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ORIGINAL ARTICLE

Correlation between diastolic seismocardiography variables and echocardiography variables

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Aims

Echocardiography is a key diagnostic tool for assessment of myocardial performance and haemodynamics. Seismocardiography (SCG) can potentially provide fast and reliable assessments of key components related to myocardial performance. The aims of this study were to investigate the correlation between SCG and echocardiographic measures, and a decrease in preload by raising the subjects to a 30° head-up tilt position would be detected by both echocardiography and SCG.

Methods and results

A total of 45 subjects were included in the study. SCG and electrocardiogram were recorded simultaneously and afterwards echocardiography was recorded. The SCG signals were divided into individual heart beats using a duration-dependent Markov model. Using a fiducial point detection algorithm, the diastolic fiducial points were identified. The amplitudes from the SCG showed a high correlation, especially with the variable e′ from the echocardiography. The peak-to-peak amplitude of the diastolic SCG complex and e′ had a high correlation of 0.713 ($P < 0.001$). The second minimum in diastolic occurring after the closing of the aortic valve was the only amplitude showing a high correlation when comparing supine with head-up tilt in the SCG. All the echocardiography variables but *E*/e′ showed a high correlation when comparing supine with head-up tilt.

Conclusion

The results found in this study showed a high correlation between the amplitudes from the diastolic SCG and the diastolic variable e′ from the echocardiography, thus indicating that the SCG could potentially be utilized to evaluate the diastolic function.

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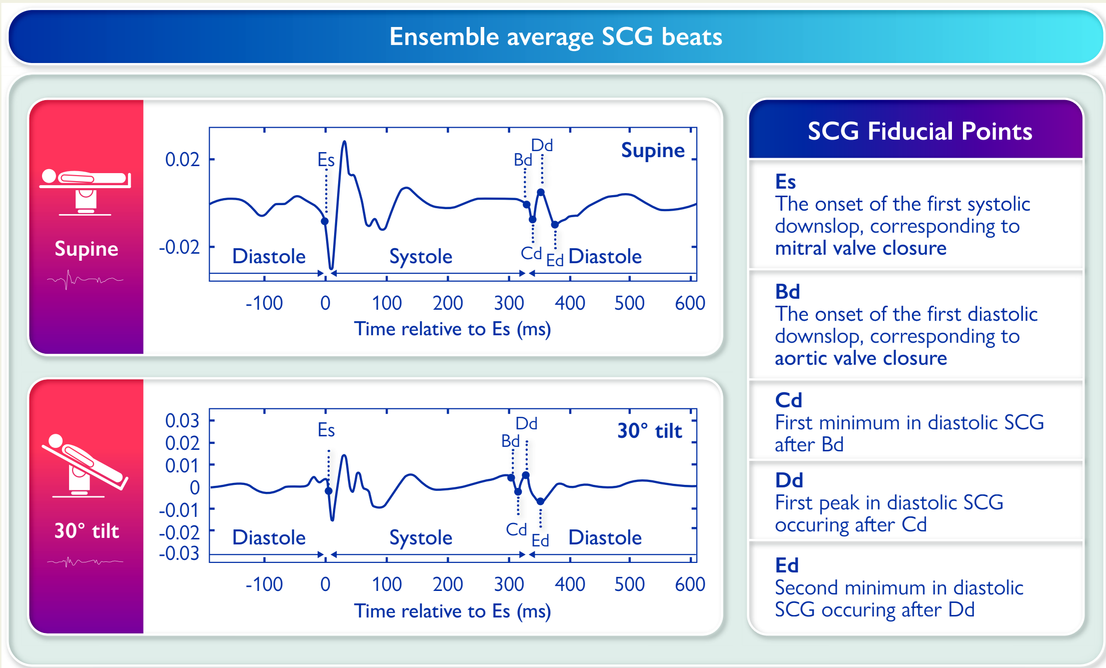
Graphical Abstract



SCG and echocardiography was recorded from the subjects in a supine and 30° head-up tilt. The SCG fiducial points were identified and analysed in the ensemble average SCG beats.

