

Non-Contact Cardiac Activity Monitoring using Pulsed Laser Vibrometer

¹Chen Chia WANG, ¹Sudhir TRIVEDI, ¹Susan KUTCHER,
²Ponciano RODRIGUEZ, ¹Feng JIN, ³V. SWAMINATHAN,
³Frank WALTERS, and ⁴Narasimha S. PRASAD

¹Brimrose Corporation, 7720 Belair Road, Baltimore, Maryland 21236, USA

²INAOE, A.P. 216, Puebla 72000, Mexico

³US Army, RDECOM-ARDEC, Picatinny, NJ 07806, USA

⁴NASA Langley Research Center, Mail Stop 468, Hampton, VA 23681, USA

¹Tel.: 1-410-472-7070

¹E-mail: ccwang@brimrose.com

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Abstract: We demonstrate experimentally the detection of detailed human cardiac mechanical activity in a remote, non-contacting, and non-ionizing manner using a pulsed laser vibrometer. The highly sensitive pulsed laser vibrometer allows the detection of the temporally-phased mechanical events occurring in individual cardiac cycles even from the surface of clothing-covered extremities of the subjects. Fine structures of the detected cardiac traces are identified with their meanings assigned and corroborated using accelerometer and electrocardiogram measurements obtained concurrently with the pulsed laser vibrometer studies. Copyright © 2014 IFSA Publishing, S. L.

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1. Introduction

The human heart plays a critical role in ensuring the survival and well-being of its host by providing the mechanical work needed to circulate nutrients, oxygen, and chemicals to various parts of the human body while transporting wastes to the designated organs where they can be secreted. Successful mechanical operation of the heart requires its various chambers and valves to operate in a well-controlled, concerted manner with relatively precise timing sequences. Significant timing errors or inaction of even a small portion of the heart can have grave health consequences. For example, the rapid and

incoherent contraction of the atria identified as atrial fibrillation can lead to debilitating stroke in a patient [1]. Information related to the mechanical operation of the human heart under varying stress conditions can also offer invaluable insight into the health conditions of the host person.

One finds abundant literature on technologies, both contact [2-4] and non-contact in nature [5-8], that offer information related to the mechanical workings of the human heart. Most of these technologies tend to focus their investigation over a person's chest or specific areas of the body like the carotid where physical impacts from the heartbeat are the most profound. While logical and convenient, such accessibility is not guaranteed in all situations,

for example, in the battlefield or some public safety scenarios. Such accessibility requirement also underscores the implied limited detection sensitivity of the said technologies. Echocardiogram is clinically popular but it requires good physical contact between the ultrasonic transducer and patient's bare chest that can cause significant discomfort. Recent reports also show the use of conventional laser vibrometers to monitor patient's heartbeat [6, 8]. Their limited sensitivity, however, required attaching retro-reflective tapes to the patient's chest to counter the optical speckle problem and improve the detection signal-to-noise ratios (SNR) [9]. Once the interrogation location is moved away from the chest or carotid areas, furthermore, mechanical signatures emanating from the heart's beating diminish rapidly. Covering the patient's body with clothing like shoes and helmets further attenuates such mechanical signatures, leading to greater difficulty in discerning the heart's detailed mechanical workings via surface interrogation means, be they of contact or non-contact in nature.

We recently deployed an optical speckle-tolerant photo-EMF pulsed laser vibrometer (PPLV) to monitor human heartbeat signatures from extremities like the fingernail without using any surface pre-treatments [10]. In this paper more data are presented demonstrating PPLV detection of heartbeat signatures from clothing-covered extremities. It is also discovered that distinctive temporal features exist within individual cardiac cycles in the PPLV cardiac trace. In the absence of imaging modalities like echocardiogram, we chose to identify, assign, and validate the meaning of the various temporal peaks in the PPLV cardiac traces by conducting concurrent studies between the PPLV and the contact accelerometer, and three-lead electrocardiogram (ECG), respectively. It is found that these temporal features are closely correlated with the contraction and closure of the various chambers and major valves of the heart.

2. Experiments

Fig. 1 shows the schematic of one typical experimental arrangement used [11]. In order to maximize the detection SNR in evaluating the cardiac signatures, the subjects were generally asked to sit or lie down in a relaxed manner during the experiments so as to minimize any impacts from surface vibrations that are not caused by heartbeat, for example, breathing and other gross physical movements. Subjects were allowed to breathe normally except when conducting accelerometer studies on the chest when they were asked to hold their breath. The PPLV standoff distance remained at approximately 1 meter. The subject pool consists of 14 subjects encompassing both sexes and originating geographically from various regions on earth, including North America, Central America, East Asia, and South Asia. The data presented in this

paper were collected from subjects not known to be blood-related.

