A remote and non-contact method for obtaining the blood-pulse waveform with a laser Doppler vibrometer*

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ABSTRACT

The use of lasers to remotely and non-invasively detect the blood pressure waveform of humans and animals would provide a powerful diagnostic tool. Current blood pressure measurement tools, such as a cuff, are not useful for burn and trauma victims, and animals require catheterization to acquire accurate blood pressure information. The purpose of our sensor method and apparatus invention is to remotely and non-invasively detect the blood pulse waveform of both animals and humans. This device is used to monitor an animal or human's skin in proximity to an artery using radiation from a laser Doppler vibrometer (LDV). This system measures the velocity (or displacement) of the pulsatile motion of the skin, indicative of physiological parameters of the arterial motion in relation to the cardiac cycle. Tests have been conducted that measures surface velocity with an LDV and a signal-processing unit, with enhanced detection obtained with optional hardware including a retro-reflector dot. The blood pulse waveform is obtained by integrating the velocity signal to get surface displacement using standard signal processing techniques. Continuous recording of the blood pulse waveform yields data containing information on cardiac health and can be analyzed to identify important events in the cardiac cycle, such as heart rate, the timing of peak systole, left ventricular ejection time and aortic valve closure. Experimental results are provided that demonstrates the current capabilities of the optical, non-contact sensor for the continuous, non-contact recording of the blood pulse waveform without causing patient distress.

Keywords: *Blood Pulse Waveform, Laser Doppler Vibrometer, Carotid Artery, Dicrotic Notch, Arterial Pulse, Non-Contact*

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I. INTRODUCTION

A Laser Doppler Vibrometer (LDV) was used to remotely record the arterial, blood pulse waveform (BPW) by directing the laser beam onto the skin surface above an artery to measure the surface velocity. The waveforms can be monitored in real-time and recorded for subsequent analysis of the patient's physiological condition. Information on patient condition with regard to the shape of the waveform as a result of heart muscle contractions and valve operations, as well as the timing of various cardiac cycle events can be obtained from the waveform measurement. Additionally, monitoring the blood pulse waveform at multiple points along the arterial path can provide blood flow velocity information as well as reveal changes in the waveform due to the arterial path structure, possibly revealing arterial obstructions. This technique is non-invasive and has been used to measure the blood pulse waveform over various arteries including the pedal, radial, femoral, brachial, popliteal, facial, posterior tibial, and carotid arteries. The non-contact method of monitoring an arterial pulse waveform can be appreciated in cases where very limited contact to the patient is desired, such as with trauma or burn victims and neonatal patients.

Test results are presented where the laser beam from the LDV was directed onto the skin surface area above a subject's carotid artery. The laser light reflected from the skin surface undergoes a Doppler shift due to the surface motion that occurs along the axis of the laser beam. The reflected light, frequency modulated by the skin surface motion, is detected by the LDV interferometer and demodulated to obtain the velocity of the skin surface. The blood pulse waveform, characterized by the displacement of the skin surface, is obtained by integrating the velocity waveform that is measured directly as the artery under the skin contracts and expands.

Traditionally, blood pulse waveforms, or blood pressure waveforms are obtained invasively by inserting a catheter with a pressure sensor tip into an artery, such as the femoral artery[1]. This technique provides reliable time history of the pressure waveform with calibrated blood pressure values. Although the time history of the blood pulse waveform is measured using the laser sensor, the actual pressure values that cause the arterial motion have not yet been realized from the data, since the distensibility, or impedance of the arterial wall is not known.

Other means of measuring the rhythmic pulsation of the heart at different locations within the circulatory system have been attempted. Impedance cardiography, for example, has also provided a way to non-invasively monitor the pump action of the heart. Systems that use laser light have been widely used as a tool to measure other physiological quantities. A photometric pulse detector (PPD), which works by reflectance principle, has been used to measure an arterial pulse at the temporal artery by making contact to the skin area[2]. An optical method known as photoelectric plethysmography detects blood pulse waves as a change in the light intensity modulated by blood contents in the tissue. The operation of this system is based on the fact that the heartbeat causes the change of blood contents in tissue and the light penetrating the tissue is absorbed by the blood[3].

