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Developing a Protocol for Aligning and Correlating Seismocardiography with Echocardiography

Dennis LAWIN[a,b], Ulf KULAU[c] and Urs-Vito ALBRECHT[a,1]
[a] *Department of Digital Medicine, Medical School OWL, Bielefeld University, Bielefeld, Germany*
[b] *Bielefeld University, Medical School and University Medical Center OWL, Public Hospital of Bielefeld, Department of Cardiology and Intensive Care Medicine, Bielfeld, Germany*
[c] *Department of Smart Sensors, Hamburg University of Technology, Hamburg, Germany*
ORCiD ID: Dennis Lawin https://orcid.org/0000-0002-1292-7845, Ulf Kulau https://orcid.org/0000-0002-1662-880X, Urs-Vito Albrecht https://orcid.org/0000-0002-8989-6696

Abstract. Seismocardiography (SCG) monitors health metrics through body surface vibrations from heart activity. The BEAT experiment required echocardiography (ECHO) to correlate SCG signals with cardiac events. Since no standardized ECHO protocol existed, the authors developed one. The protocol focused on recording mitral and aortic valve openings and closings using multiple ECHO modalities for accuracy, ensuring usability, comfort, and efficient data collection. It was tested on healthy subjects and allowed post-hoc analysis of cardiac function. This standardized protocol aims to enhance comparability across SCG studies and offers a reliable method for correlating SCG signals with cardiac events.

Keywords. Ballistocardiography, cardiac events, echocardiography, seismocardiography, validation, protocol

1. Introduction

Seismocardiography (SCG) uses vibrations generated by the heart and blood flow to monitor health metrics like heart rate and rhythm detected on the body surface in the heart region [1]. Since the early 1990s, Echocardiography (ECHO) has been utilized to answer physical questions in seismocardiography (SCG) [1]. Within the scope of the BEAT experiment [2], a standardized protocol for applying the ECHO method was needed to ensure standardization, comparability, and repeatability across studies, as significant variability in methods and study communication currently exists. Without a protocol, results lack reliability, data is not reproducible, and meaningful comparisons between studies are impossible, hindering progress in SCG-ECHO research. As no such

[1] Corresponding Author: Urs-Vito Albrecht, Department of Digital Medicine, Medical School OWL, Bielefeld University, Universitätsstraße 25, 33615 Bielefeld, Germany; E-mail: urs-vito.albrecht @uni-bielefeld.de.

standardized protocols could be identified in the literature, the authors developed and utilized their own approach. This article will present the results to the community to offer a protocol allowing for better comparability between SCG studies utilizing ECHO.

2. Materials and Methods

The authors, from different professional backgrounds (digital) medicine, echocardiography, and electrical engineering), developed the protocol and tested its usability in five sessions between Sept. and November 2021. The requirements were decided through discussions among the authors, considering usability, efficiency, and relevance. The protocol was designed to maximize insights into cardiac timings, ensure data reliability, allow post-hoc assessments, and be easily adaptable without modifying certified hardware. The authors have agreed on a protocol that provides maximum insight into cardiac timings and mechanics, allowing correlation with BCG/SCG signals. The focus was on recording aortic and mitral valve openings and closings, using different ECHO modalities for verification and accuracy. The protocol had to enable post-hoc assessments of cardiac function, be comfortable for subjects, and be easy to learn and follow, allowing external professionals to use it. Efficiency was key, with a target duration of under 20 minutes, and the method had to facilitate objective, direct data collection. It also needed to be adaptable to different research needs. No tampering with ECHO hardware or software was permitted to maintain device certification. The protocol emphasized valve timings, blood flow velocities, and myocardial contraction/relaxation in relation to the ECG. In the third to fifth sitting, the protocol was tested by three investigators on four healthy subjects. Patients with cardiac disease were excluded to focus on assessing cardiac timings in healthy individuals. Future research will address BCG/SCG analysis in diseased patients after defining the physiological signals in healthy individuals [1].

The study was approved by the Ethics Committee of the Ärztekammer Westfalen-Lippe and WWU Münster, Germany, on 15.02.2022 (2022-068-f-S; Chairman: Prof. Dr. W. E. Berdel).

