Pilot study on the separability of the native heart sounds and device support noise in patients implanted with left ventricular assist devices

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Abstract*— The assessment of heart sounds in patients with Left Ventricular Assist Devices (LVADs) presents significant challenges. The persistent mechanical hum produced by the pump obscures the natural heart sounds, complicating the detection of critical issues such as valve dysfunction, suction events, and abnormal blood flow patterns. Currently, echocardiography is frequently employed for monitoring; however, its application is not practical for home environments. This study explores the potential of phonocardiography (PCG) as a non-invasive method for monitoring cardiac function in patients with LVADs, specifically by accurately estimating cardiac time intervals (CTIs). PCG signals were collected from patients equipped with the HM3 LVAD, Abbott™. We employed Power Spectral Density (PSD) and Time-Frequency (TF) analysis to identify the dominant frequency components produced by the pump and their respective timings. A template-matching technique was applied to isolate the pulsatility mode of the LVAD from the PCG, thereby enabling the detection of native heart sounds. From this refined signal, we extracted the closure times of the heart valves. Our approach successfully differentiated native heart sounds from the in-band noise generated by the device, demonstrating the efficacy of PCG in LVAD patients. The identified CTIs provide important insights into the heart's compensatory mechanisms under these conditions and hold promise for continuous, non-invasive cardiac monitoring. This study presents the significant potential of PCG as an alternative to echocardiography for evaluating cardiac health in LVAD patients. Future research should focus on refining automated detection algorithms and validating this technique across larger patient populations to enhance its feasibility for monitoring in home settings.

***Clinical Relevance*— This study provides clinicians with a non-invasive method to assess cardiac function in LVAD patients, overcoming issues from pump noise. Phonocardiography helps detecting complications early and reduces reliance on echocardiography, allowing for easier home monitoring and improved patient management.**

I. INTRODUCTION

Heart failure (HF) is a significant global health issue, affecting millions of patients worldwide [1]. For individuals with end-stage HF who do not respond to medical therapy, left ventricular assist devices (LVADs) have become a lifesaving intervention [2]. These mechanical circulatory support devices help maintain cardiac output by continuously pumping blood from the left ventricle to the aorta, effectively reducing symptoms and improving quality of life [3].

Despite the benefits of LVAD therapy, it introduces new clinical challenges, particularly during routine outpatient follow-ups. A key aspect of cardiovascular assessment at the bedside—heart sound auscultation—is significantly hindered in LVAD patients due to the continuous noise generated by the pump [4]. This mechanical hum often obscures native heart sounds, making it difficult for clinicians to identify potential complications such as valve dysfunction, suction events, or abnormal blood flow patterns [5].

telemonitoring solutions play a crucial role in the early detection of complications in LVAD patients, as healthcare transitions towards home-based monitoring, facilitating proactive care [6]. It is already demonstrated the applicability of telemonitoring of pump parameters in the latest LVADs. However, these parameters are very limited, and the status of the hemodynamics of the right heart is still missing. Phonocardiography (PCG) is an excellent option for telemonitoring, due to its non-invasive nature, portability, and affordability. It is believed that isolating the components of heart sounds can have a significant clinical impact, providing an accurate non-invasive estimation of the Cardiac Time Intervals (CTIs), which are hemodynamic time metrics correlated with the heart's compensation status [7]. Separating the contribution of the left- and right-heart sides would enable a right-heart assessment that is otherwise not possible. By enabling clinicians to track heart and pump function remotely, these advancements can improve patient outcomes, enhance

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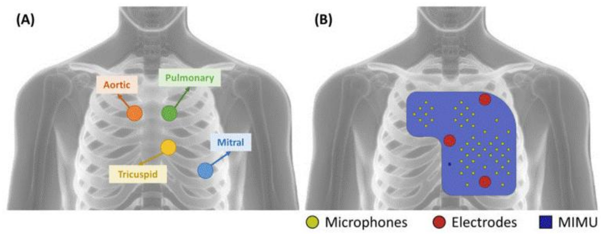

Figure 2. Comparison between (A) the traditional auscultation areas and (B) the distribution of the sensors in the wearable multi-sensor array.

quality of life, and optimize healthcare resource utilization [8]. Developing robust remote monitoring techniques is, therefore, essential in the evolving landscape of LVAD patient care [9].

