Effects of Bio-Impedance Sensor Placement Relative to the Arterial Sites for Capturing Hemodynamic Parameters

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***Abstract*— Accurate measurement of the heart pulse waveform based on blood volume changes inside the arteries is crucial for reliable estimation of hemodynamic parameters such as blood pressure and cardiac output. Placement of blood volume sensors such as bio-impedance sensors close to the arterial sites is essential for the accurate measurement of the pulse waveform. The effect of sensor location relative to the wrist arteries on the pulse waveform had not been studied previously on human subjects. In this paper, we explore the effect of arterial and off-arterial placement of the bio-impedance sensor on important pulse waveform features such as pulse transit time (PTT), which is the travel time of the arterial pressure pulse between two sensors, and diastolic peak error (DPE), a measure of pulse signal sharpness. Placing the current injection and voltage sensing electrodes of a bio-impedance sensor on the radial artery provide greater accuracy for such features. We find that arterial PTT has a significantly lower standard deviation compared to off-arterial PTT indicating better signal quality. Similarly, we observe that DPE is much smaller for arterial bio-impedance which confirms our expectations. Based on these features, the location of the artery can be determined using an array of sensors placed around the artery.**

Keywords – hemodynamic parameters; diastolic peak error (DPE); pulse transit time (PTT); sensor placement; wrist bio-impedance;

I. INTRODUCTION

Every year, 525,000 Americans have their first heart attack, and cardiovascular diseases (CVD) account for 1 in 4 deaths in the US [1]. Effective diagnosis and management of CVD are essential to improving health outcomes and reducing health care costs, which amount to $200 billion per year. Hemodynamic parameters provide prognostic information regarding cardiovascular risk [2], which help clinicians in choosing effective treatment options for their patients. Recent studies showed that hemodynamic parameters such as blood pressure and cardiac output could be estimated from the heart pulse waveform based on blood volume changes inside the peripheral arteries. Cardiac output was measured from several characteristic points such as diastolic, systolic and dicrotic points of the heart pulse waveform measured from a photoplethysmography (PPG) sensor placed on the finger [3]. Cuffless blood pressure (BP) methods rely on measuring pulse transit time (PTT) which is the time taken by the pressure pulse to travel between two points on an artery [4,5]. For example, BioWatch, a cuffless BP device, correlated systolic BP with PTT acquired from the time delay between the electrocardiogram (ECG) R-peak and the maximum slope point of a PPG signal measured from the wrist [6]. Recently, we demonstrated the accuracy of bio-impedance (Bio-Z) measurements from an array of sensors for reliable cuffless BP estimation based on several features extracted from the Bio-Z signal, such as PTT, amplitude and fall time [7,8]. Bio-Z is better than PPG at measuring local blood volume changes inside the artery because it reaches greater depths in the tissue, which increases the accuracy of PTT measurements and BP estimation. All these methods rely on detecting reliable characteristic points from the heart pulse waveform, which requires accurate sensing of the waveform morphology inside the arteries. The location of the sensor placement on the skin relative to the artery is crucial for accurate measurement of the heart pulse waveform. Simulations by several groups showed that the optimal placement of Bio-Z electrodes is essential for detecting lung edema, prostate cancer, and neuromuscular diseases [9-11]. Another group also concluded that placing sensors near major arteries in the thorax also yields sharper changes in Bio-Z due to increased blood flow [12]. Therefore, in our case, placing sensors close to the target peripheral artery minimizes noise due to body tissue and maximizes detection of blood volume changes in the target artery. Our hypothesis is that placing the sensors closer to the target artery will enable detection of higher changes in impedance with sharper peaks due to increased blood flow, with commensurately higher conductivity [13], compared to obtaining Bio-Z from other body tissue. A sharper Bio-Z signal will have higher accuracy for extracting the characteristic points and features, which will enable more accurate estimation of hemodynamic parameters.

Our proposed method investigates the effect of Bio-Z sensor placement relative to the artery in two configurations: arterial and off-arterial. We used the radial artery as the target artery since it is closer to the skin, and its location is less subject to variability than the ulnar artery. The off-arterial placement was chosen in between these two peripheral arteries.

The contributions of this paper are as follows:

- We measure Bio-Z from a pair of sensors on the wrist in an arterial and off-arterial configuration to

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show the variation of features such as PTT, time, and amplitude with proximity from the artery.

- We introduce diastolic peak error (DPE), a measure of Bio-Z signal diastolic peak sharpness, as a new metric for quantifying arterial proximity which can be used in the future for artery localization using an array of electrodes [14].
- We show that placing Bio-Z sensors on the artery is essential for obtaining a sharp signal and accurate features.