Laser Doppler techniques have found considerable application in biology and medicine. One such application is in assessing blood flow velocity through the arteries and capillaries. Light is capable of measuring the velocities of red blood cells even at relatively slow speeds with which they move through the capillaries. The spectral purity of the laser makes it practical to detect even the slight frequency shifts produced by the interactions between photons and moving red blood cells[4]. Essex[5] discussed the development of the laser Doppler scanner, and the use of such device to build an image of the skin in terms of its blood flow. Laser Doppler vibrometer techniques have also been employed to measure low surface vibration velocities produced when excitation forces, with low energy levels, were employed to put teeth into vibration[6]. Measurements of skin surface vibration have been demonstrated using an optical interferometer system that measures surface velocity based on the Doppler frequency shift principle. Such vibration is proportional to the pulsatility of the underlying blood vessel especially the arteries and the heart[7]. An optical stethoscope, also based on Doppler principle covers most of the auditory range of a conventional stethoscope and can also detect skin vibration due to pulse waves propagating through the vasculature[8]. Lee[9] verified through both experiment and theory that skin surface motion can be related to the underlying vascular movements. The underlying artery causes skin vibration in the order of few hundred microns. The mean displacement of the carotid arterial wall resulting from the pumping action of the heart was found to be about 520 um[10]. Such displacement data can be used to estimate the order of magnitude expected of the skin vibration. Vibration velocity of the tissue surrounding certain blood vessels can also be estimated and compared with the information obtained by the Doppler shift.

The blood pulse waveform, associated with the velocity and displacement of the vibratory skin as blood moves through the arteries, can be analyzed to derive the timing of cardiac events, such as heart rate, the timing of peak systole, left ventricular ejection time and aortic valve closure (dicrotic notch). Additional timing information can also be resolved with simultaneously recording of the electrocardiogram (ECG) along with the blood pulse waveform (BPW). Analysis of the combination of the ECG and BPW can provide information on the systolic time interval (STI), including the Left Ventricular Ejection Time (LVET), Pre-ejection Period (PEP), and Electromechanical Systole (QS2). These time intervals are important for health care professionals to assess patient condition.

This study investigates the use of a Laser Doppler Vibrometer (LDV) for non-contact measurement of the arterial, blood pulse waveform. Experimental data is presented to demonstrate the feasibility of the non-contact, laser-based detection method of measuring the blood pulse waveform. Analytical results to extract the timing of several cardiac events from the recorded waveform, with and without the electrocardiogram signals, are shown to provide insight on the type of information that can be derived from the measured blood pulse waveform.

II. THEORETICAL DISCUSSION

2.1 Cardiac function and timing

The heart is the central organ of the circulatory system and consists of four chambers, including two separate pumps that simultaneously inject an equal quantity of blood for both the pulmonary and systemic circulation. Pulmonary circulation supplies deoxygenated blood to the lungs while systemic circulation supplies oxygenated blood to all other organs. Systemic circulation consists of the aorta, the arteries, the arterioles, the capillary network, and the veins[11]. The carotid artery, whose pulsatile motion will be monitored with the LDV, branches off from the aorta and travels up through the neck. Transmission of the arterial pulse over the short distance from the aortic root to the carotid artery site takes approximately 40ms and introduces virtually no waveform distortion.

The pump action of the heart occurs primarily as a result of the ventricular contraction. The cardiac cycle is divided into two periods; ventricular contraction (systole) and ventricular relaxation (diastole). During systole, the beginning of ventricular contraction and resulting first rise in the pressure inside the two ventricular chambers causes the two atrioventricular valves to close. The pressure rises without moving blood from the ventricles until it exceeds the pressure in the aorta and pulmonary artery. At this point the two semilunar valves are forced open and the flow of blood into the arterial trunks begins.

Blood flow through an artery is influenced by several factors including the geometry of the artery, the roughness and compliance of the arterial wall, and other characteristics and acting forces. As the blood is pumped through the arteries, the pressure forcing the blood flow causes a pulsatile, lateral movement of the vessel walls. Both the effective length of the arterial system and the pulse wave velocity influence the timing of the return of the reflected pressure wave. Therefore, a decrease in the aortic length or an increase in the pulse wave velocity can have the same effect on the blood pulse waveform[9].

