Noninvasive Monitoring of Cardiac Preload and Contractility by Heart Beat-Derived Mechanical Vibration on the Chest Wall in Guinea Pigs

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Abstract

Background
Myocardial motion produces compression waves that are transmitted to the surface of the chest and vibrate the chest wall. Piezoelectric transducers, which detect mechanical vibrations, may be useful for evaluating cardiac and/or breathing movements when the sensor is placed under an animal’s body.

Methods
We assessed heartbeat-related chest vibration signals (CVS) detected with a piezoelectric transducer in anesthetized guinea pigs while simultaneously monitoring the electrocardiogram, heart sounds, aortic pressure, and central venous pressure.

Results
CVS displayed characteristic features as the ventricle and/or atrium contracted and relaxed during cardiac cycles. A transient positive wave, which occurred approximately at the onset of the R wave on the electrocardiogram, was followed by a profound negative wave during systole. The negative wave peaked early in systole and then gradually returned. A small notch was observed at the second heart sound. A dome-shaped positive wave was observed during diastole that connected to the transient positive wave of the next cardiac cycle. In response to phlebotomy (blood volume, 15 ml/kg), the size of the dome-shaped positive wave decreased, whereas saline transfusion (20 ml/kg) increased the positive wave during diastole. Administration of isoproterenol markedly increased the transient positive wave at the onset of systole, whereas phenylephrine affected the transient positive wave only slightly.

Conclusions
Our findings suggest that CVS may be useful to identify cardiac cycles and to evaluate cardiovascular dynamics during changes in blood volume and/or cardiac contractility.

Keywords: Piezoelectric sensor, Chest vibration signal, Monitoring, Preload, Contractility

Citation: Adachi T, Ohba T, Fujisawa S, Ono K. Noninvasive monitoring of cardiac preload and contractility by heart beat-derived mechanical vibration on the chest wall in guinea pigs. J.ATAMIS 2016 1:15-19.

Introduction
Monitoring cardiovascular function in acutely ill patients in the emergency, perioperative, and intensive care periods is of paramount importance because hemodynamic instability and heart failure are two frequent causes of critical conditions. Evaluating the determinants of cardiovascular function, preload and afterload, and contractility, is also critical for making diagnostic and therapeutic decisions that improve patient prognosis.

Cardiovascular dynamics are assessed by vascular pressure measurement in a peripheral artery, central vein, or pulmonary artery, or with echocardiography and other recent devices, and electrocardiography (ECG). While advanced monitoring devices have improved acute care, measurements from these devices do not necessarily indicate intravascular volume status and/or contractility. For example, arterial pressure is influenced by both contractility of the left ventricle and afterload. Central venous pressure (CVP), traditionally used to assess fluid status, does not appear to be associated with intravascular volume, and its value
as a tool for guiding fluid resuscitation remains a matter of debate. Also, advanced technology, increased effort, invasiveness, and expense are ongoing issues with this technology. A simple, noninvasive and low-cost monitoring method is expected to lead to improved medical safety and reduced costs.

Seismocardiography (SCG) is a noninvasive technique that uses an accelerometer. The accelerometer measures mechanical vibrations that are generated by heart movement and transmitted to the chest wall, and the device is used to determine left ventricular (LV) systolic and diastolic function, myocardial contractility, or ischemia. The piezoelectric transducer that is part of the accelerometer is useful for detecting cardiac and/or breathing movements when the sensor is placed under the body of small animals or humans. The measurement is achieved by simply placing animals on the piezoelectric sensor and using an ideal high-pass filter to isolate heart sounds from the raw piezoelectric sensor signals. The signals contain mechanical vibration signals arising from the heart beat, i.e., contraction and relaxation of ventricles, blood ejection, and closing and opening of valves. These mechanical signals may change in response to changes in cardiovascular dynamics such as cardiac preload, contractility, and vascular resistance. Our aim was to determine whether the piezoelectric sensor could distinguish changes in cardiovascular dynamics with changing blood volume or administration of cardiovascular drugs.