Keywords Echocardiography • Seismocardiography • Diastolic variables • Non-invasive • Cardiology • Preload

Introduction

Every year around 17 million people die from cardiovascular diseases, making it a leading cause of death globally.[1] Most cardiovascular diseases can be managed with early detection, which is of great benefit since the treatment becomes easier, more effective, and economical. There are different non-invasive tools used in clinical practice to evaluate the condition of the heart, such as the electrocardiogram (ECG) and echocardiography.

The primary tool used for evaluation of cardiac mechanics is echocardiography, which is routinely used in diagnosis, management, and follow up of patients with suspected or known heart diseases.[2] Echocardiography provides a detailed evaluation of myocardial performance; it is mobile and even portable, but it requires extensive training to provide robust and reliable data. Some of the disadvantages of echocardiography is that it requires expensive equipment and specialist staff and that it is a time-consuming diagnostic tool, which can lead to long waiting times.

Seismocardiography (SCG) is a non-invasive measure of cardiac function.[3] The SCG utilizes the vibrations produced by the beating heart which relates to the contraction of the atria and ventricles as well as the opening and closure of the valves.[3] The SCG records the vibrations from the chest using an accelerometer a technique that was introduced by Patrick Mounsey in 1957 using an accelerometer.[3] Although the SCG provides measures of cardiac contractility and timing of events in the cardiac cycle, the technique did not reach clinical use. With the progression of microelectromechanical systems, it has now become possible to produce smaller and lighter accelerometers, thus transforming the SCG from a measuring method mainly used in supine position, to a potential wearable technology.[4]

The SCG displays a low-frequency amplitude wave during atrial systole, a high amplitude during ventricular systole and another wave during early ventricular filling.[5] Simultaneous recording of an SCG, ECG, and echocardiography has demonstrated that the waves of an SCG correlates to known physiological events including the mitral valve opening and closure, the isovolumetric contraction, ejection, aortic valve opening and closure (AC), and cardiac filling.[5] The utility of SCG in estimating the left-ventricular ejection time was also shown.[5] The study by Sørensen *et al.*[4] also found a relationship between fiducial points in the SCG and the events from ultrasound images, hence establishing a correlation between the SCG and cardiac events.

Although the relationship between the SCG waves and cardiac performance is not fully understood, these measurements of cardiac events could potentially make the SCG a diagnostic tool for evaluation of the cardiovascular system.[5] Advantages of the SCG are that it can be recorded continuously with a high temporal resolution, it is low cost, that it is less time-consuming than echocardiographic assessment, it does not require any specialist staff for application and the digital data and waveforms enable development of algorithms. Early detection of cardiovascular diseases could be improved by routine monitoring of cardiovascular measurements, which could even be conducted at home.

The assessment of the left ventricle (LV) diastolic function is an integral part of routine evaluation of patients showing symptoms of dyspnoea or heart failure.[6] A study by Mogelvang *et al.*[7] presented that the diastolic function was the first affected when a cardiovascular disease occurred. The study by Hoffmann *et al.*[8] showed that in chronic artery disease (CAD), the early diastolic longitudinal velocity (e′) from the echocardiography was the first to get affected and decrease. This indicated that e′ was a sensitive predictor of chronic CAD, which agrees with other previous findings on e′ and early diastolic function being reduced at an early stage in the development of chronic CAD. In the study by Sørensen *et al.*, the focus was to define waves in the SCG, to define the fiducial points related to the waves, and to relate the fiducial points to events in the cardiac cycle. In this study, the fiducial points identified by Sørensen *et al.* will be used to investigate if the SCG could be utilized to determine the diastolic function.

The aims of this study were to investigate the correlation between SCG and echocardiographic measures and if a decrease in preload by raising the subjects to a 30° head-up tilt position, would be detected by both echocardiography and SCG.

