Mapping the Effect of Breast Tissue on Wearable Phonocardiography

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Abstract

Wearable phonocardiography (PCG) devices have the potential to improve the detection and monitoring of cardiovascular disease by recording the sounds of the heart during everyday activities. However, the efficacy of wearable PCG in females is poorly understood, particularly regarding how breast tissue may impact the quality of heart sound recordings. In this study, we recruited healthy volunteers without heart murmurs and measured breast tissue thickness using anatomical landmarks. We assessed the signal-to-noise ratio (SNR) by defining the first heart sounds (S1) as the signal and diastolic and systolic sounds as noise, then analysed the correlation between SNR and breast tissue thickness along the left sternal border. Our findings revealed that increased breast tissue thickness significantly reduces the SNR. This conclusion highlights a shortcoming of current wearable PCG devices, which typically use a universal design. Future wearable PCG devices should account for the damping effects of breast tissue in sensor placement to improve accuracy and effectiveness in monitoring cardiovascular health in female patients.

1. Introduction

Cardiovascular disease (CVD) is the leading cause of death for both women and men [1], yet it is often perceived as a predominantly male issue. A 2017 study showed that only 45% of women were aware that CVD is the top cause of death for women [2]. Furthermore, surveys indicate that only 22% of primary care physicians and 42% of cardiologists felt adequately prepared to treat female patients [2]. According to the British Heart Foundation, 50% of women receive the wrong initial diagnosis after a heart attack [3]. Women also tend to delay seeking medical attention for CVD symptoms, with reasons ranging from embarrassment due to misconceptions about weight gain to discomfort with disrobing for examinations and reluctance to attend follow-up visits [2,4].

Wearable phonocardiography (PCG) presents a promising solution for monitoring cardiovascular health. PCG analysis can aid in the diagnosis of valvular heart disease (VHD) [5] and coronary artery disease [6]. A PCG device that can be worn during exercise may further increase diagnostic accuracy by detecting quiet abnormal murmurs that are louder when the heart is stressed [7]. An easy-to-use, wearable device may also enable at-home monitoring of diagnosed patients, reducing the need for frequent hospital visits. However, there has been limited research on the feasibility of wearable PCG specifically for females.

For PCG diagnosis, four primary auscultation sites are important: the mitral, tricuspid, aortic, and pulmonary valves. Each site corresponds to a specific valve, enabling targeted listening for diagnostic purposes [8]. The best sites for listening to heart sounds are assumed to be the same for all individuals [8]. However, heart sounds propagate through various tissues before being detected by sensors on the chest. This propagation may dampen heart sounds, particularly in women with breast tissue, typically between the second and sixth ribs [9]. This interference is especially relevant for the first heart sound (S1), which is typically auscultated at the fourth intercostal space (ICS) on the left sternal border [10]. Some wearable PCG devices use multiple sensors around the torso, which can overcome damping effects by obtaining recordings from many locations and using only the best-quality recordings [11]. However, a large array of sensors could be bulky and impractical for continuous use.

Research into the effect of anatomical differences on heart sound quality is sparse. One study examined radar-measured heart sound quality and found a lower signal-to-noise ratio (SNR) in women than in men. However, it did not investigate the specific anatomical differences between female participants [12].

By determining the effect of tissue on heart sounds, it may be possible to reveal better auscultation sites for wearable PCG. This study aims to investigate the effect of breast tissue on heart sound signal quality to improve wearable heart monitoring of females. To our knowledge, no prior research has focused on this issue.

2. Methodology

2.1. Experimental setup

We conducted this study on 21 female and 11 male volunteers presumed healthy, with no known heart disease. The participants were categorised as males and females based on their biological sex. All participants were above 18, and ethical approval was obtained from the Ethics Committee of the Department of Engineering, University of Cambridge.

We identified nine anatomical locations along each participant's left sternal border, specifically targeting the

first five ribs and the intercostal spaces between them. These locations include the tricuspid site at the fourth ICS and the pulmonary site at the second ICS. Participants initially identified these locations, which the researcher subsequently confirmed through palpation. Recordings were taken using ADXL355 accelerometers with a sampling rate of 2000 Hz. The sensors were attached using medical tape on bare skin, and four 30-second recordings were taken at each location. Additionally, for female participants, tape measurements were taken to estimate the breast tissue thickness at the second and fourth ICS, as illustrated in Figure 1.

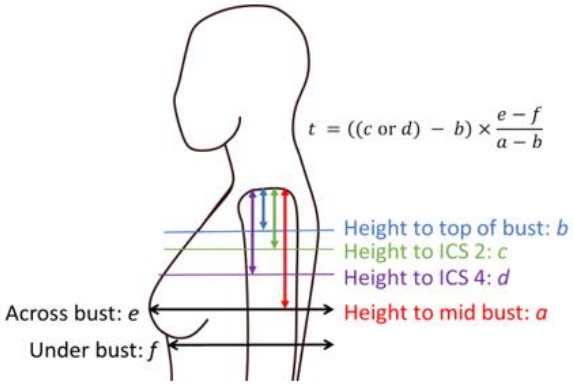

Figure 1. Estimation for breast tissue thickness. Height measurements were taken from the top of the shoulder, and bust measurements were recorded circumferentially around the torso. Breast tissue thickness at ICS 2 and 4 was calculated using the equation for *t*.