In this paper, Section II explains the hardware and signal processing methodology. Section III covers the reporting and discussion of the experimental results. The conclusion is presented in Section IV.

II. Methods

We measure heart pulse waveform from Bio-Z which is a non-invasive electrical method that measures the impedance changes of body tissue and fluids in response to an AC current excitation, and contains Bio-Z variations (ΔZ) corresponding to the changes in blood volume with the arrival of oxygenated blood as a pressure pulse. In this work, we propose features for localizing the Bio-Z sensor's arterial proximity. Local blood volume changes were measured from the wrist using our custom Bio-Z sensors. We chose the radial artery for arterial location because it is easier to find and nearer to the skin of the wrist than the ulnar artery. For off-arterial Bio-Z, we placed Bio-Z sensors between the radial and ulnar arteries. Next, we developed features from characteristic points on the ΔZ signal and compared their performance for arterial vs. off-arterial Bio-Z.

A. Hardware

To measure Bio-Z, we use a trimmed Covidien Ag/AgCl pre-gelled adhesive electrode pair for current injection and two electrode pairs for voltage sensing two Bio-Z channels. We connect these electrodes to the output of an OPA211 current amplifier and to the inputs of two AD8421 instrumentation amplifiers (IA), respectively. In Fig. 1, an

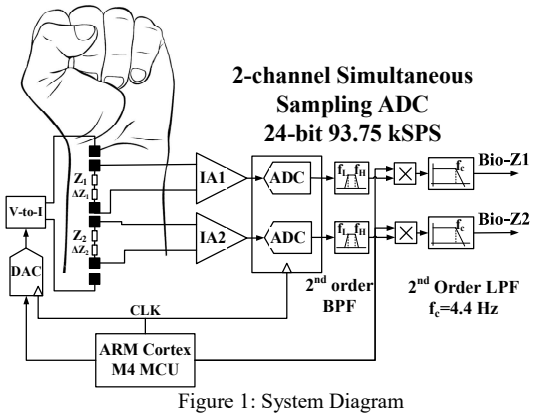

Figure 1: System Diagram

ARM Cortex M4 microcontroller (MCU) controls signal acquisition from the outputs of the IAs via a Texas Instruments 24-bit four channel analog to digital converter (ADC) sampling at 93.75 kSPS and amplitude modulation by configuring the TI 16-bit digital to analog converter (DAC) input's frequency, amplitude and time duration. The AC current was injected with carrier frequency of 10.4 kHz and current amplitude less than 1 mA RMS in compliance with safety standards. Signals acquired at the ADC are sent to a PC by the MCU through a parallel over USB link using the FTDI FT2232H. In MATLAB, we apply a bandpass filter with cut-off frequency ±0.5 kHz around the carrier frequency, multiply the sampled signal by the digital carrier and filter the recovered real and complex parts of the Bio-Z signal with a 2nd order low pass filter with a cutoff frequency of 4.4 Hz. After demodulation and filtering, we downsample and perform envelope detection on the real part of the Bio-Z signal to retain only the ΔZ changes.

B. Arterial vs. Off-arterial Bio-Z

We use the Huntleigh Dopplex MD2 Bi-Directional Doppler, which measures blood flow in the arteries to locate the radial and ulnar arteries as shown in Fig. 2. Next, we apply two voltage sensing pairs at channels (ch.) 1 and 2 or ch. 3 and 4 inside a current injection pair for collecting two channels of arterial or off-arterial Bio-Z, respectively. Since the radial artery is closer to the surface of the skin, and its location is consistent in individuals, we only use the radial artery in our arterial setup. Fig. 3 shows typical arterial and non-arterial ΔZ. During systole, large volumes of blood are

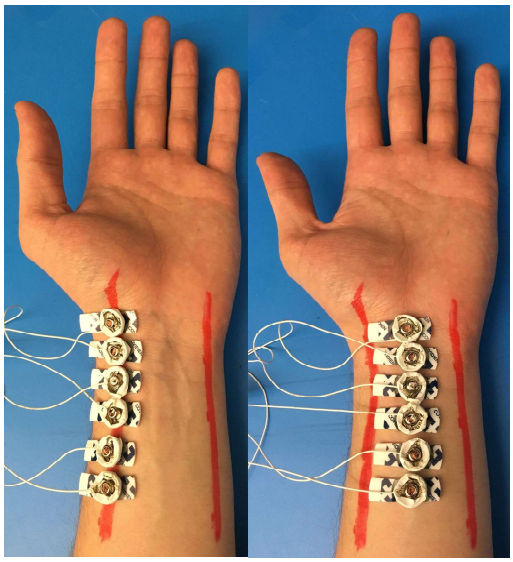

Figure 2: Left: Arterial electrodes (Channel 1 and 2; on radial artery), Center: Off-arterial electrodes (Channel 3 and 4; between radial and