Methods

In the current study, SCG, ECG, and echocardiography data were collected from subjects without any known cardiovascular disease, with subjects in a supine and a 30° head-up tilt position. The SCG measures were correlated to echocardiography diastolic measures. The subject was first in a supine position while recording the ECG and SCG. Immediately afterwards the following ultrasound images were recorded with subjects laying on the side: Pulsed Wave Tissue Doppler Image in the lateral mitral annulus, Pulsed Wave transmitral flow, Pulsed Wave Doppler in Left-Ventricular Outflow Tract, Apical two-, four-, and five-chamber view. The same procedure was repeated when the subjects were tilted in a 30° head-up position to decrease the preload. The experimental protocol was approved by the scientific ethical committee of Northern Jutland (N-20120069). The subjects signed a written informed consent before they participated in the study. All methods were performed in accordance with relevant guidelines and regulations.

Study population

The subjects were recruited through posters and flyers placed at Aalborg University and in shopping malls in the city of Aalborg. Forty-five subjects were recruited, and the inclusion criteria were: healthy males and females at the age of 20–80 years old. Exclusion criteria included:

- Pre-existing cardiovascular heart disease including hypertension
- Any type of inability to cooperate during the examination
- Use of cardiovascular-related medications and cardiac devices

Experimental design

For all the subjects, three lead ECG, echocardiography, and SCG were recorded. Each subject's height, weight, age, and sex were recorded before the trial started.

The subject was placed in a supine position and three accelerometers were attached to the subject's skin with double adhesive tape. One accelerometer was placed at the xiphoid process, one at the intercostal space 4 (IC4), and one at the right carotid artery. However, in the current study only the SCG signal from the xiphoid process was used for analysis. The accelerometers used were Silicon Designs 1521 placed in a 3D-printed plastic housing (19 mm wide, 21 mm long, and 11 mm high, it weighed 5 g).

The ECG recording was performed while the subjects were in supine position and 30° head-up tilt position with a four-electrode setup that was placed on the right and left shoulder and on the right and left iliac crests. The ECG and accelerometers were connected to an iWorx228 data acquisition system, and the signals were sampled at 5000 Hz to a PC using LabScribe software (iWorx System Inc., USA). The echocardiography images were recorded with a Vivid E9 (GE Healthcare, USA).[4]

Signal processing

All the recorded data from the iWorx system was processed in MATLAB (Mathworks, USA).

Since data were recorded continues during the whole session, windows for analysis were selected when the subjects were in supine position and afterwards in a tilting position. The analysis windows were chosen based on visual inspection to ensure a continues analysis without noise contamination from body movement or talking to subjects. The SCG signals were divided into individual heart beats using a duration-dependent hidden Markov model (DHMM).[9] Since the DHMM was originally developed for heart sound segmentation, the SCG signals were high pass filtered (>15 Hz) and the envelope of the filtered SCG was used as input the DHMM model as described by Schmidt *et al.*[9] The onset of the first heart sound defined the onset of the systole and the second heart sound the onset of the diastole. Next the systolic and diastolic segments were aligned and averaged to produce a low noise mean SCG beat as described by Sørensen *et al.*[4] By utilizing a custom developed fiducial point detection algorithm, the diastolic fiducial points C_d, D_d, E_d, E_s, G_s, B_d, and F_d were identified as by Sørensen *et al.*[4] The potential risk of heart sound-based segmentation is that the systole and diastole become exchanged if the method interpreted S1 as S2 and vice versa. Therefore, the DHMM segmentation was validated with the ECG, and no cases of exchanged systoles and diastoles were found.

The automatically identified fiducial points were manually validated and corrected if not placed accordingly, see all annotated fiducial points in Supplementary Material online. *Graphical Abstract* presents average SCG and fiducial points from a subject in supine and tilted position.

Diastolic seismocardiography variables

The time intervals between the diastolic SCG fiducial points were measured, which in this study was hypothesized to correlate to the diastolic function assessed by echocardiography, including the time from the diastolic onset point B_d to the C_d, D_d, E_d, and F_d fiducial points and the time from the C_d point to the D_d and E_d points.

In addition, the amplitudes of the C_d, D_d, and E_d fiducial points and the peak-to-peak value from C_d to D_d were measured.