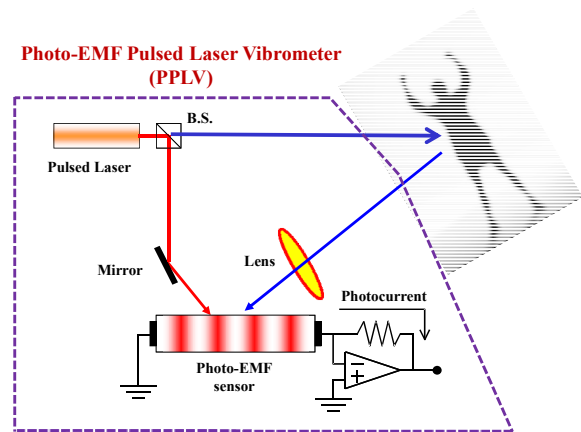


Fig. 1. Schematic depicting the experimental arrangement used in this paper. B. S. = beam splitter.

Fig. 2 depicts the PPLV cardiac traces obtained from various subjects on different occasions.

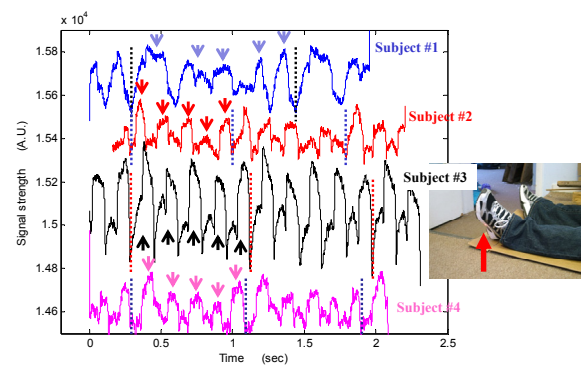


Fig. 2. PPLV cardiac traces obtained from Subjects #1 - #4 under various conditions described in the text. The small arrows note the presence of various temporal peaks within individual cardiac cycles. The inset shows the PPLV cardiac trace being retrieved from Subject #3's sneaker surface.

Subject #1's PPLV cardiac trace was obtained from the surface of his gray-color pajama over the general region of upper left thigh while that of subject #2 was retrieved when the laser beam was targeted at the surface of her black-color velvet pants over the general area of right shin. Subject #3's PPLV cardiac trace was obtained from the surface of his left sneaker, as the inset shows, and that for Subject #4 was collected from her left shin, from the surface of her black-color dress pants. The adjacent vertical dotted lines drawn in Fig. 2 enclose periods which we believe to represent individual cardiac cycles as they are characterized by the longer-scale (~ 1 second) periodicity in the PPLV cardiac traces. The heartbeat rates calculated herein from Fig. 2 correspond well with those obtained via palpation and other known characteristics of the subjects. For

example, Subject #1 exhibited in Fig. 2 the at-rest heartbeat rate of approximately 50 beats-per-minute (bpm), a relatively slow value that is commensurate with his extensive running habits. Common features among the PPLV cardiac traces depicted in Fig. 2 include the observation of five temporal peaks, with varying magnitude and temporal width from one another, within each perceived cardiac cycle. Furthermore, of the five temporal peaks within each cardiac cycle, there always exists one major peak with the largest amplitude and longest temporal duration.

Since the PPLV detects dynamic surface displacements, it is likely that the five temporal peaks in the PPLV cardiac cycle are related to the temporally-phased mechanical operations of the heart which cause the body surface to vibrate. Fig. 3 illustrates the concurrently obtained PPLV cardiac trace and the three-lead chest ECG waveform from Subject #5. The PPLV's interrogation location was on the general area of the left shin.

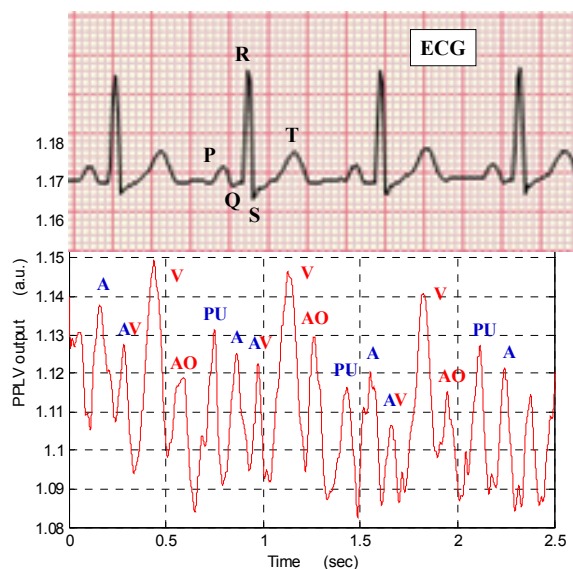


Fig. 3. PPLV cardiac trace (lower panel) and ECG waveform (upper panel) concurrently measured from Subject #5.