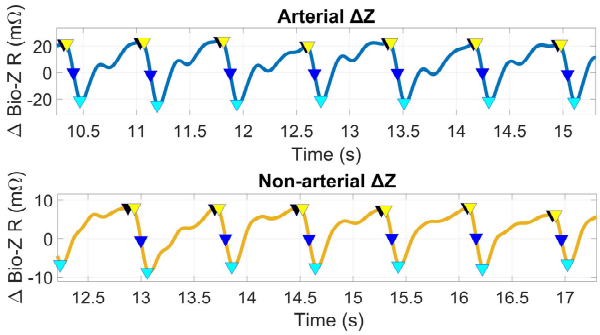

Figure 3: Arterial (top) and off-arterial (bottom) ΔZ

ejected from the heart and travel through the arteries. Due to the conductivity of the blood, this corresponds to the trough or foot of the signal, while the peak corresponds to diastole when the smallest volume of blood is present in the artery. Seen more clearly during arterial ΔZ, a smaller peak and trough following systole correspond to a reflection event which occurs in peripheral arteries due to branching [15].

C. Characteristic points

After Bio-Z acquisition, we detect four characteristic points on the ΔZ signal: the Peak (PK), Peak Tangent (Pk-Tan), Maximum Slope (MS) and Foot (FT). To find the Maximum Slope point, we take the derivative of the ΔZ signal and find the minimum over a window of time ~1/heart rate over all the Bio-Z cycles. From the MS point, we find a local maximum and minimum and label them the Peak and Foot, respectively. With the MS and PK points, we find the intersection between a horizontal line through the peak and a line through MS equal to the slope at that point. These points are used for measuring PTT, amplitude, fall time and DPE which are features we investigate for localizing the Bio-Z signal. Motion artifacts and noise sometimes prevent accurate detection of these characteristic points. When point detection fails, the heart cycles from the Bio-Z channels lose synchronization which prevents accurate measurement of PTT. Therefore, we perform dynamic time warping (DTW) parallel to the artery, for ch.1 and 2 and separately for ch. 3 and 4., to synchronize the signals. Following DTW we build an index of unique values and remove the remaining values while retaining their indices.

D. Features

PTT has been well correlated with blood pressure [7]. For a successful measurement of blood pressure, it is important to characterize PTT and identify potential differences between arterial and off-arterial Bio-Z. We propose that variation in resting PTT is due to noise, so PTT measured away from the artery will have higher standard deviation and different mean than PTT measured on the artery. Diastolic peak error and fall time are time-based features that show the signal sharpness in the time domain and provide a characterization of the signal to noise ratio. As measures of signal sharpness, we suggest that DPE and fall time for arterial ΔZ will be lower than for non-arterial ΔZ. Amplitude variations in ΔZ intensity correspond to blood volume changes. Higher amplitude ΔZ is present near the artery which means larger blood volume changes. For SNR or SINAD, we take the largest peak in the Fourier spectrum as heart rate and evaluate the impact of including the 1st and 2nd harmonics of this peak as part of the signal or noise, respectively, to more effectively characterize ΔZ.

1) Pulse Transit Time

PTT is measured by two voltage sensors as the difference between a characteristic point of two ΔZ signals for a given cardiac cycle. In Fig. 4, we calculate PTT MS and PTT Pk-Tan as the difference in time for two sensors, ch. 1 and 2 for arterial PTT or ch. 3 and 4 for off-arterial PTT, at the MS and Pk-Tan points, respectively, and investigate their performance comparing arterial and off-arterial ΔZ.

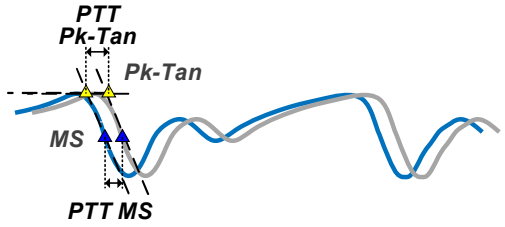

Figure 4: PTT measured with MS and Pk-Tan methods

2) Amplitude, fall time and DPE

Fall time and diastolic peak error are defined as the time between PK and FT and the time between PK and Pk-Tan, respectively. Arterial Bio-Z measures blood flow more effectively than off-arterial Bio-Z increasing the peak sharpness of the ΔZ waveform. This peak sharpness minimizes the difference between Pk-Tan and PK which is the diastolic peak error. Off-arterial Bio-Z measures blood flow more poorly and is, therefore, more influenced by noise sources which flatten the peak, decrease the slope to the systolic foot and thereby increase the DPE. Amplitude is defined as the magnitude between PK and FT. In Fig. 5, we show amplitude and fall time for one ΔZ cycle and DPE for the following cycle. To normalize amplitude, we divide each cycle of the amplitude by the mean real Bio-Z and then divide the standard deviation of these normalized values by their mean. These two steps equalize the variation due to large differences in mean Bio-Z or in mean ΔZ, respectively.