Echocardiography variables

The echocardiography variables were analysed by an experienced echo specialist (P.S.) with great experience in analysing tissue Doppler imaging (TDI) recording and previous reports on variability have been provided throughout the past >20 years.[4,7,8] The variables from the echocardiography used were: The LV end-diastolic volume (LVEDV), isovolumic relaxation time (IVRT), mitral valve e-velocity (*E*), early diastolic mitral annular velocity (e′), *E*/e′, stroke volume (SV), and heart rate (HR). These are standard echocardiography variables when assessing the cardiac performance.[10]

The following parameters were measured by analysing the echocardiography manually: Biplane LV volumes and LVEF by AutoEF, peak e and a transmitral flow and the ratio, onset, and peak of e′, timing from onset of QRS, onset and peak of LV outflow tract flow, onset, and peak of transmitral e, and LV outflow tract velocity time integral.

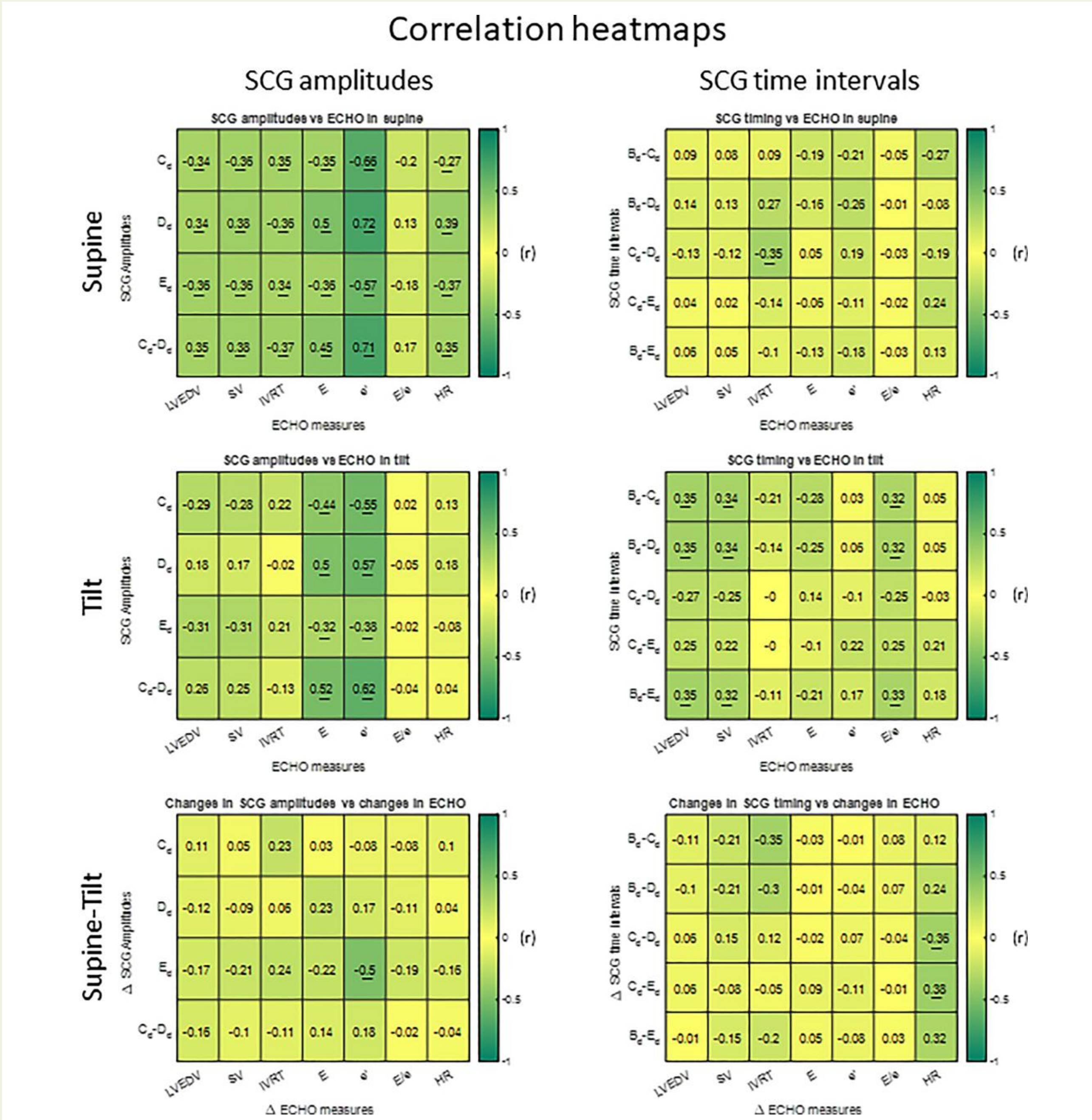


Figure 1 Heatmap demonstrating Pearson's correlation between the diastolic seismocardiography variables and the echocardiography variables. The four top figures illustrate correlation between seismocardiography measures and echocardiography when the patients were in supine and tilted position. The two lower figures illustrate the correlation between changes in seismocardiography and echocardiography when the subject change from to supine position and tilt position. Underlined numbers are significant correlations ($P < 0.05$).

Statistical analysis

All the data from the SCG and the echocardiography were tested for normality by visualizing the histogram. Normal distribution was observed among all data points and therefore Pearson's linear correlation coefficient was utilized to assess if there was a correlation between the measurements from the SCG and the echocardiography. All the diastolic variables from the SCG were correlated to the variables from the echocardiography (*Figure 1*). *P*-values <0.05 were considered significant for rejecting the null hypothesis of no correlation. When the subjects were in a head-up tilted position, the preload was decreased. Therefore, a paired samples test between the SCG and echocardiography data in supine position compared with the data in a head-up tilted position was utilized. This was to investigate if the SCG and the echocardiography could detect a difference when decreasing the preload. All statistical analyses were conducted using IBM SPSS Statistics for Windows, version 27 (IBM Corp., Armonk, NY, USA).

