Identification of Location Specific Feature Points in a Cardiac Cycle Using a Novel Seismocardiogram Spectrum System

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***Abstract*—Seismocardiogram (SCG) or mechanocardiography is a noninvasive cardiac diagnostic method; however, previous studies used only a single sensor to detect cardiac mechanical activities that will not be able to identify location-specific feature points in a cardiac cycle corresponding to the four valvular auscultation locations. In this study, a multichannel SCG spectrum measurement system was proposed and examined for cardiac activity monitoring to overcome problems like, position dependency, time delay, and signal attenuation, occurring in traditional single-channel SCG systems. ECG and multichannel SCG signals were simultaneously recorded in 25 healthy subjects. Cardiac echocardiography was conducted at the same time. SCG traces were analyzed and compared with echocardiographic images for feature point identification. Fifteen feature points were identified in the corresponding SCG traces. Among them, six feature points, including left ventricular lateral wall contraction peak velocity, septal wall contraction peak velocity, transaortic peak flow, transpulmonary peak flow, transmitral ventricular relaxation flow, and transmitral atrial contraction flow were identified. These new feature points were not observed in previous studies because the single-channel SCG could not detect the location-specific signals from other locations due to time delay and signal attenuation. As the results, the multichannel SCG spectrum measurement system can record the corresponding cardiac mechanical activities with location-specific SCG signals and six new feature points were identified with the system. This new modality may help clinical diagnoses of valvular heart diseases and heart failure in the future.**

***Index Terms*—Cardiac diagnostic method, heart failure, seimocardiography, valvular heart diseases.**

Manuscript received April 25, 2016; revised August 8, 2016 and September 26, 2016; accepted October 19, 2016. Date of publication October 25, 2016; date of current version March 5, 2018. This work was supported in part by the Ministry of Science and Technology, Taiwan, R.O.C., under Grant MOST 104-2627-E-182-001, Grant MOST104-2754-8-182-001, Grant MOST 103-2221-E-182-003, and Grant MOST 104-2221-E-182-013, as well as CGU fund BMRPC50 and BMRP138. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. *(Corresponding author: M.-Y. Lee.)*

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Digital Object Identifier 10.1109/JBHI.2016.2620496

I. Introduction

CARDIOVASCULAR diseases are the leading causes of death in the world [1], [2]. The mortality rate of cardiovascular diseases is about 230–1700 per 100,000 populations, accounting for 24–47% of total death. The detection and diagnosis of cardiovascular diseases rely on a number of clinical modalities, including electrocardiogram (ECG), echocardiography, computerized tomography scan, magnetic resonance imaging, and nuclear myocardial perfusion scan. ECG plays an important role in the initial diagnosis and ambulatory monitoring of cardiovascular diseases. However, ECG is composed of the summation of cardiac electric signals but does not represent cardiac mechanical activities. Echocardiography is a better modality to exam cardiac function and anatomy. However, in most medical institutes, echocardiography exam is costly, time consuming, and usually not immediately available.

In 1939, Starr and Wood recorded the traces of cardiac mechanical activities on chest surface, and the recording modality was named as ballistocardiogram (BCG) [3]. They also reported

that the smaller amplitude of BCG was associated with shorter survival in patients with heart diseases [4]. Although limited information about cardiac function was revealed, the relationship between cardiac function and the amplitude of BCG was a reasonable explanation. Salerno *et al.* recorded cardiac vibration waves by using an accelerometer attached to the sternum, and the modality was named as seismocardiography (SCG) [5], [6]. The authors compared SCG traces and Doppler echocardiography to identify several feature points: Mitral valve opening (MO), mitral valve close (MC), aortic valve opening (AO), aortic valve close (AC), and cardiac rapid ejection (RE). They also showed amplitude change in patients received coronary angiography followed by nitroglycerin injection or percutaneous transluminal angioplasty. SCG had been investigated to optimize atrioventricular (AV) and ventricular-to-ventricular delays in patients with biventricular pacemaker (cardiac resynchronization therapy) implantation [7]. The results support the recording of cardiac mechanical signal for clinical diagnoses of heart diseases. Accordingly, a clinical modality was also developed for the recording of SCG signals. Later, Crow *et al.* revealed additional four feature points including isovolumic movement (IM), isotonic contraction (IC), peak of rapid diastolic filling (RF), and peak of atrial systolic (AS) acquired at the tricuspid valve site [8]. Recently, the cardiac mechanical signal recording has become an emerging method because the development of microelectromechanical systems (MEMS)-based accelerometers make miniaturization of BCG/SCG measurement feasible and ECG-based systems cannot be shrunk into the scale as integrated circuit (IC) technology [9]. The recent advances of BCG/SCG technologies were also detailed reviewed in [10] and the authors suggested that the physiological meanings of the signals must be studied and discussed further.