**Methods**

**Animals and surgical procedure**

The protocols for animal experimentation described in this paper were previously approved by the Animal Research Committee, Akita University. All subsequent animal experiments adhered to the Regulations for Animal Experimentation of the University. Male guinea pigs weighing 350–450 g were anesthetized with 2.5–4% sevoflurane under spontaneous breathing. The jugular vein was cannulated to allow phlebotomy, saline infusion, and drug injection, and was connected to a pressure transducer to monitor CVP. The carotid artery was also cannulated to monitor arterial blood pressure (ABP). After vascular cannulation, anesthesia was maintained throughout the study with oxygen-mixed air containing 2% sevoflurane under spontaneous breathing.

**Detection and acquisition of chest vibration signals using the piezoelectric sensor**

Measurement of the vibrations induced on the chest surface by the heartbeat was achieved using a piezoelectric transducer sensor device (ATC-402, Unique Medical, Tokyo, Japan), as previously reported. Briefly, guinea pigs were placed on the device in a prone position with the chest at the center of the sensor (disk-shaped, 35 mm outer diameter, EE35A-30A batteries; FDK Corporation, Tokyo, Japan). The raw piezoelectric sensor signals, ECG, ABP, and CVP results were digitized with a converter (PowerLab 26T; ADInstruments, Colorado Springs, CO, USA) and stored on a laptop computer using LabChart 7 Pro (ADInstruments). The raw piezoelectric sensor signals include large bandwidth accelerometer vibrations derived from the chest surface; therefore, we refer to chest vibration signals (CVS) in the present study. The CVS were high-pass filtered with a cutoff frequency of 80 Hz to extract heart sound components of the cardiac cycle (CVS-HF). The CVS-HF data were stored simultaneously.

**Experimental procedure**

Sixteen guinea pigs were divided into three groups: phlebotomy group (n = 6), isoproterenol group (n = 5), and phenylephrine group (n = 5). In the phlebotomy group, a 15 ml/kg blood sample was gradually phlebotomized via the jugular vein, and the phlebotomized blood was then autotransfused into the animal. In the subsequent trials, 20 ml/kg saline and additional 20 ml/kg saline were cumulatively transfused. The interval between each intervention was approximately 6 minutes. The isoproterenol group received 0.1, 0.3, 1, 3, 10, and 30 µg/kg isoproterenol at 6-minute intervals. The phenylephrine group received 1, 3, 10, and 30 µg/kg phenylephrine after achieving steady cardiovascular parameters.

The CVS and CVS-HF data were evaluated 5 minutes after each intervention, except in the phenylephrine group where the CVS values were measured approximately 1 minute after phenylephrine administration. Data were collected from the parts which included little or no respiration artifact (Fig. 1A). Control values were obtained prior to the experimental procedures.

**Data analysis and statistics**

All data are presented as mean ± standard deviation (SD). Data were analyzed using repeated measures analysis of variance. Post-hoc testing was performed using Bonferroni correction. Differences were considered statistically significant at p < 0.05.

**Results**

**CVS waveforms**

Fig. 1A shows representative waveforms for the ECG, CVS, CVS-HF, AP, and CVP measurements during cardiac cycles (Fig. 1A). A large and transient positive wave, which occurred at the onset of the R wave on the ECG and corresponded to the first heart sound in the CVS-HF, was followed by a profound negative wave during systole. The negative wave peaked during systole and then gradually returned. A small notch corresponding to the second heart sound was seen and was followed by a dome-like shape.

![Figure 1. Simultaneous recordings of the electrical and mechanical heart activities.](image-url)

**A**: representative recordings of ECG (top), CVS, CVS-HF, AP, and CVP measurements during cardiac cycles (Fig. 1A). A large and transient positive wave and a dome-like shape indicate the first heart sound in the CVS-HF, was followed by a profound negative wave during systole. The negative wave peaked during systole and then gradually returned. A small notch corresponding to the second heart sound was seen and was followed by a dome-like shape.