At this time, few studies have explored the acoustic properties of heart and pump sounds in LVAD patients [4], [5], [10]. Some approaches have attempted to use signal processing techniques to enhance heart sound detection despite pump noise interference [11], [4], but challenges remain in effectively extracting the time of closure of the heart valves in real-world clinical settings. While these studies provide valuable insights into LVAD acoustics [10], [11], to our knowledge, a standardized and reliable method for quantifying CTIs is currently lacking.

To address this issue, we conducted a case study analyzing audio-recorded signals from patients implanted with LVAD. Our aim was to evaluate the clinical condition of the heart by estimating the time closure of the valves, considered as a precursor for acute heart failure events.

This study proposes to estimate the time closure of the heart valves by applying signal processing techniques to acoustic signals. By isolating and examining the contributions of heart sounds, we aim at demonstrating the feasibility of acoustic-based monitoring in LVAD patients. This approach could provide clinicians with a new, non-invasive tool for rapid bedside assessment, as well as for home monitoring, potentially enhancing early detection of complications and optimizing patient care.

II. MATERIALS

A. Recording system

The recordings analyzed in this study were obtained using a flexible multi-sensor array specifically designed for cardiac sound acquisition, as detailed in [12]. This device features a flexible printed circuit board (PCB) that includes 48 microphones. Additionally, it incorporates three electrocardiogram (ECG) electrodes and a magneto-inertial measurement unit (MIMU), as shown by Fig. 1. The system captures data at a sampling rate of 1 kHz, a frequency suitable for the band of signals to examine as demonstrated in our previous studies [14].

Each recording session lasted for two minutes, during which the device collected acoustic signals from the chest. All recordings are significantly affected by pump noise, which hinders traditional auscultation and must be managed carefully. Recordings were collected during ambulatory follow-ups at the Cardiac Surgery Unit of A.O.U. Città della Salute e della Scienza (Ospedale Molinette) from patients implanted with LVAD. The experimental procedures involving human subjects described in this paper were approved by "Comitato etico interaziendale A.O.U. Città della Salute e della Scienza di Torino A.O. ordine Mauriziano di Torino – A.S.L. Città di Torino" under the number 0068172 in date 01/06/2023.

For this study, we analyzed signals collected from subjects who were implanted with the HeartMate III device by Abbott™. We acquired a total of 21 recordings, selecting one of the 48 available signals classified as a high-quality channel for each recording. This dataset serves as the basis for further signal processing and analysis, with the goal of examining the role of heart sounds in patients with LVAD.

B. LVAD working principles description

The HM3 is a fully magnetically levitated pump that provides a continuous centrifugal flow. It is surgically attached to the apex of the heart, with the inlet cannula placed in the left ventricle. Blood flows into the central axis of the rotor and is propelled outward by centrifugal force toward the pump outlet, which is connected to the aorta [13].

