Envisioning the Future of Health Informatics and Digital Health
J. Mantas et al. (Eds.)

doi:10.3233/SHTI250113

Echocardiography Correlation with Seismocardiography—Systematic Review

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Abstract. A methodological systematic review included literature retrieved from Scopus, PubMed, and IEEE-Explore. 61 studies on seismocardiography (SCG) and echocardiography (ECHO) were found. After screening for aortic and mitral valve timing events, 12 studies were selected. These studies focused on correlating SCG signals with ECHO using M-mode, PW-Doppler, CW-Doppler, and TDI. Variations in sensor placement and subject positioning highlighted the need for standardization. Our review stresses the importance of clear objectives, standardized protocols, and recording disease-specific impacts on heart mechanics for future research.

Keywords. Seismocardiography, Echocardiography, Cardiac timing events, Standardization

1. Introduction

Echocardiography (ECHO) has been used since the early 1990s to investigate key physiological questions in seismocardiography (SCG) research, particularly in analyzing cardiac timing events such as valve openings and closings [1, 2]. With numerous studies in this field, understanding the methodologies and protocols applied is essential. This article reviews the protocols used in SCG and ECHO studies to identify common practices and enhance comparability, forming the basis for developing our standardized protocol. The review critically analyzes and compares the methodologies and protocols used in SCG and ECHO research, particularly those related to cardiac timing events. The aim is to identify best practices, inconsistencies, and areas requiring standardization. By analyzing methods in the literature, we aim to improve standardization, reliability, and comparability for future cardiac monitoring studies.

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2. Methods

The methodological systematic review was conducted on 19/06/2023 using Scopus, Pubmed, and IEEE-Explore for the study retrieval. Titles and abstracts were searched for the keywords 'seismocardio*', 'SCG', 'ballisto*', or 'BCG' combined with 'echo'. After removing duplicates, two authors screened the results for eligibility. Only articles in German or English were included. Eligible articles were reviewed for their focus on the simultaneous recording of BCG/SCG and ECHO, the use of standardized ECHO protocols, the advantages and disadvantages of the methods, and the specific devices and transducers used. The focus was on articles examining AV or MV timing events.

3. Results

A total of 61 articles published between 1971 and 2023 were identified. Of these, 37 were excluded for reasons such as not applying the ECHO method (n=20), addressing the wrong topic (n=16), or having a veterinary focus (n=1). Additionally, articles that did not primarily focus on the timing events of the aortic valve (AV) or mitral valve (MV) were excluded (n=14). This left 12 articles for inclusion in the discussion: 8 of these examine the timing events of both valves in their open and closed states, and 4 address at least one valve state (see Table 1).

Table 1. Results of the literature research

Source	Objective	Position	Valve event	ECHO mode
Agam et al. (2022) [3]	Correlation between SCG and ECHO	Supine, 30° head-up	AVC	TDI in the lateral mitral annulus, PW in MV, PW-Doppler in LVOT, B-mode in A2/4/5CH
Akhbardeh et al. (2009) [4]	Correlation SCG and ECHO	NA	AVO, MVO6	M-mode, CW-Doppler
Chen et al. (2022) [5]	Misalignments	Supine	AVO, AVC, MVO, MVC	M-mode in PLAX, Doppler in MV and AV
Crow et al. (1994) [2]	Relationship SCG & echocardiography	NA	AVO, AVC, MVO, MVC	M-mode, Doppler
Dehkordi et al. (2019) [6]	Precision of extraction of cardiac timings SCG	Supine	AVO, AVC, MVO, MVC	M-mode, Doppler, TDI
Dinh et al. (2016) [7]	Timing of SCG signals during an exercise test	Upright	AVO, AVC, MVO, MVC	PW-Doppler in MV
Isilay et al. (2022) [8]	SCG for monitoring of cardiac patients	Supine	AVO, AVC, MVO, MVC	M-mode in AV and MV
Leitão et al. (2018) [9]	Development MEMS accelerometer for SCG	Supine	AVO peak amplitude, AVC	NA
Lin et al. (2018) [10]	Multi-channel SCG spectrum measurement system	Supine	AVO, AVC, MVO, MVC	B-mode, M-mode, Doppler, TDI
Sørensen et al. (2018) [11]	Correlation: fiducial points, cardiac events	Supine	AVO, AVC, MVO, MVC	M-mode, PW-Doppler, M-mode + TDI
Steffensen et al. (2023) [12]	Wrist acceleration BCG during exercise	Supine & semirecumbent	AVO	M-mode, CW-Doppler
Zanetti et al. (1991) [13]	Points of the cardiac cycle in SCG	NA	AVO, AVC, MVO, MVC	M-mode, PW-Doppler

