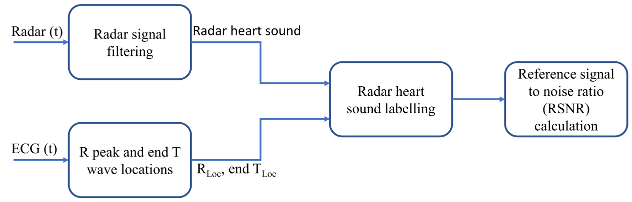

Fig. 2. Block Diagram of the Proposed Methodology.

sensor signal. Heart sound signals that exhibited clear signals for over 90% of the recording and had high quality were rated as ”A”.

This dataset, that is being used for this study, contains 176 recordings from the default scenario. These recordings were rated on signal quality by the author, who used a scale of A, B, or C to evaluate the overall signal quality. Our study only included recordings that received an overall rating of A and were recorded by placing radar and PCG sensor at the front i.e, on the thorax portion. This resulted in a total of 73 recordings covering all 11 subjects receiving an A rating and recorded by positioning the radar and PCG sensor in the front.

B. Proposed methodology

To compare the data of males and females in the dataset, the quality of the recordings was used as a parameter. To calculate this parameter, the radar signal was filtered to extract the radar heart sound. The R peak and end T wave were then used to label the four states of the radar heart sound. Finally, the signal quality was measured using reference signal-to-noise ratio (RSNR) for each recording. The figure 2 illustrates the block diagram for the proposed methodology. The RSNR parameters were then used to analyse the significant differences between male and female recordings using a two-tailed unpaired t-test. The following sections describe the filtering, labeling, and RSNR calculation techniques in more detail.

C. Data pre-processing and data labeling

In this study, a zero-phase forward-backward fourth-order Butterworth bandpass filter was employed to extract the radar heart sound from the raw radar data. The filter was designed with cut-off frequencies ranging from 16 to 80 Hz, and the filter parameters were taken from Will et al [16].

The figure 3 below illustrates the graph for person 3. The data was recorded in the default scenario, with the PCG sensor placed at the 4R position and the radar positioned at the 4L position.

A reference segmentation of the data was performed as a first step to assess its quality. Using the reference ECG signal that was simultaneously recorded with the radar signal, the radar heart sound signal was automatically divided into four states: S1 (first heart sound), systole, S2 (second heart sound), and diastole. The R-peak and end-T-wave positions computed from the synchronous ECG signals were used to

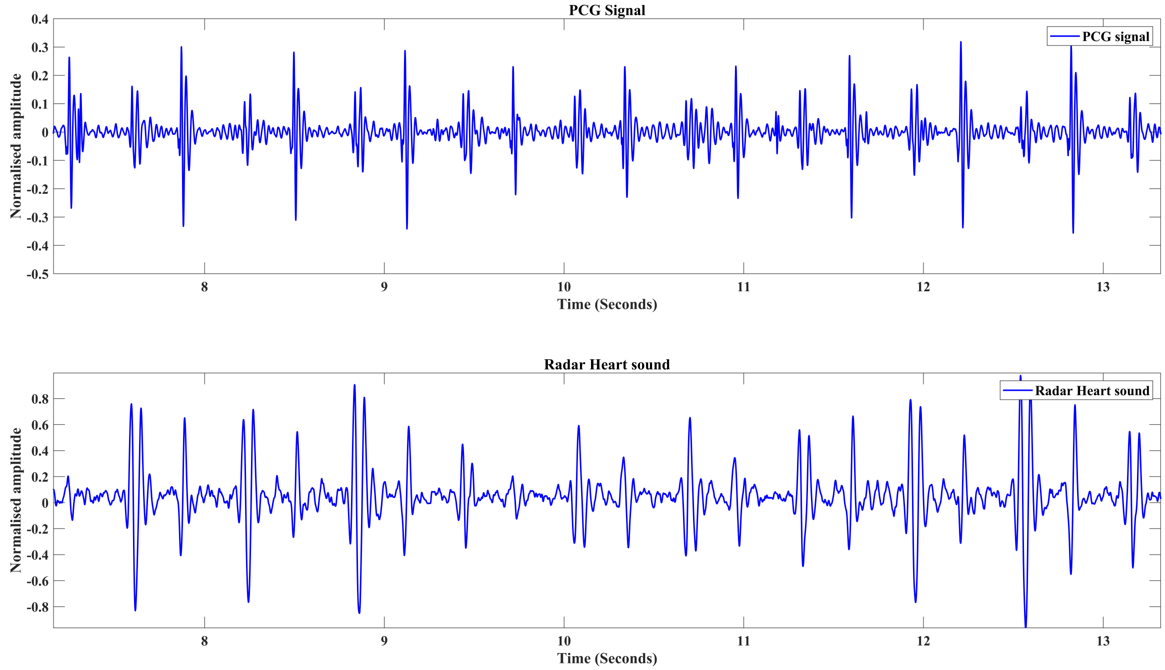

Fig. 3. Examplary Filtered PCG and Radar data of Person 3 (Radar 4L PCG 4R)

determine the positions of the S1 and S2 sounds within the radar-based heart sounds.