At the termination of the ventricle contraction and the onset of diastole, pressure in the cavities begins to fall, causing immediate closure of the semilunar valves. Relaxation of the seminular muscle now produces a rapid fall in pressure in the two ventricle cavities, and the moment the pressure falls below the atria pressures the two atrioventricular valves open, permitting the ventricles to fill with blood from the atria. During both systole and diastole, there is a short period of time, which no blood flow occurs. This occurs between the time one set of valves closes and the others open and it is known as the isometric contraction and relaxation of the cardiac muscle[11].

During the cardiac cycle, pulsatile blood flow is introduced into the arterial system. This flow and the arterial wall resistance against such flow define the arterial pressure wave. The sudden dilation of the aorta by the blood ejected from the left ventricle is transmitted along the arterial system as a wave of elastic displacement of the arterial wall. This represents the arterial pulse wave or the arterial blood pressure waveform, which is an index of the heart rate, and in addition reflects the quantity of blood injected into aorta, and elasticity of the large arteries[11]. Meinders et al[12] shows relationship between arterial pressure waveform and arterial cross-section by deriving pressure waveforms from the change in arterial cross-sections in the left common carotid artery. After the arterial cross-section and pressure

waveforms are known, compliance, distensibility, pulse wave velocity and elastic modulus can be derived as a function of the distending pressure. Therefore a study of the common carotid artery shows that as the pulsatile blood flow travels through the arteries, it causes expansion and contraction of these arteries and therefore change in the diameter occurs. The LDV system is used to measure the skin motion due to the arterial expansion and contraction.

2.2 Optical properties of the skin

The optical properties of skin tissue influence all biological signal measurements that employ light energy. Models that predict reflection and transmission of light by tissue have been developed. However the accuracy of these models depends on how well the optical properties of tissues are known. Optical parameters are obtained by converting measurements of observable quantities like reflection into parameters that characterize light propagation in tissue. Such conversion process is based on a particular theory of light transport in tissue[13]. The theory of light transport in tissue is preferred in tissue optics instead of analytical approaches using Maxwell equations because of the inhomogeneity of biological tissue.

The reflectance from the skin is dependent upon the optical properties of the skin structure including the blood-free epidermis, as well as dermis layers as shown in Figure 1. The thickness of epidermis including the stratum corneum is 10-150 mm. The dermis layer is approximately 1-4 mm thick and contains elastic collagen fibers and blood vessels of different sizes. The epidermal layer contributes about 6% to the total reflectance at wavelengths over range from 400 to 800 nm[14]. This is a specular reflectance at the air-stratum corneum interface, which suggests that minimal scattering occurs in the epidermis, so that it acts primarily as an absorptive medium. Van Gemert et al[15] found that for wavelengths between about 300nm and 1000nm, light scattering from nonpigmented tissues dominates absorption. And for wavelengths between 240nm and 633nm skin layers are strongly forward scattering media, meaning that the greatest scattering happens at the zero degree to the incident light.

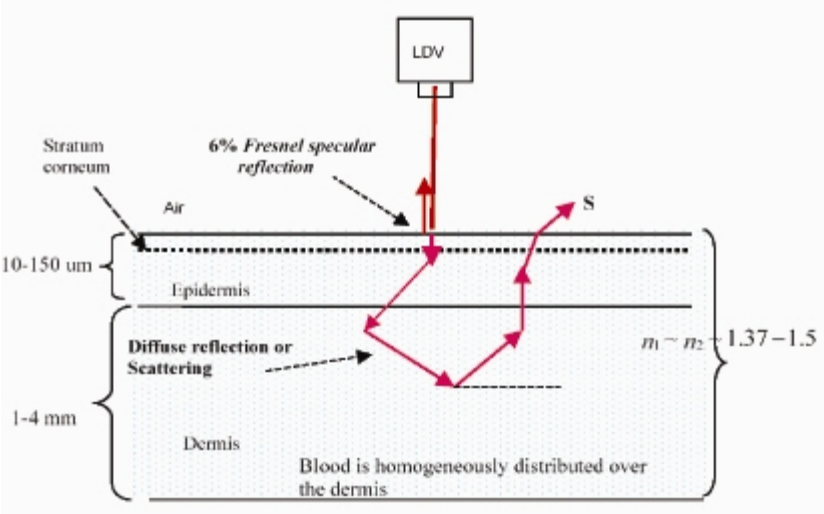

Fig. 1: Simplified model of the skin with plane parallel epidermal and dermal layers[15].