Table 1 Significant differences from the seismocardiography measurements between the subjects in a tilted position compared with when in a supine position

Paired samples test SCG measures: tilted vs. supine position	Amplitudes (g)				Time intervals (ms)				
	D_d	C_d	E_d	C_d to D_d	B_d to D_d	B_d to C_d	C_d to D_d	C_d to E_d	B_d to E_d
Means in supine position	0.011 ± 0.008	–0.008 ± 0.005	–0.010 ± 0.003	0.020 ± 0.01	22.123 ± 5.191	9.8 ± 3.987	–12.330 ± 3.071	39.903 ± 9.588	49.703 ± 10.211
Means in tilted position	0.011 ± 0.007	–0.008 ± 0.006	–0.008 ± 0.004	0.019 ± 0.01	24.005 ± 12.857	11.249 ± 8.7	–13.757 ± 5.233	40.849 ± 12.634	52.097 ± 17.822
Difference	–0.0	–0.0	0.0	0.0	1.9	1.4	–0.4	0.9	–2.4
P-value Tilted vs. supine	0.470	0.828	0.000**	0.500	0.204	0.544	0.569	0.569	0.326

The means of the diastolic measurements from the SCG is also presented.
g, gravity.
$^{**}P < 0.01$ and $^{*}P < 0.05$ were considered significant.

Results

A total of 45 subjects were initially enrolled. One subject from the original 45 subjects decided to withdraw. When collecting the SCG data in supine position, five subjects were excluded, since the algorithm utilized could not estimate the fiducial points for the diastolic variables. When collecting the SCG data in tilted position, four subjects were excluded for the same reason. This resulted in data from 38 subjects in supine position and 39 subjects in tilted position. In one recording (N25 tilt position), the manual review of fiducial points identified wrongly placed diastolic fiducial points. Therefore, after multiple authors agreed on the correct position according to Sørensen *et al.*,[4] the point was corrected. The echocardiography data were collected manually, and no subjects were excluded. The mean age was 49.3 years, the mean weight was 71.2 kg, and the mean height was 174.7 cm for the subjects in tilted position. The mean age was 45.6 years, the mean weight was 72.9 kg, and the mean height was 174.7 cm for the subjects in supine position.