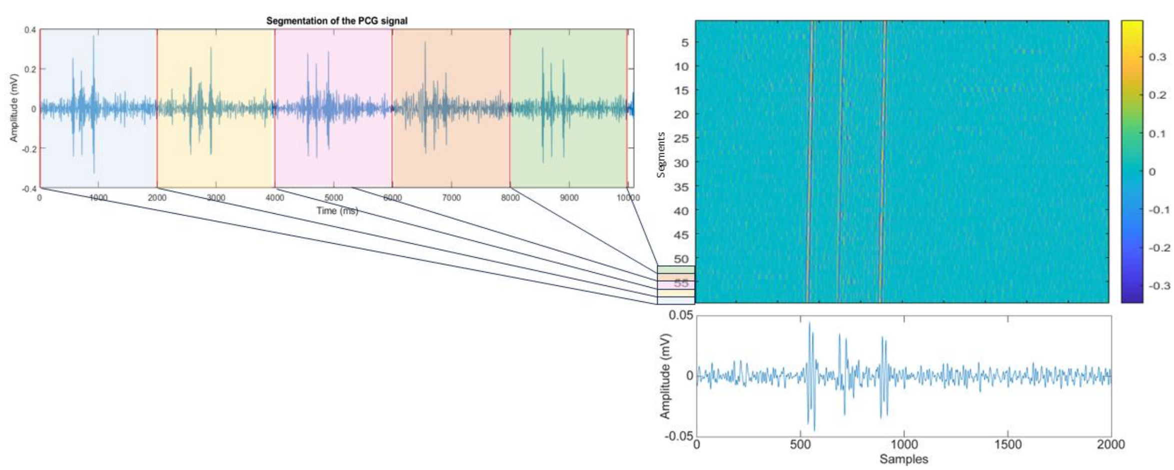

Figure 1. Segments of the signal are segmented into 2-second length fragments (a). (b) illustrates the intensity of the signal, ranging from blue to yellow, of the segments arranged in rows. The averaging results in the template matching are shown in (c).

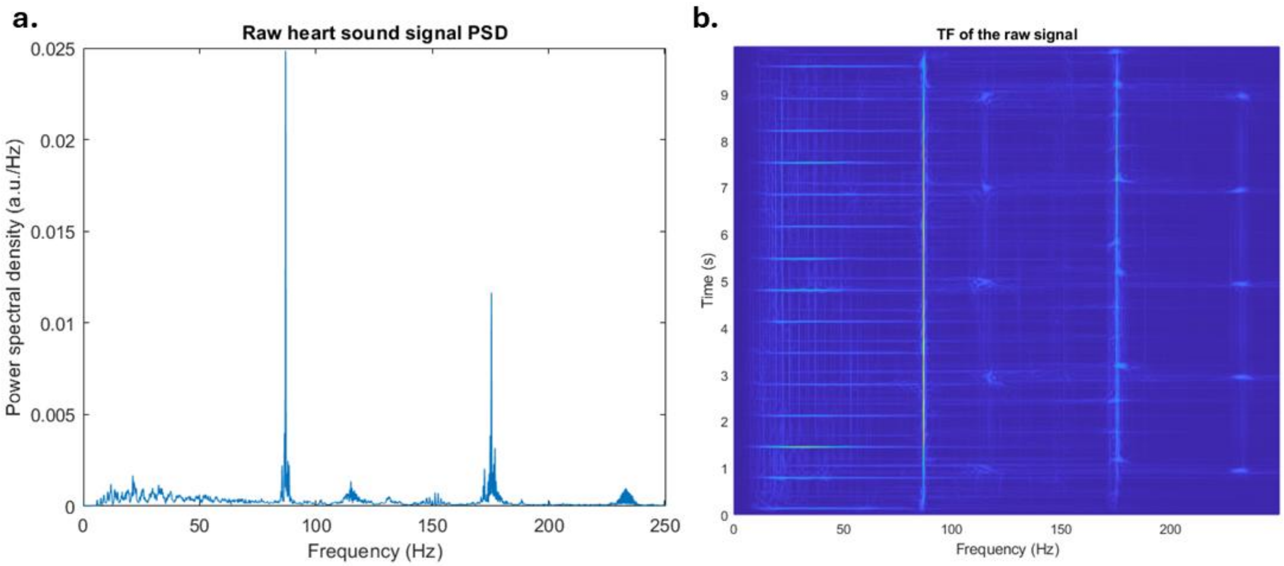

Figure 3. Power spectral density (a) and time-frequency transform (b) of the raw signal.

Its normal operational speed ranges from 4500 to 6000 rpm. In addition to continuous flow, the pump automatically shifts to a pulsatility mode during use. This mode ensures better hemodynamic compatibility and helps preventing the formation of blood clots [3].

III. METHODS

A. Spectral analysis

The signal, as it was acquired from the recording system, was analyzed using traditional spectral analysis via Welch method. The Power Spectral Density (PSD) of the raw signal was calculated by applying a Chebyshev window with a length of 8192 samples and an overlap of 2048 samples. The number of points for the Fast Fourier Transform (NFFT) is set to 16384. These parameters were selected based on a visual inspection of the resulting PSD, and they were tuned to achieve a PSD shape with sufficient frequency resolution.

The purpose of calculating the PSD is to evaluate the power components present in the signal and identify the band in which the heart sounds are included.