Light penetration through tissue is important because the skin tissue is composed of several layers, which in turn can be broken down into sub-layers. Radiation at some wavelengths penetrates deeper than others and the absorption and scattering of such wavelengths in a tissue varies. Such scattered light once detected and demodulated provides information on the lateral displacement and velocity of the vessels and therefore the necessary information to show an arterial blood pulse waveform.

Measurements done during this study used an LDV to probe the surface area of the skin directly above the carotid artery on the neck of a person. Little skin preparation was needed, especially since this is an area with minimal hair growth. Any hair follicles that exist buried within the skin tissue layers will contribute to some extent to the absorption and scattering of the light and to the physiological noise present in the tissue. Such characteristics of light as it travels in a

tissue should be accounted for and explained by the diffusion of light in tissue theory. Retro reflective tape at some instances was used to enhance the intensity of the reflected light at the detector, while preventing optical transmission into the skin layers.

2.3 Interferometer system description

One method to optically detect a small displacement or movement of an object is by means of interferometry. The principle of Laser Doppler Vibrometer (LDV) operation is based on the interference of two beams of light. The two laser (reference and measurement) beams arrive at the photodetector surface after one has undergone an optical path change and Doppler frequency shift. The measurement beam illuminates a surface and undergoes an optical path length change as the surface moves along the direction of the laser beam. This optical path difference is caused primarily by the vibration of the skin. The phase difference between the two beams inside the interferometer is represented by their beat frequency at the photodetector.

An LDV, Polytec PI model OFV-353 was used to obtain initial measurements of the blood pulse waveform by non-contact means at the subject's skin over the carotid artery. The system works on the basic principle of laser interferometry for Doppler shift velocity detection. Red light from a Helium Neon (HeNe) laser source is divided evenly by a beam splitter (BS1) into a reference beam and a measurement beam. The frequency of the reference beam is shifted using an acousto-optic modulator (Bragg cell) to introduce a 40 MHz signal. The modulation of the reference beam is desired in order to discern the direction (along the axis of the laser beam) of the movement obtained from Doppler shift of the returned signal. The measurement signal goes trough the polarizing beam splitter (BS2) and Quarter Wave Plate (QWP), which behaves as a directional coupler. The light output from the vibrometer goes straight to the object under test, and the reflected beam is redirected to beam splitter (BS3). The reference beam and the return beam from the object are detected by detectors D1 and D2 and are subsequently combined and demodulated to obtain velocity and displacement information. Figure 2 shows a block representation of such a system, which is based on Mach-Zehnder interferometer[16].

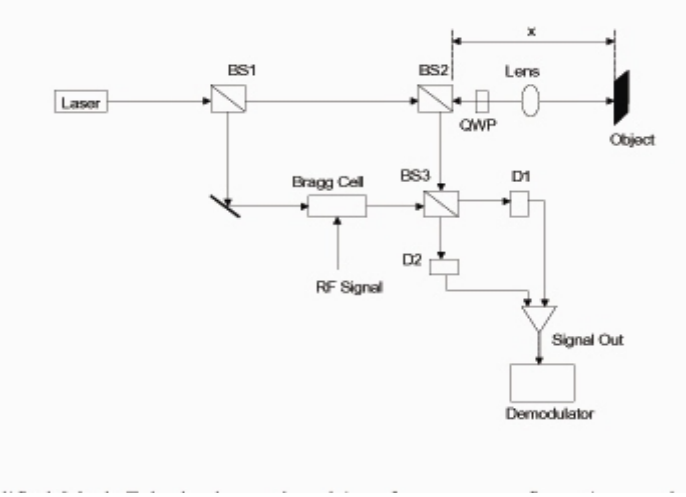

Fig. 2: Modified Mach-Zehnder heterodyned interferometer configuration used in the Polytec Laser Doppler Vibrometer[16].