However, most investigators recorded BCG or SCG signals using a single accelerometer placed on the sternum, where summation of cardiac vibration was acquired. The single-channel recording method does not define the exact sources of signals and is not able to differentiate the location whenever an abnormal finding is detected. Therefore, Zanetti and Tavakolian suggested multichannel SCG to record complete signals from a whole heart in a review article [11]. It is better for the detection of cardiac diseases with multichannel signal acquisition, which may partly reduce the influence of signal attenuation and timing delay in the single-channel method. Moreover, no research article about the multichannel SCG had been published so far.

Sarlabous *et al.* first introduced mechanocardiography (MCG) as an alternative name of SCG or BCG to represent the signal recording of cardiac mechanical activities [12]. Although MCG is more meaningful and precise to represent the mechanical vibrational signals from cardiac activities, the term SCG is used to avoid confusion in the readers. In this study, we sought to develop a multichannel SCG technique to record location-specific signals and to identify more feature points as compared to the single-channel SCG. Cardiac mechanical vibrations are generated by valvular motion, blood flow, myocardial contraction, and relaxation. Four accelerometers were placed at the clinically four valve auscultation sites in this study. We hypothesized that the multichannel SCG system could record location-specific waveforms, and the cardiac mechanical characteristics could be extracted from the location-specific traces to discover new feature points. The analysis of SCG and Doppler echocardiography in 25 healthy subjects was conducted to identify the new feature points and to determine the timing sequence of these new feature points.

II. Material and Methods

This study was reviewed and approved by the Institutional Review Board (IRB) of the Chang Gung Memorial Hospital. Twenty-five healthy subjects, 13 males and 12 females, with no known cardiac conditions were enrolled in this study. Written and informed consents were obtained from these subjects. The ECG and multichannel SCG signals were simultaneously recorded and compared with echocardiographic images in the proposed system framework.

A. System Framework—SCG, ECG, and Echocardiography

The multichannel accelerometer-based SCG spectrum measurement system synchronized with echocardiography was proposed to obtain location-specific SCG waveforms and to extract new SCG feature points (see Fig. 1). The self-built system included three subsystems: the multichannel SCG measurement, the three-lead ECG recording, and the synchronous data collection subsystems. The multichannel SCG measurement system was composed of multiple accelerometer sensing modules and an embedded microcontroller system board. The accelerometer sensing modules were placed at four valvular auscultation sites for SCG signal acquisition and were connected to the embedded microcontroller system board for data processing and conversion. The analog SCG and ECG signals were amplified, filtered, and transferred to the host computer through the synchronous data collection subsystem for data processing, storage, and display.

All the accelerometer sensing modules were electrically isolated to avoid electrical interference. The core of the sensing modules was the accelerometer (LIS331DLH, from STMicroelectronics, Geneva, Switzerland), which was set for a sensing range of ± 2 g at a 12-bit digital data resolution and a sensitivity of 1 mg ($1\ \text{mg} = 2^{-10}$ g, i.e., $1/1024$ g, where g is the gravitational acceleration). The embedded microcontroller system board in the multichannel SCG measurement subsystem was equipped with the microcontroller (ADuC7020, from Analog Devices Inc., Cambridge, MA, USA), which communicated with multiple accelerometer sensing modules using an inter-IC (I^2C) interface. Data were collected by the microcontroller, processed, and converted to analog signals with the built-in digital-to-analog converters, and subsequently connected to the synchronous data collection subsystem (PowerLab $16/35$, from AD Instruments, Dunedin, New Zealand). At the meantime, the output analog signals from the bio amplifier of the three-lead ECG signals were also connected to the synchronous data collection subsystem. As the results, all the SCG and ECG signals were sampled at a frequency of