Seismocardiography and echocardiography measurements

Figure 1 presents a heatmap demonstrating the correlations between the diastolic SCG variables and the echocardiography variables, when the subjects were in a supine and tilted position. The SCG variables D_d and C_d to D_d were highly correlated with the variable e′ from the echocardiography; this was the case in both positions.

Changes in preload

Table 1 presents the paired samples test between the measurements from the SCG when the subjects were in a tilted position compared with the ones when the subjects were in a supine position. *Table 2* presents the paired samples test between the measurements from the echocardiography when the subjects were in a tilted position compared with the ones when the subjects were in a supine position.

The results from *Table 2* showed a significant difference between every variable from the echocardiography but *E*/*e*′, whereas the SCG variable E_d was the only amplitude change correlated significantly to changes in preload induced by tilting (*Table 1*).

Correlation plots illustrated in *Figure 2* were utilized to showcase the correlation between the diastolic variables from the SCG and the echocardiography measures. Correlation plots of e′ from the echocardiography and the amplitudes from the SCG were illustrated, since they showed the highest correlation when the patients were in a supine position (*Figure 1*). The intrasubject correlations between SCG amplitudes in supine and tilt were $r = 0.81$ for C_d, $r = 0.85$ for D_d, $r = 0.75$ for E_d and $r = 0.90$ for C_d to D_d.

Discussion

In this study, the fiducial points described in results were utilized and the diastolic variables from the SCG and the echocardiography variables were investigated.

Although most of the correlations found were not high (*Figure 1*), the SCG variables D_d and C_d to D_d were highly correlated with the variable e′ from the echocardiography in supine position (*Figure 1*).

This latter finding emphasizes a possible correlation between the SCG and cardiac events as concluded in the study by Sørensen *et al.*[4]

Current literature illustrates that the SCG contains defined points associated with the cardiac cycle either at the local extrema[11,12] or at the slopes of the signal before and after the fiducial points.[3,4] All the studies also used echocardiography to correlate with the results from the SCG.

Potential of seismocardiography estimated e′

The diastolic variable e′ from the TDI is used to evaluate the LV diastolic function based on the assumption that it reflects the myocardial relaxation in the long axis. This could indicate that the correlation found in this study between the amplitudes from the SCG and e′ from the echocardiography in supine position (*Figure 1*) could result in the SCG being utilized to evaluate the LV diastolic function. Both

Table 2 Significant differences from the echocardiography measurements between the subjects in a tilted position compared with the ones in a supine position

Paired samples test echocardiography measures: tilted vs. supine position	LVEDV (mL)	SV (mL/beat)	IVRT (ms)	*E* (m/s)	e′ (m/s)	*E*/e′	HR (b.p.m.)
Means in tilted position	82.7 ± 24.9	50.5 ± 15.5	81.5 ± 27.6	0.6 ± 0.1	0.1 ± 0.04	0.20 ± 0.8	67 ± 10.3
Difference	12.9	7.9	–10.9	0.18	0.02	–0.01	–1.9
P-value	0.000**	0.000**	0.017**	0.000**	0.017**	0.120	0.035*
Tilted vs. supine							

$N = 44$. The means of the diastolic measurements from the echocardiography is also presented.
**$P < 0.01$ and *$P < 0.05$ were considered significant.

the echocardiography e′ and the diastolic SCG measures are related to velocity of the diastolic relaxation. The SCG measures acceleration, the first derivative of velocity, in the early diastolic phase and e′ is a measure of the velocity of the mitral annulus in the filing phase of the diastole, and accordingly both the echocardiography variable e′ and the diastolic variables from the SCG are measures of velocity of the diastolic relaxation.

In a study by Mogelvang *et al.*,[7] the prognostic impact of the echocardiography variable e′ was investigated. A significant difference was seen in e′ when comparing the hypertension, diabetes and ischaemic heart disease (IHD) groups to the control group, thus indicating a decrease in the diastolic performance. This could indicate that SCG could potentially be utilized in a normal health evaluation to determine a decrease in the diastolic function, especially in patients with diabetes and hypertension who are at higher risk, thus detecting potential cardiovascular diseases.