B. Time-Frequency analysis

A Time-Frequency (TF) analysis was conducted on the raw signal to better understand the nature of the frequency components that emerged from the spectral analysis.

First, the correspondent analytic signal was obtained using the Hilbert transform. Subsequently, the discrete Choi-Williams TF transform [15] was applied with the following parameters:

- Window length: 1 second
- Number of time lags: half the size of the input signal
- Kernel parameter ($\sigma = 1$)
- Sample frequency: 1 kHz (as defined by the recording system).

C. Filtering

The process of extracting heart sounds from pump sounds uses a combination of filters designed to eliminate unwanted components, allowing us to focus solely on the native cardiac sounds. Three filters were applied to the raw signal in cascade.

First, we used two bandstop filters to focus on heart sounds while attenuating noise from the pump. These filters target the main frequency of the pump and its second harmonic, each with a width of 10 Hz and a reduction of 60 dB in the stop band. Then, since most of the heart sounds we want to hear happen within the first few tens of hertz, we also use a low-pass filter to attenuate components above 60 Hz and a high pass filter at 20 Hz. The appropriateness of these choices were already demonstrated in [14].

D. Signal cleaning in the time domain

Switching to the time domain, the filtered signal is analyzed morphologically to isolate the heart sounds from the remaining signal contributions related to the pump. Based on the working principle of the VAD detailed in [13], the pulsatility mode can be related to a sequence of three peaks in the signals due to the change in speed of the pump every two seconds.

Based on this statement, the signal is divided into segments lasting 2 seconds. Within these 2-second segments, the pulsatility components of the pump are aligned, while heart sounds are not aligned due to their differing pseudo-periodicity. As a result, when we perform averaging, only the pulsatility mode contribution is visible, making it easily detectable (see Fig. 2). We utilize this characteristic by applying template matching, using the average 2-second segments as our template. Once the pulsatility mode components have been identified throughout the signal, they are removed to prevent interference with the processing of the time closure of the valves. The parts of the signal in correspondence to the artifact are set to zero.

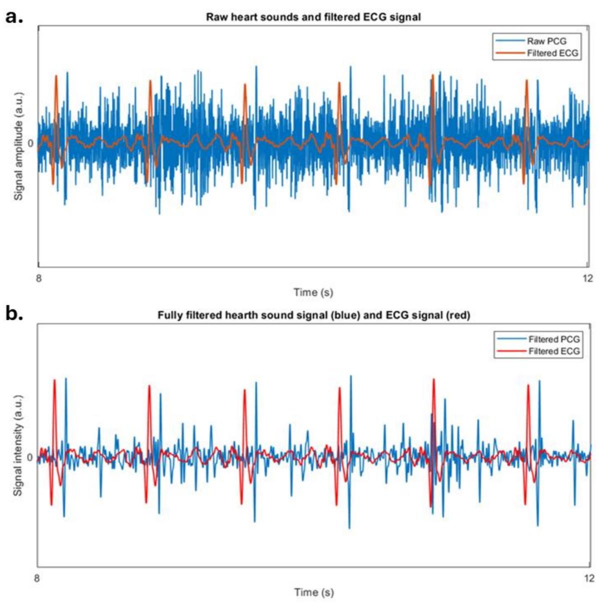

Figure 4. Comparison of the raw signal acquired (a) and the signal after the filtering process (b).

E. CTI estimation

To estimate the CTI, the detection of valve closures is [MK1]performed by segmenting the cardiac signal into distinct heartbeats. This segmentation process relies on the peak of the R-wave, which is obtained from the simultaneous ECG, serving as a reference point. Within this framework, the two primary heart sounds—S1, often associated with the closure of the atrioventricular valves, and S2, linked to the closure of the semilunar valves—are identified as the most prominent peaks in the Shannon Energy Envelope (SEE), allowing for a clear analysis of the heart mechanical activity. The algorithm was detailed in a previous work [14].

IV. RESULTS

A. Spectral analysis

The resulting PSD of the signal acquired from the recording system highlights the presence of various contributions in frequency, as shown by Fig. 3(a). This example features a patient with an LVAD speed set to 5200 rpm. The dominant peak is easily associated with the rotational frequency of the pump. It appears at 87 Hz, meaning that the speed at that time was actually 5200 rpm, an acceptable value for that pump. The algorithm accurately detects the fundamental of the speed sound. The difference between this detection and the actual speed is 0 Hz ± 1 Hz, based on the average of all recordings.