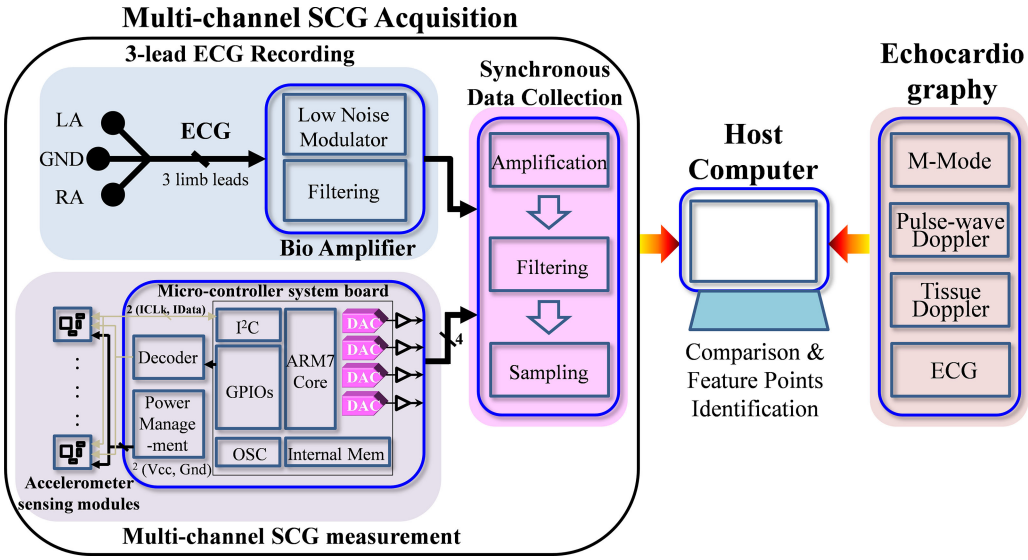

Fig. 1. System framework of the proposed multichannel accelerometer-based SCG spectrum measurement system and echocardiography.

400 Hz in the data collection subsystem and the synchronized data consisting of multichannel SCG and ECG signals were transmitted to the host computer. An echocardiographic system (GE Healthcare, VIVID 7, Little Chalfont, U.K.) with a 2.5-MHz phased-array multifrequency transducer (M4S) was used. The M-mode and Doppler images from echocardiographic system were recorded and synchronized with ECG signal. The timing of valvular opening and closing was identified with m-mode echocardiographic images. The timing of peak blood flow through each valve was identified using pulse-wave Doppler images. Tissue Doppler was used for left ventricular wall motion of the six segments.

The whole data processing flow is very similar with the work described in [13], where the collected raw signals went through denoising process and then features were extracted before signal classification. The results present in this paper are the novel findings in multichannel SCG spectrum system during the feature extraction with the proposed framework.

B. Testing Procedures

Simultaneous SCG and ECG signals were acquired from 25 healthy subjects at supine position. The schematic diagram of sensor placement is shown in Fig. 2(a). Four SCG sensors were placed at the heart auscultation sites for mitral, tricuspid, aortic, and pulmonary valves. Three ECG leads were placed at right and left arms and the left leg. We chose lead I ECG traces as the standard lead for data analysis and comparison. Heart and respiratory rates were checked to make sure that the subjects were in stable and resting condition during data acquisition. Each subject received three sessions of 5-min data acquisition with a 5-min break between sessions.

Echocardiography was performed immediately after the SCG and ECG recording by a single echocardiographer. Lead I ECG was recorded with three electrodes placed at the same locations as in the SCG testing. Standard parasternal long, parasternal short, apical four chamber, apical two chamber, and apical long views were performed for all image recording and measurements. The timing of valvular opening and closing was identified with m-mode echocardiographic images. The timing of peak blood flow through each valve was identified using pulse-wave Doppler images. Tissue Doppler was used for left ventricular wall motion of the six segments. After the images were obtained, cine loops were transferred to a computer for the offline analysis using the GE EchoPAC dimension system. Fig. 2(b) shows the location-specific SCG traces and echocardiography images with synchronized ECG signals, for new feature point identification.