Figure 1 illustrates that some of the SCG amplitudes are positively correlated with the echocardiography variables, and some are negatively correlated. The reasoning behind this is that the SCG amplitudes (C_d and E_d) are negative, since the peak is a result of inward acceleration.

Diastolic seismocardiography and cardiorespiratory fitness

In the study by Sørensen *et al.*,[13] the estimation of cardiorespiratory fitness as VO_2max with the SCG was investigated. The study by Sørensen *et al.* utilized the SCG to investigate the correlation between VO_2max and the timing and amplitudes of SCG fiducial points, the same fiducial points utilized in this study.[4] In the study by Sørensen *et al.*, a strong correlation between VO_2max and the diastolic AC peak-to-peak amplitude was found, which was the same as the C_d to D_d amplitude in the current study. This indicates that the SCG amplitude quantifications VO_2max relate to quantification of diastolic relaxation and thus filling efficacy of the LV.

Preload alteration of diastolic seismocardiography

Although a strong correlation was found between the SCG variables D_d and C_d to D_d with the echocardiography variable e′ in supine position, a lower correlation was found when the patient was in a tilted position (*Figure 1*), thus indicating that the D_d and C_d to D_d points might be less sensitive when a decrease in the preload occurs. This was further confirmed by *Table 1* where only the E_d amplitude was significantly altered by the tilting of the subjects. E_d was also the least correlated SCG amplitude with e′ during supine and tilt position. But when looking at the delta value between supine and tilt, it was the SCG measure that correlated best to e′. This indicates that E_d is a weak estimator of intersubject variability in e′, but a more sensitive parameter to track intravariability in e′. Therefore, E_d could be useful for monitoring changes, but not to estimate absolute values of e′.

The variable e′ is a measure of diastolic relaxation and dependents on several factors including myocardial compliance and preload.[14] However, current results indicated that the SCG amplitudes C_d and D_d are preload-independent measures of diastolic relaxation which could offer unique insight into myocardial compliance. A study from Hasan Shandhi *et al.*[15] showed that SCG timings correlated well with decrease in preload. Thus, confirming that some SCG measures are sensitive to decrease in preload.

Study limitations

A limitation of this study is the low number of subjects and its exploratory approach. The diastolic variables were measured shortly after the subjects were moved to a 30° tilt position, which could have resulted in the autonomic nerve system adjusting for the change in preload and therefore influencing the results.

The high correlations found in this study were both amplitude features. It is expected that amplitude features are dependent on placement of sensor, subcutaneous fat, and skin elasticity. Despite these potential limitations, a strong correlation was still found between the SCG amplitudes and the echocardiography variable e′. Future development to correct for this interaction could further improve the correlation.

The lack of consensus on annotation of SCG fiducial points as well as the high intersubjects' variation of the SCG morphology is a challenge to this type of study.[16] However, we find the intersubject variability of the diastolic SCG morphology relatively low compared with the intersubject variability of the systolic complex. As seen in the Supplementary Material online, a step valley (the C_d point) followed by a larger peak (the D_d point) can be identified in most subjects.