**B**: parameter measurements; As indicates the amplitude of the transient systolic positive wave and Sed indicates the area under the last 20 ms of the end-diastolic positive wave. ECG, electrocardiogram; CVS, chest vibration signals; CVS-HF, high pass filtered chest vibration signals; AP, arterial pressure; CVP, central venous pressure.
Experiments (Fig. 1B).

The end-diastolic wave (Sed) is decreased by phlebotomy and increased by saline transfusion. CVS, chest vibration signals showed a marked increase in the transient systolic positive wave (As) and the area under the last 20 ms of the end-diastolic positive wave (Sed) in following systolic positive wave (As) and the area under the last 20 ms of the end-diastolic positive wave (Sed) in following systolic positive wave (As). The As/control ratio was 1.03 (SD, 0.05), 1.08 (SD, 0.05) and 1.48 (SD, 0.29), 1.72 (SD, 0.35), and 1.78 (SD, 0.15) following phlebotomy and returned to 1.27 (SD, 0.35), respectively. In contrast, CVP was not changed by phlebotomy, but significantly increased in response to saline infusion (Fig. 3B). A statistically significant correlation was observed between Sed/control ratio and CVP (n = 24, Pearson’s correlation test, Pearson’s r = 0.636, p = 0.001) (Fig. 3C).

Effects of changes in blood volume on CVS

CVS decreased in response to a decrease in blood volume (15 ml/kg phlebotomy); i.e., the As decrease was accompanied by a decrease in Sed. Following autotransfusion of the phlebotomized blood, both CVS and CVS-HF values recovered. However, subsequent transfusion of 20 ml/kg saline and an additional 20 ml/kg saline resulted in significant increases in Sed while As remained almost unchanged. Averaging the results of the six experiments, the Sed/control ratio decreased to 0.66 (SD, 0.15) following phlebotomy and returned to 1.13 (SD, 0.36) in response to autotransfusion. Infusion of 20 ml/kg saline and an additional 20 ml/kg saline increased the Sed/control ratio to 1.47 (SD, 0.26) and 1.72 (SD, 0.35), respectively. In contrast, CVP was not changed by phlebotomy, but significantly increased in response to saline infusion (Fig. 3B). A statistically significant correlation was observed between Sed/control ratio and CVP (n = 24, Pearson’s correlation test, Pearson’s r = 0.636, p = 0.001) (Fig. 3C).

Effects of changes in cardiac contractility on CVS

CVS waveforms in response to isoproterenol administration showed a marked increase in the transient systolic positive wave (Fig. 4). Quantitative evaluation revealed that isoproterenol increased the As/control ratio in a dose-dependent manner as follows: As/control ratio was 1.00 (SD, 0.04), 1.05 (SD, 0.09), 1.48 (SD, 0.29), 1.72 (SD, 0.24), and 1.78 (SD, 0.15) following administration of isoproterenol with 0.1, 0.3, 1, 3, and 10 µg/kg, respectively. APmean tended to decrease at > 1 µg/kg isoproterenol, although the results were not statistically significant (Fig. 5B). Heart rate increased in response to isoproterenol in a dose-dependent manner (Fig. 5C).

Effects of changes in afterload on CVS

Representative signal changes in response to phenylephrine administration are shown in Figure 6. In contrast to the effect of isoproterenol, the amplitude of the systolic positive wave changed only slightly. The As/control ratio was 1.03 (SD, 0.05), 1.08 (SD, 0.13), 1.06 (SD, 0.26), and 0.97 (SD, 0.35) with phenylephrine administration at 0.1, 0.3, 1, and 3 µg/kg, respectively (Fig. 7A), and there was no statistical significance. APmean increased significantly in response to phenylephrine whereas heart rate remained unchanged (Fig. 7B, C).