Using the ECG waveform as a reference, Fig. 3 reaffirms the presence of five temporal peaks within each cardiac cycle identified by the PPLV, consistent with our findings presented in Fig. 2. Furthermore, assignments of the meaning of the various PPLV cardiac peaks can be achieved by referencing them temporally with the known characteristics of the ECG waveform and the results are summarized in Table 1. Note that the amount of mechanical work done by the ventricles is of the strongest strength among those exerted by the various parts of the heart since the ventricles are responsible for pumping the blood throughout the whole body. It is thus expected that the mechanical signatures generated by ventricular contraction shall be of the greatest strength as a

result. Accordingly, the peak labeled V in Fig. 3 which exhibits the largest amplitude and widest temporal duration compared to the other PPLV cardiac peaks is ascribed to the ventricular contraction of the heart. This assignment is also consistent based on the temporal comparison of the PPLV traces with that of the ECG waveforms. The assignment of the other PPLV traces in comparison to the ECG temporal characteristics is summarized in Table 1.

Table 1. Assignment of PPLV cardiac peaks based on temporal comparison with ECG waveform characteristics.

Cardiac mechanical event	ECG timing	PPLV cardiac peak
Atrial contraction	P – R interval	A-peak
AV-valve closure	R-peak	AV-peak
Ventricular contraction	S – tail end of T-wave	V-peak
Closure of aortic valve	Tail end of T-wave	AO-peak
Closure of pulmonary valve	T – P interval	PU-peak

Fig. 3 and Table 1 also indicate the presence of timing split between the closure of the aortic and pulmonary valves. While the aortic valve in general closes prior in time to the pulmonary valve [1] and that the leaflets of the pulmonary valve close within the T – P interval of the ECG waveform, the amount of timing split (> 100 ms) between the AO- and PU- PPLV cardiac peaks depicted in Fig. 3 appears to exceed the generally referenced values (tens of millisecond). The unambiguous assignment of the PU-peaks thus would require the use of other modalities like echocardiogram.

Concurrent PPLV and accelerometer studies were also conducted to further support our observations. Within the relatively low frequency range (\sim Hz) the heart operates, the contact accelerometer measures the subject's chest wall movements with limited sensitivity. Such limited sensitivity implies that the accelerometer readings are mostly local in nature and hence by placing the accelerometer over different locations over the chest, mechanical operations of various parts of the heart can be differentiated. Fig. 4 displays the PPLV cardiac trace and the chest wall acceleration curve obtained when the accelerometer was placed firmly next to the apex of Subject #1's ventricles. Fig. 4 shows that maximal acceleration occurs right at the end of the V-peak. Since maximal acceleration corresponds to minimal surface displacement, one thus concludes that the subject's chest wall suffers maximal deflation at the end of the V-peak. As maximal chest deflation occurs after the blood has been forced out of the ventricles, one would thus re-affirm that the V-peaks in the PPLV cardiac trace directly reflect ventricular contraction. Fig. 4 also shows the presence of relatively high speed PM- accelerometer spikes that correspond in

time to the AV-peaks of the PPLV cardiac trace. Such PM-spikes appear right prior to ventricular contractions and are observable only when the accelerometer was placed close to the ventricles. The PM-spikes could not be detected when the accelerometer was placed over the atria. Hence it is concluded that the corresponding AV-peaks are caused by the closure of the atrio-ventricular valves that also include the flexing of papillary muscles and related connective tissues. Note that the subject was asked to hold his/her breath during the accelerometer data collection period while the accelerometer was firmly pressed onto the chest. The ensuing discomfort in the subjects negatively impacted the quality of both the PPLV and accelerometer data shown in Fig. 4.

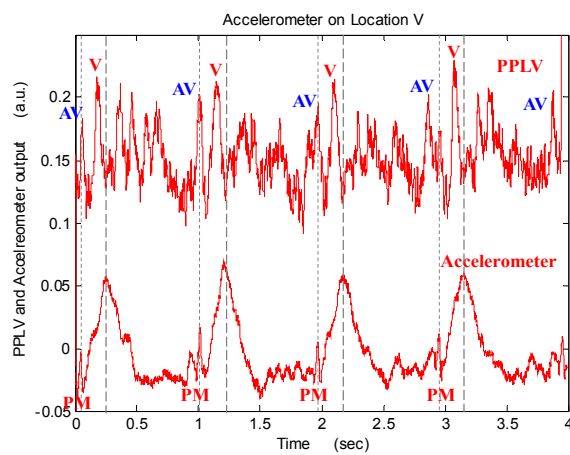


Fig. 4. PPLV cardiac trace (upper) and accelerometer readings (lower) synchronously measured from Subject #1. The y-axis represents surface displacement for the PPLV cardiac trace while it is acceleration for the accelerometer trace. PM: papillary muscles. The PPLV was monitoring the surface of the subject's blue jeans over his thigh.

3. Conclusions

In conclusion, we have demonstrated the non-contact detection of detailed mechanical workings of the heart from clothing-covered extremities of subjects using a high sensitivity pulsed laser vibrometer. Distinctive temporal features in the PPLV cardiac trace are identified and attributed to the various mechanical operations of the heart by using concurrent studies between the PPLV and electrocardiogram, and contact accelerometer, respectively. While further studies are warranted from a large subject pool to verify unambiguously the assignments of the PPLV cardiac trace features, our early results show a promising noninvasive stand-off

technique for monitoring the human heart activity in such applications as triaging and evaluating subjects in environments like battlefield and other public disaster situations.

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