3. Results

The protocol is outlined in Table 1. Subjects should be at rest, with the ultrasound device's ECG connected and clearly displayed. Recordings should be made at the end of expiration to reduce lung attenuation. Temporal resolution can be improved by maximizing the frame rate, minimizing the penetration depth to just reach the region of interest, and narrowing the ultrasound window. Three sequences of five cycles (five R-R intervals) per imaging modality should be stored, and data exported in DICOM and RAW DICOM formats. The ECHO views, windows, and modalities follow clinical gold standards. B-mode images of the parasternal long-axis (PLAX) and short-axis (PSAX) views through the aortic (AV) and mitral valves (MV) should be captured for a basic overview. Specific modalities for cardiac timings and functions are then applied as listed in Table 1. Each cardiac event should be assessed using at least two ECHO modalities, with M-mode and flow velocity measurements (PW or CW Doppler) preferred for valve opening and closure. Although tissue velocity measurements at the mitral valve annulus have been recommended [3, 4], this approach was excluded due to significant variability in

local tissue velocities. Instead, the protocol focuses on modalities that directly visualize valve motion.

Table 1. Standardized echocardiography protocol for the identification of cardiac events in seismocardiography.

View	Image modality	Measure of interest
PLAX•		
	B-mode	Cardiac anatomy and function
	M-mode through the zone of coaptation of the mitral valve leaflets	Mitral valve opening, Mitral valve closure, Atrial contraction
	M-mode through the zone of coaptation of the aortic valve cusps	Aortic valve opening, Aortic valve closure
PSAX•		
	B-mode of Aortic valve	PSAX∗ Aortic valve anatomy and function
	B-mode of Mitral valve	Mitral valve anatomy and function
	Optional: B-mode + TDI basal	Myocardial contraction, relaxation, rotation
	Optional: B-mode + TDI midventricular	Myocardial contraction, relaxation, rotation
	Optional: B-mode + TDI apical	Myocardial contraction, relaxation, rotation
A4CH#		
	B-mode	Cardiac anatomy and function
	B-mode + TDI	Onset and sequence of myocardial contraction and relaxation
	PW-Doppler at the level of the mitral valve leaflet tips	Mitral valve opening and closure; Beginning, peak, and end of the inward-directed blood flow through the MV during the early and passive filling phase of the left ventricle (E-wave); Beginning, peak, and end of the A wave corresponding to the late and active filling phase (A-wave).
A5CH#		
	B-mode	Cardiac anatomy and function
	B-mode + TDI	Onset and sequence of myocardial contraction and relaxation
	CW-Doppler through the aortic valve	Aortic valve opening and closure
A2CH#		
	B-mode	Cardiac anatomy and function
	B-mode + TDI	Onset and sequence of myocardial contraction and Relaxation

∗ Subject in left lateral position and the ultrasound transducer positioned in the third intercostal space on the left side of the sternum.

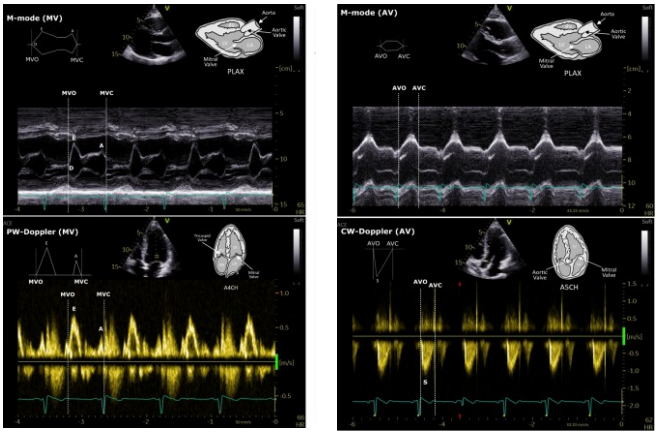
Subject in half left lateral position and the transducer placed in the 4th or 5th intercostal space in the midclavicular line.