Discussion

The major findings of this study are the following. (1) Simplified detection of preload myocardial contractility is feasible in anesthetized guinea-pigs using CVS recorded with a piezoelectric sensor placed under the animals. (2) Discrimination between important cardiovascular functions is possible using this measurement technique. Sed decreased during hypovolemia and increased as a result of volume overload with little change in As. A significant increase in the As amplitude was detected only with increased myocardial contractility.

Noninvasive measurements of mechanical vibrations of the body in response to the heartbeat have been investigated for approximately 50 years. These include ballistocardiography, SCG, apexcardiography, radar SCG, and others. Ballistocardiography signals represent movements of the whole body in response to cardiac ejection of blood into the vasculature, and SCG corresponds to local vibrations of the chest wall associated with the heartbeat, blood flow, respiration, body movements, and so on. SCG is recorded from the surface of the body using accelerometers, and contains waves corresponding to atrial and ventricular contraction, LV filling, closing and opening of the atriocavitary and semilunar valves, and maximal acceleration in the aorta. The shapes of these waves provide information about the functional status of the heart, and therefore, many studies have used SCG to determine LV systolic and diastolic function, myocardial contractility, or to detect ischemia. In the present study, the mechanical vibration signals were detected simply by placing the animals on the piezoelectric sensor, and therefore, CVS depended on the contact pressure of the sensor and reflects the force perpendicular to the chest wall. We consider that CVS might be a valid substitute for one axis of accelerometers to monitor the SCG signal. In fact, waveforms were qualitatively similar between SCG and CVS. Piezoelectric sensors offer better performance than common accelerometers for frequencies higher.
that the signals obtained from the chest wall could be a simple alternative to evaluate cardiac preload.

The As amplitude increased markedly in response to increased cardiac contractility with isoproterenol, a beta-adrenergic agonist, accompanied by a decrease in the mean arterial pressure. This finding is similar to previous findings that peak myocardial vibration, which occurs during the isovolumic contraction phase, is an index of myocardial contractility. Also, Bombardini et al. have shown that dobutamine augmented transcutaneous acceleration signals measured on the human sternum. Gemignani et al. have demonstrated that the magnitude of acceleration signals correlated strongly with the maximum first derivative of the ventricular pressure. Therefore, we consider that As can be a substitute for the peak endocardial acceleration reported in the SCG measurement. This is supported by our finding that phenylephrine, an alpha-adrenergic agonist, did not change As, but increased APmax, APmin, and APmean. It seems likely that As is rarely affected by changes in peripheral vascular resistance.

**Limitations**

CVS contains heartbeat-related mechanical vibrations that are similar, but not identical, to SCG signals. SCG includes waves corresponding to atrial contraction, mitral valve closing, aortic valve opening, point of maximal acceleration in the aorta, aortic valve closure, mitral valve opening, and rapid LV filling; however, we were not able to identify the precise time location of the events during the cardiac cycle using CVS. In this study, the heartbeat-related mechanical vibrations were detected simply by placing the animals on the piezoelectric sensor with measurements made with the guinea pigs in the prone position. SCG studies are usually performed in humans in the supine position. The size of the sensor relative to the body is larger in our study than in most SCG studies. Also, the CVS waveforms were very sensitive to the position of the sensor; therefore, fine adjustment of the sensor position was required to obtain reliable CVS amplitudes. As a result, the different sensor, animals, and experimental conditions may have caused differences in waveforms between the CVS and SCG signals. It should also be noted that Sed and As are relative parameters, and do not directly indicate hemodynamic status such as hypovolemia, volume overload, or increased contractility. Also, the amount of phlebotomized blood (15 ml/kg) and transfused saline (20 ml/kg), as well as the drug doses were relatively high. Therefore, our results cannot be used to evaluate hemodynamic instability and heart failure, clinically. Further studies are required to quantify the parameters seen in physiological and pathophysiological ranges of loading conditions or contractility. It is also important to detect the precise time location of the events during the cardiac cycle, similar to SCG. We are developing algorithms to identify the time location by incorporating more advanced signal processing techniques.