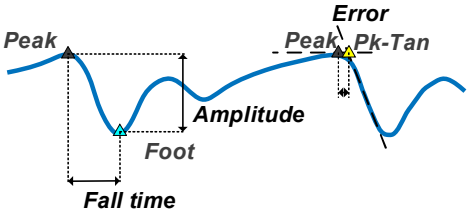

Figure 5: Fall time, Amplitude and DPE

3) Frequency domain

To calculate Signal to Noise Ratio (SNR) and Signal to Noise and Distortion (SINAD) in Fig. 6, we first pad the FFT with a minimum of four bits for smoothing the frequency spectrum. Next, we find the peaks in the frequency spectrum corresponding to the fundamental frequency component of the signal (heart rate) and the first and second harmonics between 0.9 Hz and 4.4 Hz. We find a local minimum to either side of the peaks and select the points between them. For accurate detection of the harmonics, we check that the frequency of the first and second harmonics are within 5% of the expected frequency calculated from the fundamental frequency component. We include the harmonics as part of the signal for SNR and as part of the noise for SINAD to investigate which one characterizes the signal better. For SNR, we calculate the RMS mean, shown in green under the red peak, of the fundamental frequency and two harmonics as

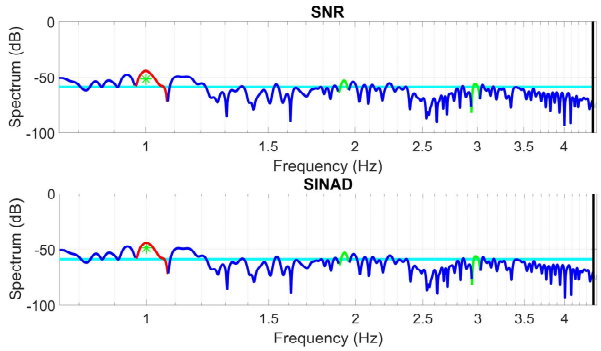

Figure 6: SNR (top) and SINAD (bottom)

the signal and the RMS of the remaining values up to 4.4 Hz which defines the noise. Similarly, for SINAD, we identify only the fundamental frequency as the signal and fold the harmonics into the noise.

III. Experimental Results

A. Data Collection

This study enrolled five male participants, between ages 20 and 36, under Texas A&M University IRB (IRB2017-0086D). We acquired data in 53 second trials and collected between ten to fifteen trials depending on the absence or presence of motion artifacts in the preceding trial. Nine trials were excluded from two of five subjects.

B. Statistically significant features

PTT, Diastolic Peak Error (DPE) and normalized amplitude of the ΔZ signal showed a marked reduction in accuracy and reliability when the sensors were placed away from the artery. Fig. 7 shows PTT measured for Subject 2 over one trial between two arterial and two off-arterial voltage sensors. Arterial PTT MS and Pk-Tan for subject 2 have a standard deviation of only 3.78 and 4.44 ms compared to off-arterial PTT MS and Pk-Tan of 6.93 and 9.85 ms. In Table I, data for all subjects show similar results. Off-arterial PTT showed a different mean and much larger standard deviation for both Pk-Tan and MS than arterial PTT. Since the ΔZ signal is weaker off the artery, the effect of noise is more pronounced. We observe this effect with many negative values in off-arterial PTT which also leads to a lower mean compared to arterial PTT. Since we have previously shown that PTT has a strong correlation to BP [7], these results indicate that arterial sensor location is critical for accurate BP estimation due to its effect on PTT.