C. Data Analysis

Similar methodology as in [8] for data analysis was adopted to find the relationship between SCG traces and echocardiography images was adopted in this research. The acquired SCG traces and echocardiographic images were synchronized and aligned on the R-peak of ECG signals from both systems for at least three consecutive similar R–R intervals of the lead I traces. By simultaneously comparing SCG traces and echocardiography images, the onset timings of the cardiac activity events identified in echocardiography images by an experienced cardiologist are then mapped to the multichannel SCG traces acquired from each valvular site. As the results, feature points of SCG traces representing corresponding cardiac events could be extracted. This kind of visual inspection of echo images are also well accepted in clinical practice. Continuous variables with normal distribution were expressed as the mean $\pm$ standard deviation, and categorical variables were expressed as number (percentage).

III. Results

Table I shows the characteristics of the 25 healthy subjects in this study. Both male and female subjects are included with age range of 21–28 in males and 20–40 in females. The subjects did not have history of valvular heart diseases, coronary artery diseases, congenital heart diseases, cardiomyopathy, major systemic diseases, or taking regular medications.

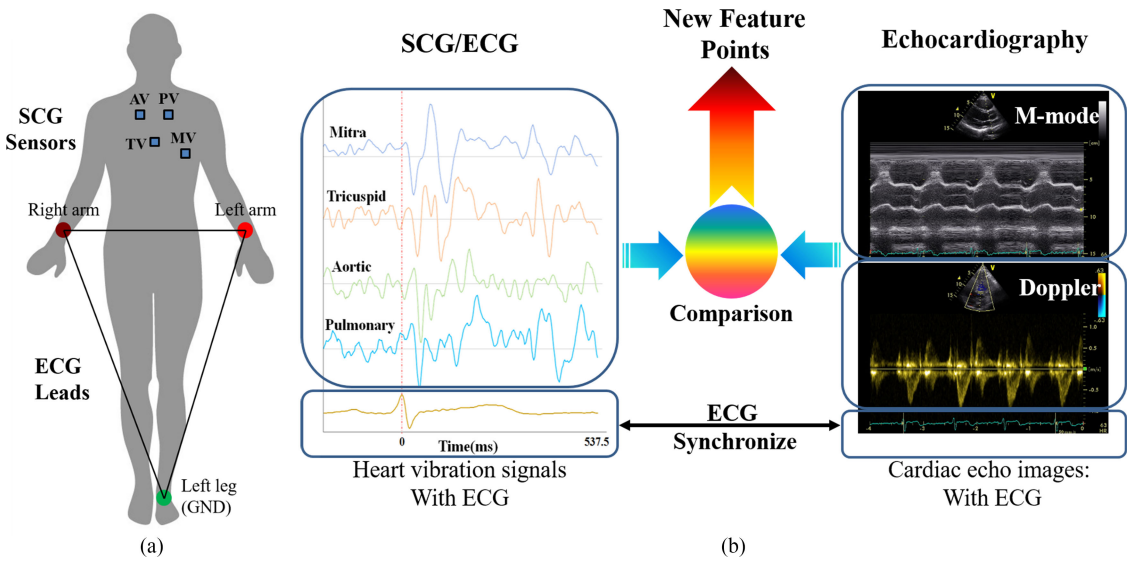

Fig. 2. (a) Locations of SCG sensor placement. (b) Synchronized SCG traces, echocardiographic images, ECGs, for feature point identification.

TABLE I
CHARACTERISTICS OF TEST SUBJECTS

Gender group	Number of subjects	Age	Height (m)	Weight (kg)	BMI
Male	13	21–28	1.65–1.8	54–101	18.7–32.6
Female	12	20–40	1.54–1.69	45–78	18.97–29

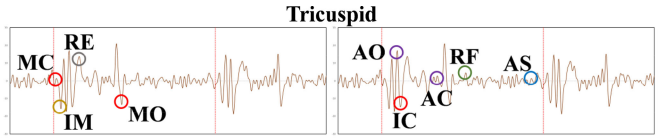

Fig. 3. Nine SCG feature points reported previously in Tricuspid channel.

A. SCG Feature Points Identified Previously

All feature points reported previously were also observed using the proposed multichannel SCG measurement system. As shown in Fig. 3, the nine feature points identified previously by Crow [8], including MC, IM, AO, IC, AC, MO, RE, peak of RF, and peak of AS can be identified in the SCG traces acquired at the conventional tricuspid valve site.