III. EXPERIMENTAL SETUP

A commercially available Laser Doppler Vibrometer (LDV) (Polytec PI model OFV353)[16] was used to measure the blood pulse waveform by probing the skin surface above the carotid artery. The LDV system emits a continuous, low power, visible red light beam (l= 633 nm), which is directed onto the skin surface. The component of the scattered light that reflects back into the LDV interferometer, parallel to the incident beam, has undergone a Doppler shift due to the skin velocity. The detected signal is then demodulated by the system electronics to obtain the blood pulse waveform. A series of tests were conducted by measuring the skin motion on the neck region directly above the carotid artery, as illustrated by Figure 3. An optional piece of retro-reflective tape may be placed on the skin surface to enhance the signal.

The LDV output signal was recorded along with the subject's ECG signal using a laptop computer based data acquisition system with a 1000 Hz sample rate. A 60 bpm signal represents a 1 Hz signal, and additional signal fluctuations were observed to be below 100 Hz, the 1000 Hz sample rate is above the Nyquist criterion for data sampling to prevent aliasing. The LDV sensitivity was set at 5 mm/s per Volt output. The velocity data was processed using a third order, high-pass Butterworth filter with a cutoff frequency of 0.0016 Hz to remove the DC offset that was imposed by the data acquisition system. The signal was then corrected to remove the imposed filter delay.

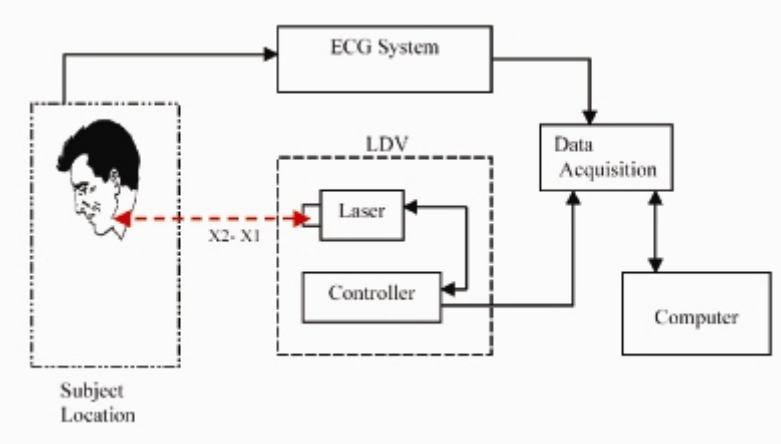

Fig. 3: Setup for simultaneous recording of ECG signal and carotid pressure waveform.

IV. RESULTS

The laser vibrometer system records surface velocity. During the cardiac cycle, variations in the blood pressure cause the artery to expand and contract. As the artery expands, the skin moves outward and the measured velocity signal increases. Likewise, the velocity is negative during contraction of the artery. As the artery motion changes direction, between a state of expansion and contraction, the velocity is zero. Zero velocity would occur at the point of maximum arterial expansion, such as at peak systole, during fluctuations in the blood flow direction such as during aortic valve closure and at the point of minimum arterial expansion at the start of left ventricular ejection. The blood pulse waveform is more clearly represented by the skin displacement, which is obtained by integrating the measured velocity signal. The skin displacement is comparable to traditional blood pulse waveforms. Two cardiac cycles of a blood pulse waveform measured on the carotid artery using the LDV are shown in Figure 4. The skin displacement waveform, calculated by integrating the measured velocity, is superimposed in Amplitude (V) in Figure 4. Two dotted vertical lines indicate (1) peak systole, which has a local maximum displacement and a zero velocity; and (2) the location of the dicrotic notch identifying aortic valve closure.

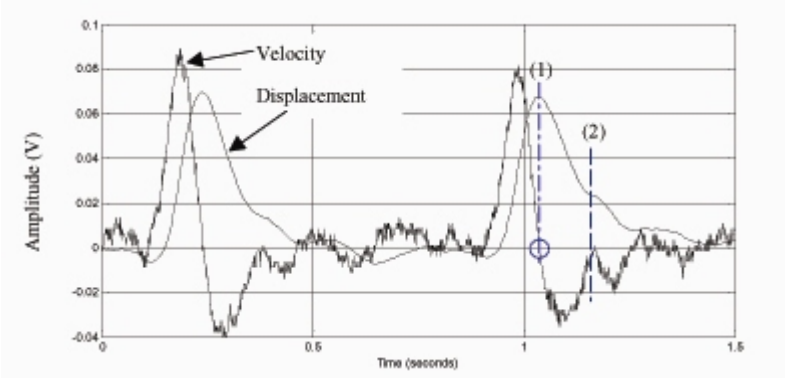

Fig. 4: LDV-measured velocity signal and the calculated displacement at the carotid artery.