4. Discussion

4.1. Study objectives

In the 12 evaluated studies, objectives varied, with ECHO frequently used to evaluate or verify cardiac event timings across different applications. Crow et al. and Agam et al. [3, 2] examined the correlation between SCG and echocardiography. Several authors focused on timing-related aspects: Zanetti et al. [13] defined specific points in the cardiac cycle via SCG, while Akhbardeh et al. [4] explored the correlation between SCG and cardiac events. Dinh et al. [7] timed SCG-based heart events, and Sorensen et al. [11] correlated SCG fiducials with specific cardiac events. Dekhordi et al. [6] assessed the precision of SCG-extracted cardiac timings, and Chen et al. [5] analyzed SCG misalignment using dynamic time warping. Three studies took a more applied approach: Lin et al. [10] evaluated multi-channel SCG for cardiac monitoring, Isilay et al. [8] explored SCG's applicability for patient monitoring, and Steffensen et al. [12] assessed wrist-worn BCG during exercise. Leitao et al. [9] focused on the technical development of a high-resolution MEMS accelerometer for SCG. Our work addressed many of these aspects, identifying ECHO modalities most suitable for precise cardiac timing determination. We emphasized optimizing images for temporal resolution and using Doppler-ECHO for valve event verification. Additionally, our standardized protocol includes TDI to assess cardiac contractility and relaxation, providing a foundation for future modifications by other researchers.

4.2. ECHO views and SCG sensor placement

Descriptions of SCG sensor placement and subject positioning varied significantly across studies, as did using ECHO to verify timing events. Depending on the placement of both the SCG sensor and the ECHO transducer, the two modalities may influence each other. Poor positioning of the subject can impair ECHO imaging and cause variations in SCG results. Several studies placed the SCG sensor on or near the xiphoid process [3, 6, 7, 11, 13], while others referred to the sternum more generally [4, 9]. Some studies specified the 4th [11] and 5th left intercostal spaces [5], valvular auscultation sites [10], or the wrist [12] as suitable locations. Subject positioning alternated between supine and upright. This lack of standardization highlights the need for uniform sensor placement and subject positioning to improve comparability. Only four studies provided detailed descriptions of ECHO views regarding ultrasound image acquisition. Akhbardeh et al. used PLAX and PSAX views to detect valve events, with A5CH applied for CW-Doppler [4]. Lin et al. used PLAX, PSAX, A4CH, A3CH, and A2CH views [10], while Sorensen et al. employed A4CH and A5CH views for PW-Doppler and TDI [11]. Dehkordi et al. used A3CH and A5CH for spectral flow and A4CH for valve timing [6]. Other studies lacked sufficient detail on ECHO views and transducer placement, which is critical for simultaneous SCG and ECHO measurements, as ultrasound pressure can affect chest movement and SCG data. To mitigate interference, careful placement of SCG and ECHO sensors is required. The authors chose a left lateral position for PLAX and PSAX views and a half left lateral position for A4CH, A5CH, and A2CH views, ensuring optimal imaging and reproducibility for future research.

4.3. ECHO modalities

M-mode, PW-Doppler, CW-Doppler, and TDI were the most commonly used ECHO modalities, although only three studies provided detailed reasoning for their specific application. The combination of ECHO methods, target structures, and cardiac functions varied across studies. Crow et al. utilized M-mode for valve movements and PW-Doppler for flow velocities during ventricular ejection, early diastole, and atrial systole [2]. Lin et al. used M-mode for timing valvular events and PW-Doppler for detecting peak blood flow, while TDI was applied to monitor left ventricular wall motion in six segments [10]. Sorensen et al. relied on TDI to approximate the mitral valve closure (MVC) point and used M-mode with TDI to assess atrial systole, MVC, aortic valve closure (AVC), and mitral valve opening (MVO). PW-Doppler was used to align flow profiles with aortic valve opening (AVO) and the sharp closure click with AVC [11]. M-mode was favored for valve event identification due to its ability to directly visualize valve motion, providing high temporal resolution and minimizing misinterpretation. Since valve opening and closing depend on blood flow dynamics, PW-Doppler and CW-Doppler were used to verify valve event timings. TDI was utilized for its high local resolution, making it ideal for analyzing tissue movement with precision.

4.4. Comparability and standardization

Improving standardization protocols for SCG and ECHO is essential due to variations in sensor placement, inconsistent subject positioning, and differences in ECHO modalities and protocols. The lack of reproducibility, inadequate reporting standards, and insufficient differentiation between basic and clinical research further hinder comparability. Disease-specific impacts on SCG and ECHO results are often neglected, and variations in sample sizes and data collection exacerbate these challenges. Addressing these issues is critical to enhancing reliability, consistency, and the broader applicability of research findings. Many aspects highlighted by our evaluation make it challenging to compare existing studies. However, improving the standardization and repeatability of SCG measurements alongside ECHO-based image acquisition, as discussed earlier, is not the only way to enhance the study landscape. Researchers must also clearly define whether their work is basic research—such as proof of concept, baseline measurements, or fundamental parameter derivation, where a small sample of healthy subjects may suffice—or whether it explores clinical applications. For example, our standardized methodology included only healthy subjects per protocol. For disease-specific research, larger sample sizes may be necessary to validate the methodology's applicability. Studies involving cardiac patients [2, 8, 10, 13] mentioned various diagnoses, including dilated cardiomyopathy and myocardial infarction, which can affect heart mechanics and influence SCG signals. To improve standardization, researchers should register and evaluate the specific disease's impact on heart mechanics when cardiac patients are included. Additionally, the number of test subjects and the amount of recorded data varied significantly across studies (ranging from single-subject tests to 86 participants), making standardization through detailed reporting—such as using a standardized checklist—crucial for improving comparability.