The R-peak of the ECG marked the beginning of S1, and the interval from each R-peak to the mean S1 duration from each R-peak was referred to as an S1 sound [18]. In the ECG, the S2 sound appears roughly at the end of the T-wave [19]. Therefore, labeling solely based on the position of the end-T-wave would be incorrect. The S2 sound would, however, be at its loudest near the end of the T-wave. In order to locate the center of the S2 sound, the highest peak in the Hilbert envelope of the radar-based heart sound signal within a defined search window surrounding the end-T-wave was used. This search window was set to the end-T-wave position minus the longest expected S2 duration. The center of the S2 sound was determined to be where the Hilbert envelope's maximum value fell within this search window. The S2 sound was defined as an interval with a length equal to the expected S2 sound and centered on this maximum position.

The time interval between the S1 and S2 sounds is referred to as systole, while the time interval between the S2 and S1 sounds is referred to as diastole.

The first and second heart sounds have predefined empirical values. The mean S1 duration was set to 122ms, the mean duration for S2 was 92ms while the duration for the standard duration for the special window was 114m [20].

The figure 4 illustrates the labeled radar heart sound, segmented using the recorded synchronized ECG signal's R peak and end T wave. The four states S1, systole, S2, and diastole were labeled as explained in the previous section.

D. *RSNR calculation technique*

To investigate the quality of the radar heart sound, a reference signal-to-noise ratio (RSNR) was defined as the key parameter. The period of S1 and S2 was taken as the signal plus noise of one heartbeat cycle, and the remaining period, i.e. systole and diastole period for the same heart cycle, was considered as noise to define the RSNR for a heart cycle. Then the RSNR value was calculated using the equation 1.

$$RSNR_{dB} = 10\log_{10}\left(\frac{Pow(S1) + Pow(S2)}{Pow(Sys) + pow(Dia)}\right) \quad (1)$$

Each individual heartbeat cycle yields an RSNR value. The signal RSNR value is determined by averaging over the N fully included heart sound cycles in a recording.

$$RSNR_{sig} = \frac{1}{N}\sum_{n=1}^{N} RSNR_n \quad (2)$$

In the example shown in figure 4, the RSNR for the illustrated heart cycle is 14.7290, while the RSNR for the complete recording was calculated as 13.309dB.

III. Result

The RSNR was calculated for the 73 recordings that were labeled as "A" for PCG and radar signals. Table 2 shows the mean ± standard deviation signal-to-noise ratio. It can be observed that the mean RSNR for males is 8.5480±2.2854, while for females, the mean RSNR is 5.8200±2.2058.

The two-sided unpaired t-test was used to perform significance testing, and it was determined that the p-value was 0.000135, indicating that the male and female RSNR values