A velocity waveform recorded by the LDV system on an adult male subject is shown in Figure 5a along with the calculated displacement signal in Figure 5b, which is the integral of the velocity signal that represents the blood pulse waveform and the simultaneously recorded ECG signal in figure 5c. The recording is 10 seconds long and contains 11 cardiac cycles. The amplitude scale for the velocity signal is in mm/s, which was converted from volts to velocity using the LDV sensitivity setting of 5 mm/s per Volt. The skin velocity ranges from approximately –5 to 8 mm/s. The skin displacement varies less than 0.4 mm. This test case was typical of the data that is repeatedly recorded using the laser vibrometer technique. The velocity and displacement signals do not identify the blood pressure quantity, only the time series waveform. The actual pressure values are not directly obtained from the remote velocity measurement. A calibration procedure would need to be developed, possibly by taking an independent reading of the actual pressure value such as with a cuff and relating the pressure to the voltage peak systolic amplitude.

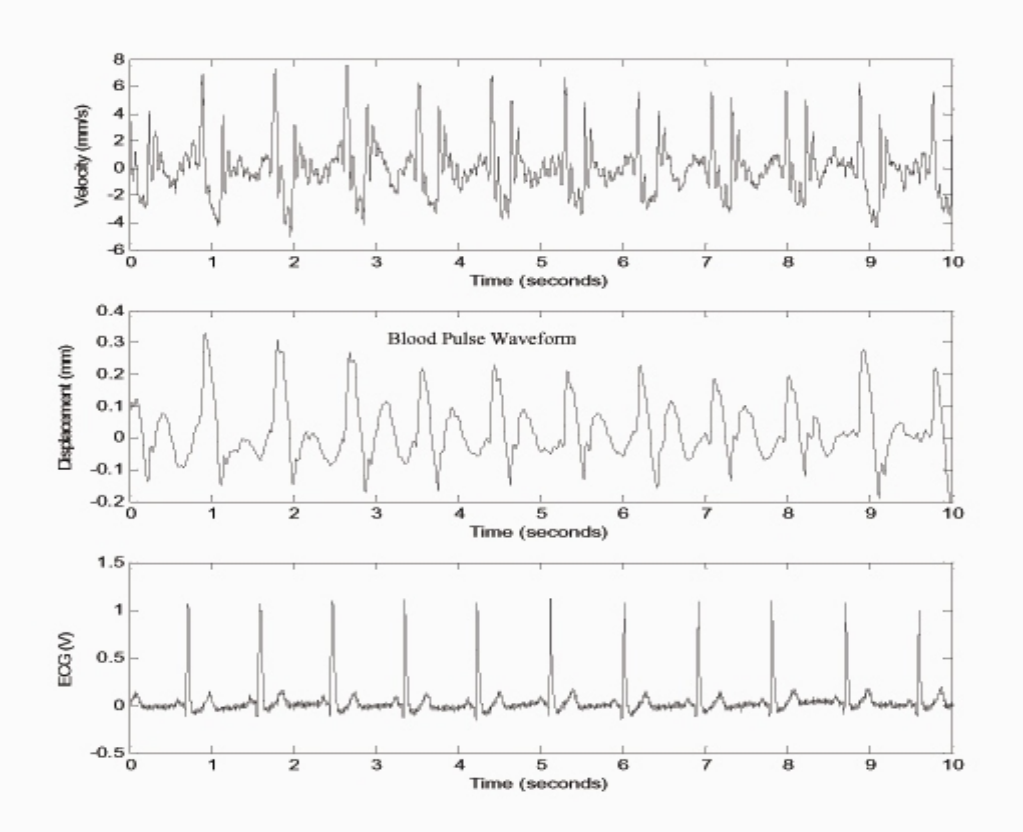

Fig. 5: Carotid artery pulse waveform (a) velocity signal measure by the LDV; (b) calculated displacement (blood pulse waveform); and (c) simultaneously measured ECG signal showing 11 cardiac cycles for an adult male subject.