B. New SCG Feature Points

In this study, six new feature points that have never been investigated in previous BCG/SCG/MCG research works were identified at the corresponding valvular locations (see Fig. 4): Left ventricular lateral wall contraction peak velocity (LCV), septal wall contraction peak velocity (SCV), transaortic valvular peak flow (AF), transpulmonary peak flow (PF), transmitral atrial contraction peak flow (MF_A), and transmitral ventricular relaxation peak flow (MF_E). The naming rules for these six new feature points were introduced below: The first letter indicates the source of the cardiac activities, (e.g., "A" stands for transaortic valve, "L" stands for left ventricular lateral wall, "M" stands for transmitral valve, "P" stands for transpulmonary valve, and "S" stands for septal wall); the second and/or third letters indicate the types of cardiac activities, (e.g., "F" stands for peak blood flow and "CV" stands for contraction peak myocardial velocity). The detailed description of each feature point is provided as follows.

1) LCV Feature Point: A left ventricular LCV feature point was identified by matching the mitral valve SCG traces with the tissue Doppler images of the left ventricular lateral wall, as shown in Fig. 4(a). The LCV feature point represents the instant at which left ventricular lateral wall contracts at peak velocity. It is compatible with the physiology that left ventricular lateral wall contraction at peak velocity, pushing the left ventricular apex toward the chest wall, which is the acquisition location of this SCG recording site.

2) SCV Feature Point: An interventricular SCV feature point could be identified by matching the tricuspid valve SCG traces with the tissue Doppler echocardiography images of the interventricular septal wall, as shown in Fig. 4(b). The tricuspid valve acquisition site was used because the interventricular septum is beneath the tricuspid valve SCG acquisition site. The SCV feature point represents the instant at which the septal wall contracts at the peak velocity. It is compatible with the physiology during cardiac systole, at which the interventricular septum moves toward posterior wall, making a downward shift of the chest wall. The time difference between SCV and LCV provide the information about synchronicity of LV contraction, and the relationship between SCV and LCV may be applied clinically to evaluate cardiac dyssynchrony.

3) AF Feature Point: AF feature point was identified by matching the aortic valve SCG traces with the pulse-wave Doppler echocardiographic images of the aortic valve [see Fig. 4(c)]. The AF feature point represents an upstroke transaor-

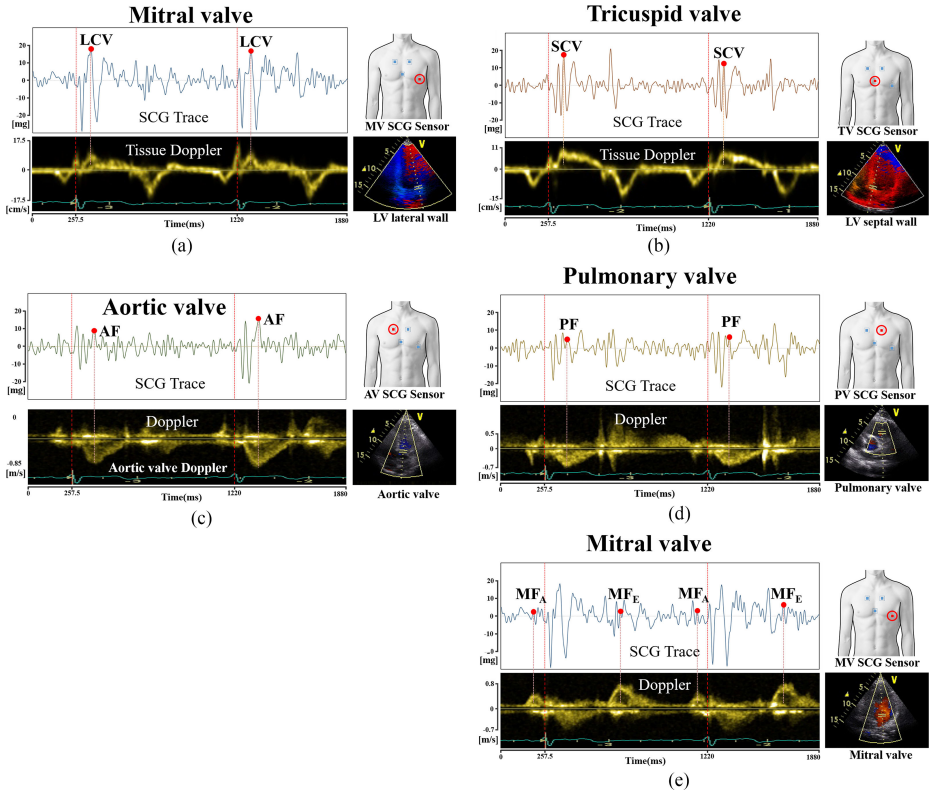

Fig. 4. Six new feature points identified. (a) LCV feature point, (b) SCV feature point, (c) AF feature point, (d) PF feature point, and (e) MF_E feature point and MF_A feature point.