The study categorised female participants into three groups based on a 25 mm threshold for large breast tissue thickness (Figure 2). This threshold, which aligns with bra sizing standards, corresponds to a 3-inch (25.4 mm) difference between the fullest part of the bust and the underbust, representative of a C-cup size in the US and UK. The groups consisted of eight participants with upper dominant (UD), eight with lower dominant (LD), and five with minimal (MT) breast tissue.

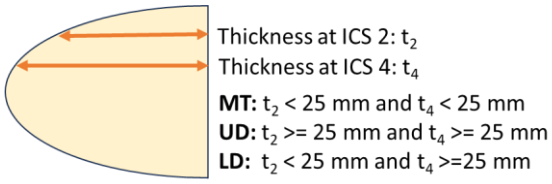

Figure 2. Categorisation of females into three groups based on the breast-tissue distribution.

2.2. Signal-to-noise ratio calculation

Healthy heart sound recordings consist of two major heart sounds corresponding to the opening and closing of the heart valves. The first heart sound, S1, occurs between systole and diastole, primarily due to the closure of the mitral and tricuspid valves. The second heart sound, S2, occurs due to the closure of the aortic and pulmonary valves. The S1 and S2 heart sounds dominate in healthy patients without murmurs, rendering other cardiac sounds negligible. Consequently, we categorised all systolic and diastolic segments as a single noise state. The S1 sound is optimally auscultated at the fourth ICS along the lower left sternal border (tricuspid site) [10]. This site also coincides with a significant amount of breast tissue in most females [9]. Although the S2 sound is better auscultated at the aortic and pulmonary sites, these locations generally have minimal breast tissue in females. Given our interest in assessing the impact of breast tissue on signal quality, we focused on the S1 sound as the primary signal of interest. We employed a machine learning model [13] to segment the recordings into S1, S2, systole, and diastole states. Figure 3 illustrates an example of a segmented recording.

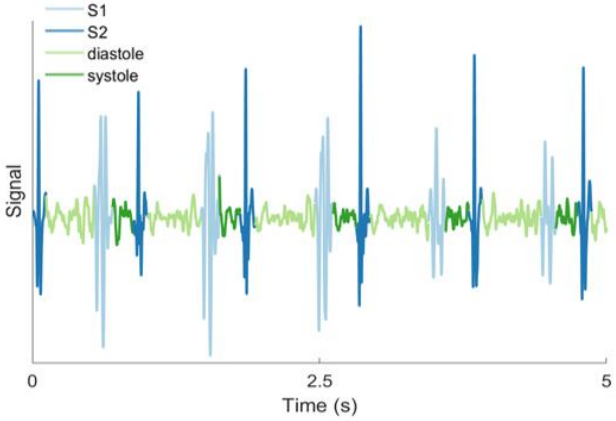

Figure 3. A segmented heart sound recording from a female in MT at ICS 3. The recording was bandpass filtered between 5 and 95 Hz to remove breathing effects

The power spectral density (PSD) of each segment in the S1 and noise states were calculated using Welch's methods, with Hann windows, 50% overlap and an FFT size of 128 samples, yielding a frequency resolution of 15.63 Hz. The median PSD at each frequency block was then calculated for the S1 and noise states. By calculating the median PSD, we could remove any extreme artefact effects. As a frequency function, the SNR was defined as the ratio of the median S1 PSD to the median noise PSD. A combined mean of the median SNRs was then calculated for the four recordings at each location. The S1 heart sound has a frequency range of around 10-150 Hz [14]. Therefore, a single mean SNR value for each of the nine locations was calculated for participants in the 31.35-93.75 Hz range. The lower bound was used to remove low-frequency artefacts such as movement, and the 93.75 Hz cutoff was used to remove lung sounds, which may overlap with the higher-frequency heart sound range [14].