The displacement waveform is similar to the impedance waveform and the velocity as the derivative of the impedance. Frey et al[17] demonstrated that left ventricular ejection time measured from a carotid artery pulse wave recording and that of the impedance cardiogram are highly correlated. Electrical impedance cardiography (ICG) reflects instantaneous electrical impedance changes within the thorax area and these changes have been attributed to the dynamics of left ventricular ejection[18]. Figure 6 shows ICG plot recorded by electrodes contacting the skin and other cardiac signals of interest, which are used in identifying key parameters of the cardiac timing. On the first derivative (dZ/dt) plot, the onset of left ventricular ejection (Oa) and the closure of aortic valve (Va) which defines LVET are shown. Such correlation was kept in mind during the analysis of the carotid pulse waveform obtained by means of LDV in this study.

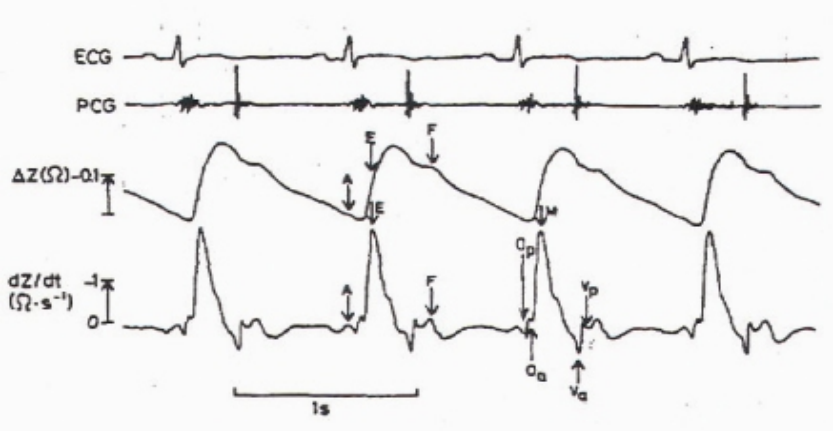

Fig. 6: Sample recording of electrocardiogram (ECG), phonocardiogram (PCG), and impedance cardiogram (Z) and its first derivative (dZ/dt) showing some cardiac timing intervals[19].

V. CONCLUSION

A Laser Doppler Vibrometer (LDV) was used to measure the blood pulse waveform at several artery locations, including the carotid artery. This study shows that commercially available LDV systems can be used to directly probe person's skin surface area and record arterial blood pulse waveforms. The LDV measures the skin velocity above an underlying artery. The skin displacement, which corresponds to the blood pulse waveform was calculated by taking the integral of the recorded velocity signal and can also be measured by some commercial LDVs. This is a non-invasive and non-contact means of obtaining the blood pulse waveform. Blood pressure values are not directly obtained from the recorded waveform. A direct measurement of the blood pressure would be needed to calibrate the actual pressure with the recorded signal.

The onset of the upstroke and the dicrotic notch, which indicate the opening and closing of the aortic valve, respectively, are observed on the recorded blood pulse waveforms. Heart rate and the left ventricular ejection time can be determined from the timing of the characteristic events in the blood pulse waveform. Simultaneous ECG and LDV blood pulse measurements were recorded and used to estimate the systolic time intervals (QS2, LVET and PEP) and heart rate on a pulse-to-pulse basis.

The blood pulse data obtained shows potential for further use of such systems to provide information for assessing the health condition of a patient, particularly in trauma situations. In trauma situations the blood pulse waveform may provide physiological information that the systolic and diastolic pressure values alone do not provide. Other surface areas of the skin can be probed with the LDV in order to measure the blood pulse waveform at various arteries including the pedal, radial, femoral, brachial, popliteal, facial, posterior tibial, and carotid arteries. Simultaneous recording of the artery at several locations can be used to determine the propagation delay of the pulse waveform through the artery and to evaluate the change in waveform characteristics that may indicate possible obstructions or arterial condition. Further evaluation of this non-contact method of measuring the blood pulse waveform from a larger number of test subjects is currently being done. The College of the Holy Cross' Human Participant Committee has approved human subject trials to be conducted at the college through May 2007. The capability of this measurement method can then be evaluated versus a patient's physical characteristics, such as size, weight, and skin condition. Finally, a comprehensive medical evaluation of the measured, carotid artery, blood pulse waveforms need to be done to relate waveform characteristics to physiological condition.

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