tic blood flow following AO in the aortic valve SCG trace. The pattern is compatible with the physiology of rapid blood flow ejection through the aortic valve to the aorta. Interestingly, the AF feature point was a downward notch in the mitral valve SCG traces, and the pattern is also compatible with volume reduction of the left ventricle at the moment of rapid blood flow ejection.

4) PF Feature Point: Similar to the AF feature point, the PF feature point was identified by matching the pulmonary valve SCG trace with the pulsewave Doppler echocardiographic images, as shown in Fig. 4(d). The PF feature point represents an upstroke of transpulmonary blood flow following pulmonary valve opening. The upstroke pattern is compatible with the physiology of rapid blood flow ejection through the pulmonary valve to the lung.

5) MF_A and MF_E Feature Points: The MF_E and MF_A feature points were identified by matching the mitral valve SCG trace with the pulse wave Doppler echocardiographic images. As shown in Fig. 4(e), these two upstrokes on the SCG traces are compatible with the physiology of mitral inflow, which pushes the left ventricular apex toward the chest wall, where the mitral valve SCG acquisition site is located.

C. Timing of the New Feature Points

Similar to ECG parameters, such as PR interval, QRS duration and QT interval, timing of the feature points may vary beat by beat and subject by subject. However, the normal ranges of the feature point timing events may be useful for the clinical diagnosis. In this study, the timing of each feature point was defined as time lag from the peak of R wave of ECG in each cardiac cycle. The values were derived from ten consecutive beats in each subject. Table II shows the summarized results (average and standard deviation of the onset timing from R-peak) and Fig. 5 shows the sequence of timing of these new feature points in a cardiac cycle. The timing of AF and PF are very close to each other. Among the test subjects, some subjects have AF occurring before PF and others have PF occurring before AF. This is because that the timings of transaortic valve and transpulmonary valve flow are very close and are variable physiologically in each subject, their sequence depends on several factors, such as intrinsic heart conduction (the presence of bundle branch block), the presence of valvular heart diseases, the presence of pulmonary hypertension, or respiratory cycles (inspiration or expiration). Because of the similarity in timing, we defined the AF and PF feature points in aortic and pulmonary

TABLE II
TIMING OF SIX NEW FEATURE POINTS

Subject group	ΔT (Event_Time–R_peak) (ms)					
	LCV (MV)	SCV (TV)	AF (AV)	PF (PV)	MF_E (MV)	MF_A (MV)
Male	73.0 ± 23	92.0 ± 5.3	128.0 ± 9.3	126.0 ± 8.1	479.0 ± 53.8	885.0 ± 105.7
Female	73.0 ± 11.8	92.0 ± 10.1	130.0 ± 8.2	130.0 ± 10.2	565.0 ± 55.1	821.0 ± 102.5
Δ	0%	0%	–1.56%	–3.17%	–17.9%	7.23%

Δ: Percentage of differences between genders $((\text{Male} - \text{Female})/\text{Male} * 100)$.

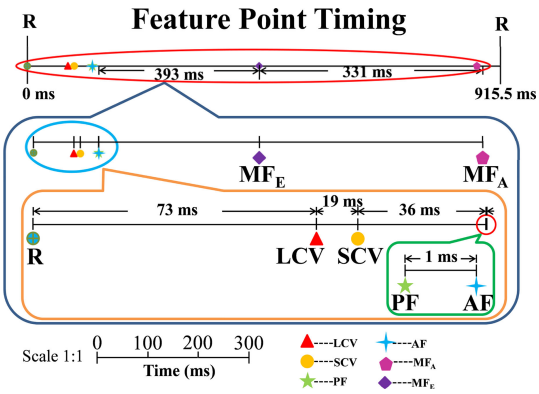

Fig. 5. Timing of six new feature points.