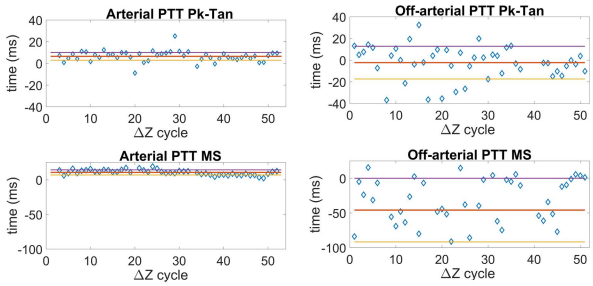

Figure 7: arterial PTT (left) and off-arterial PTT (right)

TABLE I. PTT comparison for arterial vs. off-arterial ΔZ

Features \ Setup	Arterial (CH1 – CH2)		Non-arterial (CH3 – CH4)	
	Global mean	STD	Global mean	STD
Pk-Tan (ms)	6.8	3.7	3	8.3
MS (ms)	5.4	3.1	3.5	5.6

DPE increased significantly for off-arterial placement of the sensors exemplified in Fig. 8 and quantified in Table II. As in PTT measurement, noise sources have a pronounced impact on the sensed ΔZ signal. Lower signal intensity coupled with this noise caused distortions in the off-arterial Bio-Z signal which decreased the peak sharpness and increased the mean DPE by 7 to 10 ms for arterial vs. off-arterial Bio-Z. Off-arterial sensors, Ch. 3 and Ch. 4, also exhibited greater standard deviations. After normalization, we observed decreasing amplitude for off-arterial vs. arterial ΔZ. Moving from the wrist toward the elbow, normalized intensity also decreased along the artery and off-artery due to the deeper location of the artery away from the wrist.

C. Statistically insignificant features

We found SNR, SINAD and fall time features of the ΔZ signal were not useful in distinguishing between arterial and off-arterial Bio-Z. Paired t-testing fall time distributions for arterial vs. off-arterial ΔZ eliminated fall time between PK and FT as statistically insignificant. SNR and SINAD of the

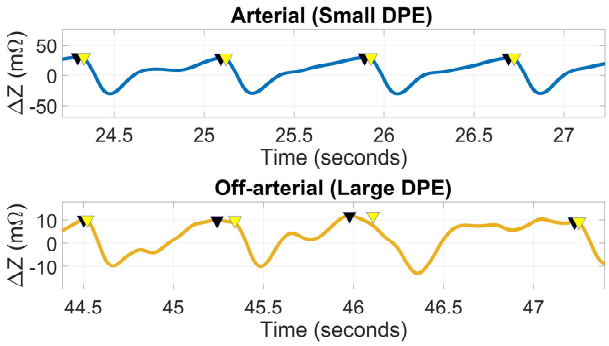

Figure 8: Off-arterial DPE (bottom) larger than arterial DPE (top)

TABLE II. Comparison of DPE, SNR-SINAD, amplitude and fall time for arterial versus off-arterial ΔZ

Features \ Setup	Arterial Setup		Off-arterial Setup	
	Global mean	STD	Global mean	STD
	Channel 1		Channel 3	
Diastolic Peak Error (ms)	26.60	6.12	33.30	14.92
SNR (dB)	11.53	2.10	9.60	2.58
SINAD (dB)	12.92	1.97	11.89	2.01
Amplitude	1.15	0.18	0.82	0.19
Fall time (ms)	132.00	9.90	127.80	8.34
	Channel 2		Channel 4	
Diastolic Peak Error (ms)	25.60	7.96	35.20	15.90
SNR (dB)	11.47	2.52	9.44	2.36
SINAD (dB)	12.16	2.60	11.21	2.34
Amplitude	0.88	0.22	0.39	0.20
Fall time (ms)	126.20	7.64	128.10	10.30

Fourier spectrum of ΔZ showed inconclusive results for distinguishing between arterial and off-arterial ΔZ. Arterial SNR and SINAD averaged only one and two dB higher, respectively, than their off-arterial metrics.

D. *Summary of Results*

Arterial PTT had a different mean and much lower standard deviation than off-arterial PTT, and arterial DPE had significantly lower mean than its off-arterial counterpart. Normalized amplitude decreased off the artery and also decreased moving away from the wrist where the artery is deeper. This supported our hypothesis that measuring Bio-Z on the artery gives better signal quality and lower noise. We observed no significance in the fall time, SNR and SINAD.

IV. Conclusion

Measuring Bio-Z signal on the artery helps maximize the quality of the ΔZ signal, improves the accuracy of the measured PTT and enables a sharp peak in the diastolic phase. Arterial Bio-Z contains lower PTT variations, lower DPE and higher signal intensity or amplitude compared to off-arterial measurement. For accurate estimation of hemodynamic parameters, it is essential that future wrist-worn wearables incorporate arterial localization techniques such as those presented here. By continuously monitoring of these features on an array of sensors, we can identify the pair closest to the artery for accurate and non-invasive round-the-clock monitoring of hemodynamic parameters.

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