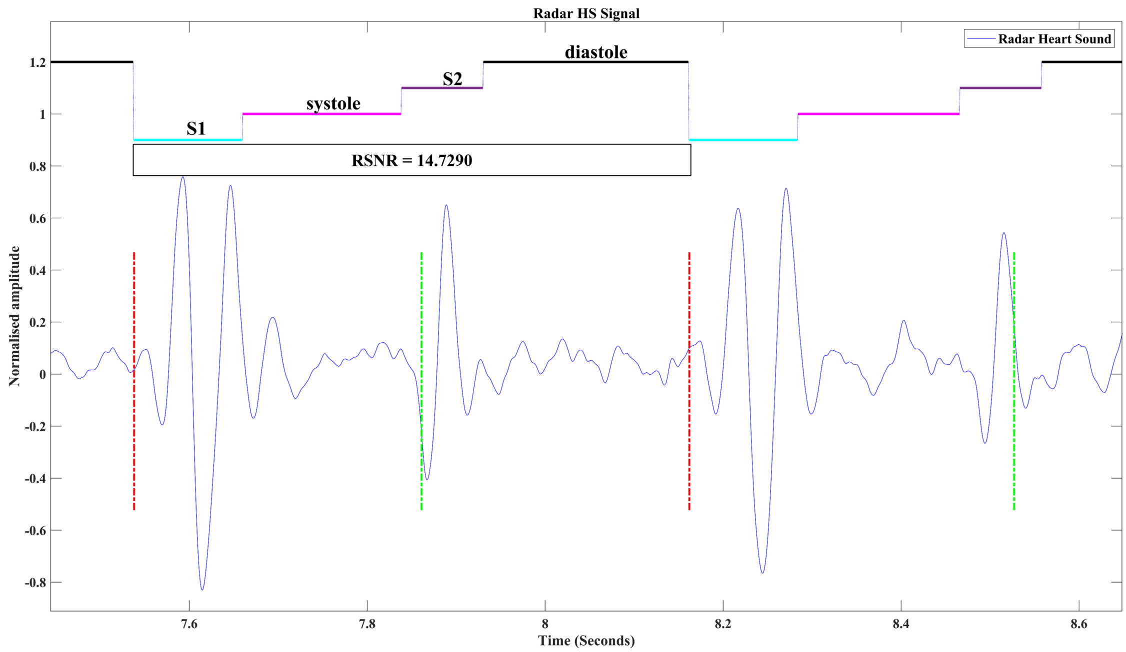

Fig. 4. Four states labeled Radar heart sound data

TABLE II
DATABASE DESCRIPTION

Dataset	RSNR		P-value
	Male (mean ± SD)	Female (mean ± SD)	
Public dataset	8.5480±2.2854	5.8200±2.2058	0.000135

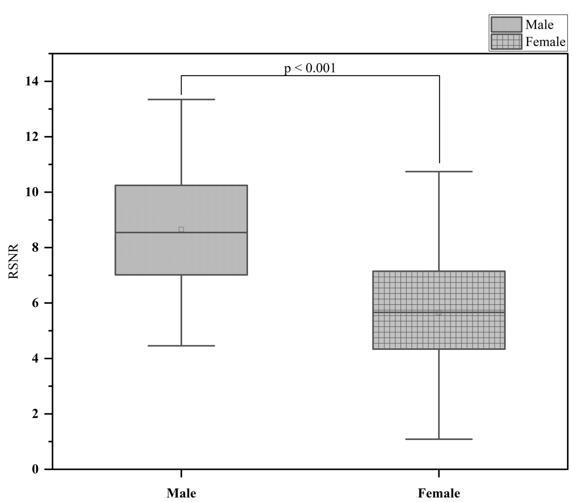

Fig. 5. RSNR of male and female

differ significantly from one another. Figure 5 illustrates the box plot for the male and female RSNR data.

IV. DISCUSSION

The study investigates how biological sex affects the quality of radar-measured human heart sound signals. A publicly accessible database of radar-recorded heart sound signals from both male and female subjects was analysed for the study. The study found that the quality of heart sound signals measured by radar differs significantly between males and females. The mean RSNR value for males was 8.5±2.28, while for females, it was 5.8±2.20. The two-sided unpaired t-test results show that the difference is statistically significant, with a p-value of 0.000135.

One possible explanation for differences in RSNR values may be due to the differences in chest surface displacement between males and females. Chest surface displacement, which is the motion of the chest wall caused by the contraction of the heart, is a crucial aspect in measuring heart sounds using radar. The presence of breast tissue in females may dampen the chest wall motion, which could be a contributing factor to the difference in chest surface displacement. Thus, while a clinical examination often requires the stethoscope to be placed under the breast fold, radar-based contact-free recording will only measure the displacement of the chest. Additionally, other factors such as higher average BMI among females may also be a contributing factor, which however was not evaluated in this study because of the size of the dataset.

The location of the heart and surrounding tissues can affect the quality of the radar signal. It is likely that there are differences in the chest anatomy of males and females, with females in general having heavier breast tissues and a smaller chest size compared with men. Both of these factors may lead to differences in the radar-based recordings associated with the heart sound, resulting in lower SNR among women.

It is also important to note that these differences in signal quality may have an impact on the quantification of non-contact based heart sound measurement using radar technology. The future direction of research should be inclined toward investigation of causes for such differences and to develop methods to improve the accuracy of radar-measured heart sound signals in both males and females. One important outcome of this work is that it has identified a possible limitation in the widespread use of the current radar based cardiopulmonary recording techniques, overcoming which should be considered for future research.

V. Limitations

There are number of limitations of this study, specifically related to the size of the database, unavailability of the anatomical measurements of the chest and breast of the participants. Thus, while this study can state that there is a gender based difference in this dataset, more work is needed for this to be generalised. It is also not possible to identify the cause of the differences, which may be due to breast tissues, the size of the chest, or BMI.

References

[1] The importance of vital signs - fire engineering. `https://www.fireengineering.com/articles/print/volume-160/issue-10/departments/fire-service-ems/the-importance-of-vital-signs.html`. Accessed: 2023-01-22.

[2] Wenyu Zhang, Gang Li, Zetao Wang, and Hao Wu. Non-contact monitoring of human heartbeat signals using mm-wave frequency-modulated continuous-wave radar under low signal-to-noise ratio conditions. *IET Radar, Sonar & Navigation*, 16(3):456–469, 2022.