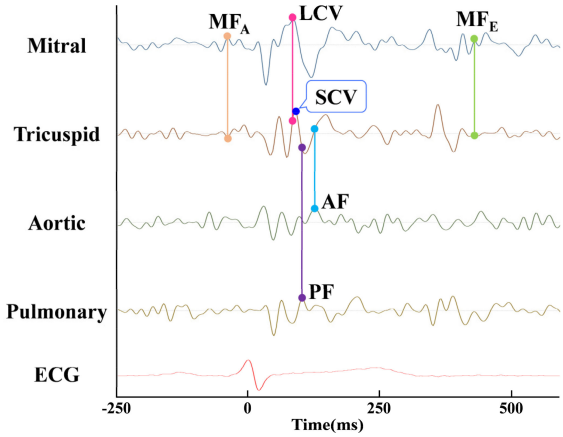

Fig. 6. Matching the new feature points to tricuspid valve SCG.

TABLE III
DIFFERENCES BETWEEN SCG AND ECHOIDENTIFIED FEATURE POINTS IN CARDIO CYCLE (ms)

Feature point	Mean	SD
LCV	–1.4	2.6
SCV	–1.7	4.6
AF	–1.1	3.6
PF	–1.1	3.2
MF_A	9.3	22
MF_E	2.8	22

sites, respectively, by matching the results of echocardiography and SCG.

In Table II, significant difference (–17.9%) of the MF_E feature point timing between male and female subject groups is also observed. This is because that the feature point MF_E is related to transmitral valve flow of left ventricular relaxation, following ventricular contraction. The timing of transmitral valve relaxation is directly linked to QT interval, which is associated with action potential duration in cardiomyocytes [14]. In previous studies, women have longer QT interval [15] and action potential duration is also longer in female animals [16], [17]. The findings indicate that female subjects have a longer systolic duration and later relaxation, leading to the later MF_E timing.

The standard deviations shown in Table II represent the inter-subject variability of the feature points identified in this paper. Larger standard deviations on some feature points mean that they are having wider range of the onset timing among different subjects. However, the onset timing of these feature points are with less variation, i.e., smaller standard deviation, on the same subject, which are not shown in this table.

In addition, similar methodology described as in [8] to measure the difference in the SCG- and ultrasound-identified feature points in the cardiac cycle was adopted. The differences were computed by subtracting the timing of the SCG feature point from the echo point. The mean and standard deviation of the differences are analyzed and shown in Table III. Negative value means that the SCG feature point occurred later than the echo-identified feature point. Differences were referenced to R point in ECG wave and were determined by subtracting R to SCG time from R to echo.

D. Pattern Variation of Feature Points

In this study, we observed timing or pattern variation of feature points among different SCG recording sites. The variation makes the identification of a feature point more difficult with a single SCG recording site, and this is probably the reason that these new feature points had not been identified in previous studies yet. We tried to look for the same pattern by matching the most similar peak or trough in conventional SCG traces, which were usually the tricuspid valve site, since the previous studies acquired SCG signals using a single accelerometer attached to middle sternum only. Fig. 6 shows the association of these feature points to the conventional SCG recording site (the tricuspid valve site). Significant location-specific pattern differences could be seen in the multichannel SCG traces: MF_A and MF_E feature points presented with prominent upstrokes in the mitral valve SCG trace but were obscure in the tricuspid valve SCG trace; AF and PF feature points presented with both upstrokes in the aortic and pulmonary SCG traces, respectively, but the tricuspid valve SCG trace showed a negative notch at that moment.

The reported six new feature points were identified through the visualized comparison with echocardiography images and SCG spectrums by synchronously matching with ECG signals. Also, these feature points are first time reported and identified with the proposed new multichannel SCG systems, hence, there is no benchmark to compare with. In this paper, the main purpose is to report the six new feature points found with the proposed multichannel SCG system. The comparison of the accuracy of the nine feature points identified in single-channel SCG measurements and multichannel SCG system will be discussed in the following articles.

IV. DISCUSSION

The major finding in this study is the new feature points identified using the multichannel SCG method and the location-specific SCG patterns. Six new feature points (LVC, SCV, AF, PF, MF_E, and MF_A) were identified by analyzing the acquired

SCG signals and the corresponding echocardiographic Doppler (including tissue Doppler) images. These feature points were not obviously visible in the conventional single-channel sternal SCG. The multichannel SCG analyses also showed pattern differences of the feature points between the corresponding sites and the conventional sternal site.