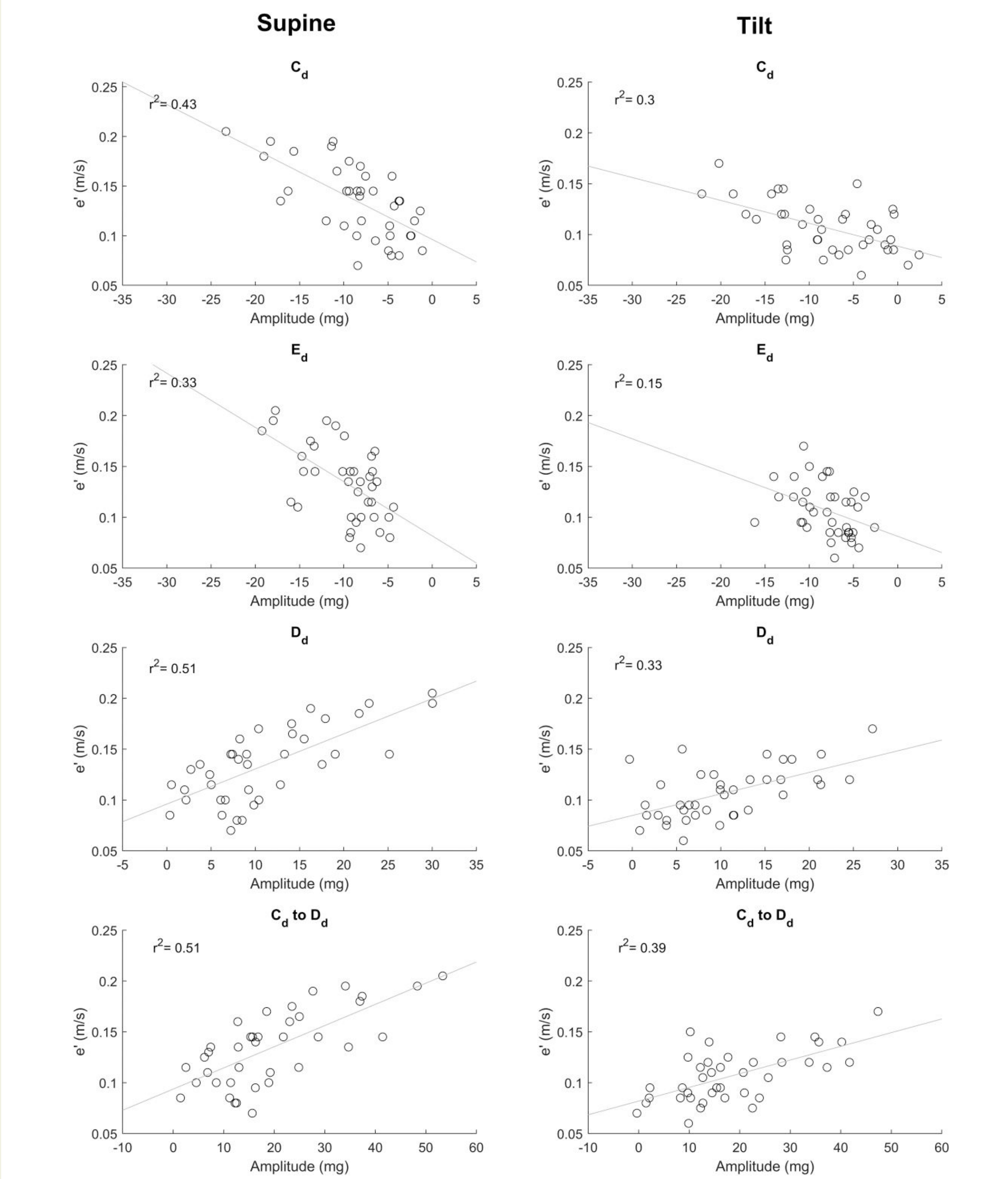


Figure 2 Correlation plots for e′ and the amplitudes from seismocardiography in tilted and supine position. mg, milligravity.

Conclusion

The diastolic SCG amplitudes D_d and C_d to D_d showed a significant correlation when compared with the echocardiography variable e′ in supine position. Only the E_d fiducial point was significantly altered by a 30° head-up tilt from supine position. This study indicates a potential value of utilizing the SCG in evaluation of the diastolic function.

Supplementary material

Supplementary material is available at *European Heart Journal – Digital Health* online.

Conflict of interest: None declared.

Lead author biography

Ahmad Agam is a 22 year old student of medicine from Denmark. He has a Bachelor of Medicine and is currently studying for his Master of Medicine. He has an interest in cardioogy, and is the lead author for the submitted paper.

Data availability

All data are incorporated into the article and its online supplementary material. The data underlying this article are available in the article and in its online supplementary material.

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