4. Discussion

4.1. The examination of relevant cardiac events according to the protocol

The onset and sequence of left ventricular contraction can be effectively visualized using Tissue Doppler Imaging (TDI) and Tissue Velocity Imaging (TVI). These techniques involve obtaining B-mode images in apical 2-chamber (A2CH), 4-chamber (A4CH), and 5-chamber (A5CH) views (Figure 1). Post-imaging analysis is then performed to determine the onset and sequence of myocardial contraction by analyzing local tissue

velocities and correlating them with the ECG (5). Mitral valve closure (MVC) is determined at the moment when the mitral valve (MV) leaflets first come into contact. This is assessed using M-mode in the parasternal long-axis (PLAX) view and is further verified by pulsed-wave Doppler (PW-Doppler) through the MV in the apical 4-chamber (A4CH) view, specifically at the end of the A-wave in the transmitral inflow (6, 3, 7). Aortic valve opening (AVO) is detected at the first movement of the aortic valve (AV) cusps during systole, as visualized using M-mode in the PLAX view. Verification is achieved using continuous-wave Doppler (CW-Doppler) in the apical 5-chamber (A5CH) view, where the timing of the initial outward blood flow through the AV during early systole marks AVO (7). The onset of left ventricular relaxation can also be visualized using TDI/TVI. Post-imaging analysis is applied to assess the onset and sequence of myocardial relaxation by analyzing local tissue velocities and correlating these to the ECG (5). Aortic valve closure (AVC) is identified when the AV cusps meet during early diastole, observed using M-mode in the PLAX view. This event is verified by CW-Doppler in the A5CH view, where the closure spike is visible in the Doppler outflow curve immediately following AVC (7). Mitral valve opening (MVO) occurs at the first opening movement of the MV leaflets during early diastole. This is visualized using M-mode in the PLAX view and is confirmed through PW-Doppler in the A4CH view, corresponding to the onset of the E-wave in the transmitral inflow. Additionally, the rapid left ventricular filling phase is measured by tracking the E-wave, which reflects the movement of the MV leaflets caused by left ventricular relaxation and filling, using M-mode in the PLAX view. The inward-directed blood flow during the rapid filling phase is also captured by PW-Doppler in A4CH, and tissue velocities assessed by TDI further help in understanding this phase (6, 3, 7). Active left ventricular filling, induced by atrial contraction, is determined using the A-wave, which represents the movement of the MV leaflets caused by atrial contraction. This is observed with M-mode in the PLAX view and verified through PW-Doppler in the A4CH view. The sequence of atrial contraction can also be analyzed by evaluating tissue velocities with TDI (6, 3, 7).



MVO/MVC in M-mode in PLAX (top left) and PW-Doppler in A4CH (bottom left), AVO/AVC using M-mode in PLAX (top right) and CW-Doppler in A5CH (bottom right).
Legend:
D = beginning of MVO; E = early and rapid filling phase of the left ventricle; A = atrial contraction.
S = peak systolic velocity through AV.

Figure 1. Echocardiographic representation of MVO/MVC and AVO/AVC.

4.2. Limitations

When obtaining M-mode to capture the excursion of the AV, clear visualization of the cusps is impeded due to displacement of the heart valve level during the cardiac cycle. This problem may be solved by the separate examination of AVO and AVC with slightly adjusted positions of the beam for each event. Nevertheless, the authors recommend applying a second modality to validate the values assessed with M-mode. Beyond this, the accuracy of identifying events of interest may also be affected by the possible lack of feasibility of ultrasound examinations in some individuals, so the protocol may not be applicable to all subjects as intended. Our method for identifying cardiac events with precision relies on the investigator's expertise, with a recommendation of at least 300 ECHO exams per investigator to ensure the necessary skills and accuracy.

5. Conclusions

The development and application of a standardized protocol can significantly enhance the comparability of SCG and ECHO studies, paving the way for more reliable insights into cardiac physiology. However, the success of such protocols depends on precise implementation, skilled investigators, and addressing variability in subject characteristics. Furthermore, future work will focus on defining clear success metrics for the protocol, including reproducibility across investigators, accuracy in identifying cardiac events, efficiency in execution, and applicability to diverse populations. Testing should involve both healthy individuals and those with cardiac conditions to ensure robustness and generalizability. Additionally, longitudinal studies and feedback-driven revisions can refine the protocol for broader adoption.

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