A. Advantages of Multichannel SCG

SCGs are the acceleration signals generated in cardiac cycles, consisting of valve opening or closing, blood flow, and myocardial motion. Some (but not all) of the vibrations are presented as heart sounds and can be detected by a stethoscope [18]. Multichannel SCG system records the underneath cardiac activities with better accuracy, because shorter the distance from the cardiac valve auscultation site, less the signal attenuation. Using the new multichannel SCG technique, the specific cardiac motion generated by the corresponding heart chambers, valves, or blood flow can be detected more accurately. The location-specific pattern differences of the feature points help identify the signal source, and the multichannel SCG may be applicable in clinical diagnosis of cardiac diseases, such as valvular heart diseases, heart failure, and ventricular dyssynchrony.

Previous studies used a single accelerometer on sternum, in conjunction with ECG, phonocardiogram, or echocardiogram, for signal acquisition [19], [20]. In this study, signals were acquired at four cardiac valve corresponding sites, and the multichannel SCG recording may be considered as a SCG spectrum. The idea of SCG spectrum is actually similar to ocean monitoring using buoy stations, and a single buoy station can only detect the nearby signals (such as levels of water). Compared with previous studies in which signals of a single spot were acquired, multichannel SCG can record more details of each part of a heart, such as differential feature point signals of each particular sites and their time delay. Moreover, the system can detect more location-specific motion of each valve or chamber instead of picking up the composite vibration signals of a whole heart in the conventional sternal SCG. A single-channel SCG system acquires only vibration over time, and therefore, the signals are composed of two-dimensional information. On the other hand, a SCG spectrum contains the vibration amplitude over time of the 2-D chest surface, representing 4-D information of cardiac activities. For example, the upstroke pattern of AF feature point is compatible with the physiology of rapid blood flow through the aortic valve to the aorta. Using the multichannel SCG system, an upright signal can be detected in the aortic valve feature point; however, at the moment, there was no significant transition in the tricuspid valve SCG waveform. The results indicate that SCG traces represent location-specific cardiac activities.

B. Clinical Implication

Cardiovascular diseases are the top leading cause of death in United States and Canada in the past decades, accounting for about 30% of annual mortality [21]. Successful treatment of cardiovascular diseases depends on accurate diagnoses and early treatment. The most commonly available clinical cardiac diagnostic tool is ECG, which provides important information for diagnosis of myocardial ischemia, infarction, and arrhythmias. Basically, ECG reveals cardiac electrical activities rather than the information of cardiac contractile function or valvular motion. For now, the diagnoses of cardiac contractility dysfunction and valvular diseases usually require other diagnostic tools, such as echocardiography. However, echocardiography is usually costly and labor consuming, requires both subspecial personnel and expensive equipment, and is not immediately available in most medical institutes. The development of a cheaper and easily available diagnostic tool to detect cardiac mechanical activities may help make prompt diagnoses, especially for inpatient and emergency departments. The concept of SCG spectrum is proposed and the acquired signals are location specific. For example, in this study, the transaortic valve flow signal was very different in the signals from mitral and aortic sites, indicating that the recording sites are important. The new technique might make the clinical diagnosis of specific diseases possible in the future.

C. Limitations

We placed only four SCG sensors at the cardiac valve auscultation sites, and signals originated from other parts of a heart might be missing, such as left ventricular anterior and posterior walls. More detail signal acquisition may be required using an SCG sensor array.

V. Conclusion

In this study, six new feature points, i.e., LCV, SCV, AF, PF, $\mathrm{MF_E}$, and $\mathrm{MF_A}$ of cardiac activity events were identified with the proposed multichannel SCG spectrum measurement system. The multichannel SCG measurement system, forming a SCG spectrum, provides the measurement of location-specific vibration signals originated from cardiac activities. The system may avoid time delay and signal attenuation, and hence, it can detect more accurate and more detailed feature points. The proposed multichannel SCG measurement system is a promising technology for cardiac mechanical signal recording, and, in conjunction with ECG, which records electrical cardiac signals, may become an important diagnostic tool to evaluate cardiac contractility and valvular function. At present, this research is in IRB phase. Once enough data are collected from normal and patient subjects in IRB experiments, the system will be ready and available for clinical use.

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