3. Results

3.1. Normalised SNR

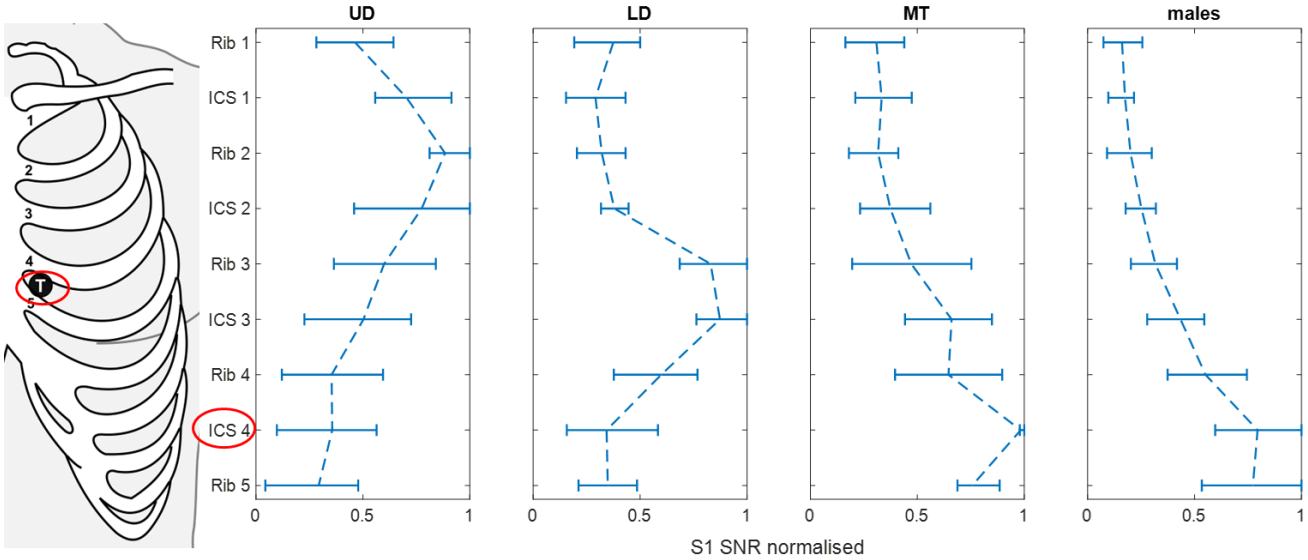

Figure 4. SNR variation along the left sternal border. The dotted line passes through the mean normalised SNR, and the error bars indicate the interquartile range. ICS 4 (circled) is the location of the tricuspid site.

To account for variability in baseline SNR values across participants, the SNR for each individual was normalised relative to their highest mean SNR value across all locations. This normalisation allowed us to compare each participant's variation in SNR along the left sternal border. Figure 4 shows each participant's SNR variation, grouped by their breast tissue distribution. The SNR for males and MT females follows a similar pattern, with the SNR increasing with increasing distance from the shoulder, peaking around ICS 4. For the UD females, the SNR peaks much earlier, at the second rib and drops after that. For the LD females, the SNR peaks lower, at ICS 3, but drops at ICS 4.

3.2. Statistical testing

We conducted a Student's *t*-test to test whether the four groups had a statistically significant difference in the variation in SNR down the left sternal border. To do this, the ratio of SNR between selected locations in Figure 4 was calculated for each group. The first pair of locations selected were ICS 2 (the pulmonary site) and ICS 4 (the tricuspid site). The two-sided Student's *t*-test was conducted on the SNR ratios between the groups, and a significance level of 5% was used.

The comparison of the ICS 2 to ICS 4 SNR ratio between males and MT females yielded no statistically significant difference (p=0.462). However, the comparisons of UD females with both males and with MT females did yield a significant difference (p-values of 0.001 and 0.008, respectively). Similarly, there was a significant difference between LD females and both males and MT females (p-values of 0.002 and 0.041, respectively). There was no significant difference between UD and LD females (p=0.141).

Additionally, the inter-group difference in the ratio of SNR at ICS 2 and ICS 3 was calculated. For the female groups with more breast tissue (UD and LD), there was a significant difference (p=0.001). The comparison of LD females with both males and MT females did not yield a significant difference (p-values of 0.163 and 0.115, respectively). Meanwhile, there was a significant difference between UD females and both males and MT females (p-values of 0.001 and 0.012, respectively).

4. Discussion and Conclusion

The tricuspid site at the fourth intercostal space (ICS 4) is traditionally considered the optimal location for detecting the S1 heart sound [10]. By comparing the signal-to-noise ratio (SNR) along the descending left sternal border, our findings confirm that the S1 sound peaks at the tricuspid site for males and females with minimal breast tissue (MT).

However, in females with upper dominant (UD) breast tissue, the SNR peaks at Rib 2 and decreases down the sternal border. Most women have negligible breast tissue up to Rib 2, and UD women exhibit significant breast tissue starting from ICS 2 and extending downward. This breast tissue likely significantly dampens heart sound,

explaining the observed SNR pattern.

In females with lower dominant (LD) breast tissue, the SNR increases to ICS 3 and decreases further down the sternal border. The LD group has more breast tissue around ICS 4 but minimal tissue higher up. This observation correlates well with our breast-damping theory.

The location and volume of breast tissue appear to directly influence the point along the sternal border where the dampening effect becomes pronounced, impacting PCG SNR. This highlights a limitation in current wearable devices, which often rely on a one-size-fits-all approach. To enhance recording SNR quality in females, it may be necessary to adjust sensor placement based on the user's breast size and tissue distribution.

This study has some limitations. It did not include anatomical measurements of male participants, as chest fat tissue can also dampen SNR. This is challenging to measure accurately since chest circumference or BMI does not precisely reflect fat tissue on the chest. A more accurate method of testing body fat percentage and distribution would be a DEXA scan [15], which tends to be expensive and not easily accessible. Additionally, the study was limited by a small sample size, which included no patients with abnormal heart sounds, and by a limited number of recording locations. Future research could benefit from incorporating additional locations, such as the mitral site, and examining the impact of breast shape on signal quality. Auscultating the mitral area is particularly challenging due to its location beneath the breast.

Acknowledgements

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