[3] Wenjie Lv, Yan Zhao, Wei Zhang, Wenqi Liu, Anyong Hu, and Jungang Miao. Remote measurement of short-term heart rate with narrow beam millimeter wave radar. *IEEE Access*, 9:165049–165058, 2021.

[4] Carlo Massaroni, Daniel Simões Lopes, Daniela Lo Presti, Emiliano Schena, and Sergio Silvestri. Contactless monitoring of breathing patterns and respiratory rate at the pit of the neck: A single camera approach. *Journal of Sensors*, 2018, 2018.

[5] G Cosoli, L Casacanditella, EP Tomasini, and L Scalise. Evaluation of heart rate variability by means of laser doppler vibrometry measurements. In *Journal of Physics: Conference Series*, volume 658, page 012002. IOP Publishing, 2015.

[6] Sumit Kumar Rai, Chetna Sharma, Vikash Shaw, Ranjan Kumar Jha, and Sanjeev Kumar. A non-contact approach for detection of sleep apnea using doppler phenomena. In *Proceedings of 6th International Conference on Recent Trends in Computing*, pages 99–105. Springer, 2021.

[7] Carina Barbosa Pereira, Michael Czaplik, Vladimir Blazek, Steffen Leonhardt, and Daniel Teichmann. Monitoring of cardiorespiratory signals using thermal imaging: a pilot study on healthy human subjects. *Sensors*, 18(5):1541, 2018.

[8] Dany Obeid, Gheorghe Zaharia, Sawsan Sadek, and Ghaïs El Zein. Microwave doppler radar for heartbeat detection vs electrocardiogram. *Microwave and Optical Technology Letters*, 54(11):2610–2617, 2012.

[9] CM Brandt, H Annoni, J Harthong, JM Reiner, and R Krauskopff. Evaluation of chest wall distortion related to cardiac activity by structured lights. a study of the apical impulse by the moiré technique. *Acta cardiologica*, 41(3):207–213, 1986.

[10] AE Aubert, L Welkenhuysen, J Montald, L De Wolf, H Geivers, J Minten, Hugo Kesteloot, and H Geest. Laser method for recording displacement of the heart and chest wall. *Journal of biomedical engineering*, 6(2):134–140, 1984.

[11] Eugene Braunwald, Douglas P Zipes, Peter Libby, et al. Heart disease: a textbook of cardiovascular medicine. *WB Saunders Ed*, 6:1435, 2001.

[12] K Mohri, T Jinnouchi, and K Kawano. Accurate mechanocardiogram sensors using amorphous star-shaped core multivibrator combined with a magnet. *IEEE Transactions on Magnetics*, 23(5):2212–2214, 1987.

[13] G Ramachandran, S Swarnamani, and M Singh. Reconstruction of out-of-plane cardiac displacement patterns as observed on the chest wall during various phases of ecg by capacitance transducer. *IEEE transactions on biomedical engineering*, 38(4):383–385, 1991.

[14] K Ikegaya, N Suzumura, and T Funada. Absolute calibration of phonocardiographic microphones and measurements of chest wall vibration. *Medical and biological engineering*, 9(6):683–692, 1971.

[15] Olga Boric-Lubecke, Victor M Lubecke, Amy D Droitcour, Byung-Kwon Park, and Aditya Singh. *Doppler radar physiological sensing*. John Wiley & Sons, 2015.

[16] Christoph Will, Kilin Shi, Sven Schellenberger, Tobias Steigleder, Fabian Michler, Jonas Fuchs, Robert Weigel, Christoph Ostgathe, and Alexander Koelpin. Radar-based heart sound detection. *Scientific reports*, 8(1):1–14, 2018.

[17] Sven Schellenberger, Kilin Shi, Tobias Steigleder, Anke Malessa, Fabian Michler, Laura Hameyer, Nina Neumann, Fabian Lurz, Robert Weigel, Christoph Ostgathe, et al. A dataset of clinically recorded radar vital signs with synchronised reference sensor signals. *Scientific data*, 7(1):1–11, 2020.

[18] Samuel E Schmidt, Claus Holst-Hansen, Claus Graff, Egon Toft, and Johannes J Struijk. Segmentation of heart sound recordings by a duration-dependent hidden markov model. *Physiological measurement*, 31(4):513, 2010.

[19] Ara G Tilkian and Mary Boudreau Conover. *Understanding heart sounds and murmurs with an introduction to lung sounds*. WB Saunders Company, 2001.

[20] David B Springer, Lionel Tarassenko, and Gari D Clifford. Logistic regression-hsmm-based heart sound segmentation. *IEEE transactions on biomedical engineering*, 63(4):822–832, 2015.