**Conclusions**

Hemodynamic instability and heart failure are major causes of critical conditions. Detection and evaluation of cardiac contractility, preload, and afterload is critical to make a diagnosis and to establish therapeutic strategies that can improve patient

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**Figure. 4.** Representative recording of CVS and other parameters in response to isoproterenol. After recording the control measurements, 0.1, 0.3, 1, 3, 10, and 30 µg/kg isoproterenol was administrated at 6-minute intervals. The transient systolic positive wave (As) that occurred at the onset of the R wave on the ECG and corresponded to the first heart sound in the CVS-HF, was increased by isoproterenol in a dose-dependent manner.

Sed decreased during phlebotomy and returned towards control values when the phlebotomized blood was autotransfused, and increased in response to saline loading. In the present study, Sed was defined as the area under a small positive wave just before the R wave on the ECG. We speculate that the wave reflects the end-diastolic volume of the left ventricle, resulting from filling of the left ventricle as well as the atrial kick. Decreased blood volume reduces cardiac preload, leading to a decrease in Sed, and the opposite is also true. CVP showed almost similar behavior during increases in blood volume, but no change was seen with decreases in blood volume. Guidelines from the European Society of Anesthesiology regarding management of severe perioperative bleeding recommend against CVP as the only variable to optimize cardiac preload during severe bleeding and recommend also including noninvasive measurement techniques. This recommendation is consistent with the view that CVP is not a sensitive indicator of circulating blood volume, although CVP has been used most often as a clinical marker of volume status. Tavakolian et al. (2014) showed that pre-ejection period and left ventricular ejection time (LVET), derived from SCG, were more sensitive detectors of early-stage hemorrhage compared with pulse pressure, heart rate, and the amplitude features extracted from SCG. It is interesting to note that Sed represents the end-diastolic volume in the present study while LVET and pre-ejection period/LVET correlate with stroke volume in the study by Tavakolian et al. (2014). These findings indicate that the signals obtained from the chest wall could be a simple alternative to evaluate cardiac preload.

**Figure. 5.** Statistical analysis of isoproterenol administration. Dose-dependent effects of isoproterenol on A (A), APmean (B) and HR (C) are shown. Data are presented as mean ± SD. Statistical significance is shown as *: p < 0.05 and **: p < 0.01. As, amplitude of the transient systolic positive wave; mAP, mean arterial blood pressure; HR, heart rate.
hemodynamics. We conclude that CVS may be useful for noninvasive and low-cost monitoring of hemodynamic status and to help estimate preload and contractility of the heart.

Our results showed that CVS changes with cardiac cycles and may be useful to evaluate cardiac dynamics during changes in cardiac preload and cardiac contractility. CVS recording, which is noninvasive, simple, and low-cost, could be used for continuous monitoring of cardiovascular dynamics, in future.

Declarations of Interest

The authors declare no conflicts of interest.

Acknowledgements

The authors state that they abide by the statement of ethical publishing of the Journal of Advanced Therapies and Medical Innovation Sciences. This work was supported by Grants-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan to Takeshi Adachi [#26861220] and Kyoichi Ono [#22500363, #23136501].

Figure 6. Representative recording of CVS and other parameters in response to phenylephrine. After recording control values, 1, 3, 10, and 30 µg/kg phenylephrine was cumulatively administrated after obtaining steady state cardiovascular parameters. The amplitude of the transient systolic positive wave (As) was barely changed, while APmean was significantly increased by phenylephrine.

Figure 7. Statistical analysis of phenylephrine administration. Dose-dependent effects of phenylephrine on A s (A), APmean (B) and HR (C) are shown. Data are presented as mean ± SD. Statistical significance is shown as *: p < 0.05 and **: p < 0.01. As, amplitude of the transient systolic positive wave; mAP, mean arterial pressure; HR, heart rate.