The second harmonic is also evident at 175 Hz. Other existing components are divided into low frequencies and other events present at around 115 Hz and 230 Hz. To better distinguish these components, the TF analysis was carried out.

B. Time-Frequency transform

Fig. 3(b) presents the Choi-Williams TF transform of a 10-second signal segment extracted from one of the signals belonging to the sample population. It is clear from this representation that the frequency components highlighted in the PSD associated with the pump rotation are evident throughout the entire time interval.

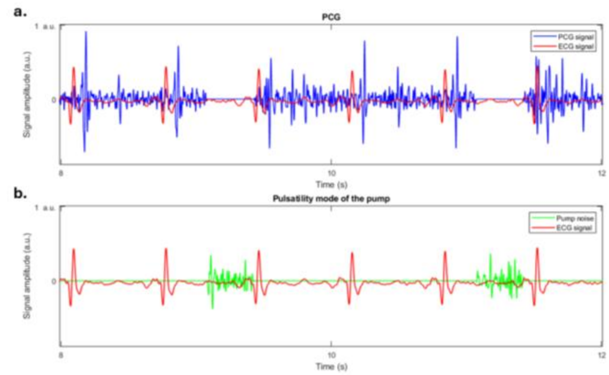

Figure 5. Comparison of the PCG signal (a) and the pulsatility mode of the pump signal (b).

In contrast, other contributions are not continuous over time. The low-frequency components appear with a recurrence of less than one second, while the frequencies at 115 Hz and 230 Hz occur every two seconds. Based on these findings, the lower-frequency events can be associated with heart sounds, as expected from expertise based on native hearts. Conversely, the events recurring every two seconds are likely related to the pump, specifically its pulsatility mode function.

C. Comparison filtered and raw signal

Fig. 4 displays the signal in the time domain, showing both the acquired data (Figure 4(a)) and the results following the filtering process (Figure 4(b)). In Figure 4(b), the heart sounds are clearly visible in relation to the R-peak of the ECG. However, spikes related to the pulsatility mode of the pump, which exhibits three consecutive peaks, are also clearly visible. This is consistent with the TF distribution, where the corresponding components spanned until the heart sounds bandwidth and cannot be fully removed by digital filtering. It is evident that the presence of the spikes related to pulsatility mode would cause problems in the sound segmentation phase since they can easily be mis detected as heart sounds.

D. Extraction of the heart sound and CTIs estimation

Fig. 5 shows the two resulting signals after the template matching in the time domain and consequently removing the pump noise (Figure 5(a)) and its individual contribution (Figure 5(b)). Being one the opposite of the other is conforming to the expectations.

In the end, from the cleaned PCG signal, the CTIs are estimated, and the time closure of the heart valves with respect to the R-peak of the ECG is presented in Table 1. The values extracted are consistent with what is declared in the literature. Fig. 6 shows the variability of the estimated time closures among the population of the study.

TABLE I. ESTIMATION OF THE TIME CLOSURE OF THE HEART VALVES

Heart valve	*Time closure (mean ± std)*
Mitral	64 ± 12 ms
Tricuspid	103 ± 11 ms

Heart valve	*Time closure (mean ± std)*
Aortic	348 ± 42 ms
Pulmonary	385 ± 48 ms

V. Discussion

Auscultating heart sounds in patients with LVAD poses a considerable clinical challenge due to the uninterrupted mechanical hum generated by the pump [16]. This constant noise effectively obscures native heart sounds, complicating the recognition of critical indicators of complications such as valve dysfunction, suction events, or abnormal blood flow patterns. Consequently, the heavy reliance on echocardiography to detect these complications limits the feasibility of home-based cardiac monitoring. Phonocardiography stands out as a vital approach to tackle this issue, offering an accurate, non-invasive estimation of CTIs [7]. While existing methods have begun to explore the sound spectra from both the pump and the heart [5], [10], a key advancement focuses on quantifying CTIs to assess the heart's compensatory function.