5. Conclusion

Our evaluation emphasizes the difficulties in comparing SCG studies due to varying methodologies and a lack of standardization. To enhance comparability, researchers must clearly define their goals, differentiate between basic research and clinical applications, and adopt standardized methods, especially for sensor placement, subject positioning, and ECHO views. Additionally, the effect of specific diseases on heart mechanics should be recorded when including cardiac patients. A standardized protocol would provide for a reproducible framework to improve SCG and ECHO precision and can be adapted for future research.

References

[1] Salerno DM, Zanetti JM, Green LA, Mooney MR, Madison JD, Van Tassel RA. Seismocardiographic changes associated with obstruction of coronary blood flow during balloon angioplasty. Am J Cardiol. 1991 Jul 15;68(2):201–7, doi: 10.1016/0002-9149(91)90744-6
[2] Crow RS, Hannan P, Jacobs D, Hedquist L, Salerno DM. Relationship between seismicocardiogram and echocardiogram for Events in the Cardiac Cycle. American Journal of Noninvasive Cardiology. 1994;8(1):39–46, doi: 10.1159/000470156
[3] Agam A, Søgaard P, Kragholm K, Jensen AS, Sørensen K, Hansen J, et al. Correlation between diastolic seismocardiography variables and echocardiography variables. European Heart Journal - Digital Health. 2022 Oct;3(3):465–72, doi: 10.1093/ehjdh/ztac043
[4] Akhbardeh A, Tavakolian K, Gurev V, Lee T, New W, Kaminska B, et al. Comparative analysis of three different modalities for characterization of the seismocardiogram. Proceedings of the 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Minneapolis, MN: IEEE; 2009. p. 2899–903, doi: 10.1109/IEMBS.2009.5334444
[5] Chen CH, Lin WY, Lee MY. Computer-Aided Detection of Fiducial Points in Seismocardiography through Dynamic Time Warping. Biosensors. 2022 May 30;12(6), doi: 10.3390/bios12060374.
[6] Dehkordi P, Khosrow-Khavar F, Di Rienzo M, Inan OT, Schmidt SE, Blaber AP, et al. Comparison of Different Methods for Estimating Cardiac Timings: A Comprehensive Multimodal Echocardiography Investigation. Front Physiol. 2019 Aug;10:1057, doi: 10.3389/fphys.2019.01057
[7] Dinh A, Bui FM, Nguyen T. An accelerometer based system to measure myocardial performance index during stress testing. In: 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE; 2016. p. 4877–80, doi: 10.1109/EMBC.2016.7591820.
[8] Işilay Zeybek ZM, Racca V, Pezzano A, Tavanelli M, Di Rienzo M. Can Seismocardiogram Fiducial Points Be Used for the Routine Estimation of Cardiac Time Intervals in Cardiac Patients? Front Physiol. 2022 Mar 18;13:825918, doi: 10.3389/fphys.2022.825918
[9] Leitão F, Moreira E, Alves F, Lourenço M, Azevedo O, Gaspar J, et al. High-Resolution Seismocardiogram Acquisition and Analysis System. Sensors. 2018 Oct 13;18(10), doi: 10.3390/s18103441
[10] Lin WY, Chou WC, Chang PC, Chou CC, Wen MS, Ho MY, et al. Identification of Location Specific Feature Points in a Cardiac Cycle Using a Novel Seismocardiogram Spectrum System. IEEE J Biomed Health Inform. 2018 Mar;22(2):442–9, doi: 10.1109/JBHI.2016.2620496
[11] Sørensen K, Schmidt SE, Jensen AS, Søgaard P, Struijk JJ. Definition of Fiducial Points in the Normal Seismocardiogram. Sci Rep. 2018 Oct;8(1):15455, doi: 10.1038/s41598-018-33675-6
[12] Steffensen TL, Schjerven FE, Flade HM, Kirkeby-Garstad I, Ingeström E, Solberg FS, et al. Wrist ballistocardiography and invasively recorded blood pressure in healthy volunteers during reclining bike exercise. Front Physiol. 2023 May;14:1189732, doi: 10.3389/fphys.2023.1189732
[13] Zanetti JM, Salerno DM. Seismocardiography: a technique for recording precordial acceleration. In: [1991] Computer-Based Medical Systems@m_Proceedings of the Fourth Annual IEEE Symposium. Baltimore, MD, USA: IEEE Comput. Soc. Press; 1991 [cited 2024 May 25]. p. 4–9, doi: 10.1109/CBMS.1991.128936