This research investigates the practicality of employing PCG to capture heart sounds and CTIs in individuals with HM3 LVAD. By utilizing advanced signal processing methods, we successfully differentiated between native heart sounds and noise from the mechanical pump, which facilitated a comprehensive evaluation of hemodynamic function. Considering the growing significance of remote monitoring in the care of LVAD patients, these results aid in the advancement of non-invasive tools that can improve cardiovascular assessment both at the bedside and at home.

Spectral analysis revealed distinct frequency components linked to both the LVAD and the native heart's activity. The prominent peak at 87 Hz corresponds to the pump's rotational speed of 5200 rpm, with harmonics identified at 175 Hz. Additionally, frequencies at 115 Hz and 230 Hz exhibited intermittent patterns during TF analysis, indicating that these patterns weren't solely due to the continuous operation of the pump. The low-frequency components, recurring at intervals of less than one second, aligned with heart sounds, whereas the periodic signals at 115 Hz and 230 Hz, occurring every two seconds, were likely associated with the LVAD's pulsatility mode. This distinction is clinically significant, as it demonstrates the ability to identify and isolate heart sounds despite strong mechanical noise.

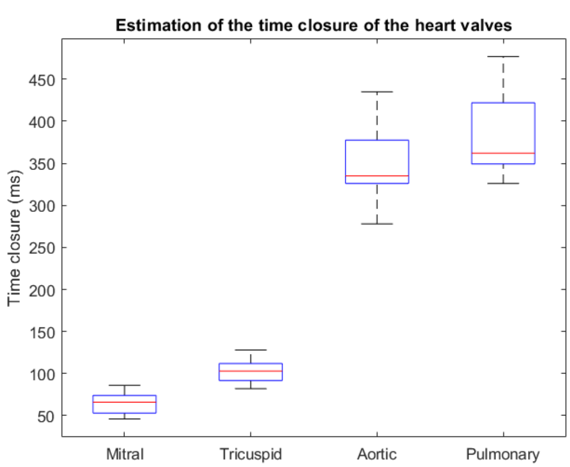

Figure 6. Variability of the time closure of the heart valves among the population.

One major challenge highlighted in this study was the interference from pulsatility-related artifacts when analyzing heart sounds. The raw time-domain signals revealed that the pulsatility mode generated distinct spikes, with three consecutive peaks overlapping within the frequency range related to heart sounds. As a result, conventional filtering techniques proved inadequate for fully eliminating these artifacts. This highlights the need for advanced signal separation methods that go beyond basic frequency-based filtering to ensure accurate extraction of heart sounds.

By employing template matching techniques, we successfully isolated heart sounds from the noise produced by the LVAD, which allowed us to estimate closure times for the heart valves. Table 1 presents the closure times we obtained that closely align with established physiological values for patients suffering from heart failure. The variability observed across different subjects, as illustrated in Fig. 6, highlights the limitations of generalizing these measurements across all patients. Instead, this underscores the importance of individualized evaluation and longitudinal follow-up monitoring to better assess each patient's hemodynamic status and detect potential changes over time. Most importantly, these results indicate that estimating CTIs is indeed possible in patients with LVAD, addressing a critical gap in current non-invasive monitoring methods.

VI. Conclusion

This study demonstrates the feasibility of distinguishing native heart sounds from LVAD-generated noise using PCG and advanced signal processing techniques. By applying PSD analysis, TF transforms, and template matching, we successfully isolated heart sounds and mitigated the effects of the pulsatility mode of the HM3 LVAD, enabling the accurate estimation of heart valve closure times.

These findings highlight the potential of PCG as a non-invasive tool for assessing cardiac function in LVAD patients, offering a complementary or alternative approach to echocardiography for continuous and home-based monitoring. The ability to quantify CTIs in this population is particularly significant, as it provides clinicians with objective hemodynamic insights that are otherwise difficult to obtain.

Future research should focus on refining automated algorithms to further improve heart sound extraction and CTI estimation. Additionally, validating this method in a larger patient cohort will be crucial for a broader validation and for determining its clinical applicability and potential role in early complication detection. Ultimately, integrating PCG into routine LVAD monitoring could enhance patient management, facilitate timely interventions, and improve long-term outcomes in individuals requiring mechanical circulatory support.

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