2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

A Non-invasive Radial Arterial Compliance Measuring Method using Bio-Impedance

Xiaochen Tang, *Member, IEEE,* Matija Jankovic, *Student Member, IEEE,*
and Roozbeh Jafari, *Senior Member, IEEE*

***Abstract*— Arterial compliance is one of the essential indicators of certain types of cardiovascular disease, with both systematic and local compliance exhibiting significance. Radial arterial compliance (RAC) has been regarded as an important type of local compliance in several long-term pathophysiological studies. Bio-Impedance (Bio-Z) is a non-invasive signal which can be used to unobtrusively monitor blood volume changes, captured using wearable sensors. In this paper, a compliance monitoring technique based on Bio-Z is proposed for long-term RAC measurements. Both the distensibility-blood pressure (BP) relation and compliance-mean artery pressure relation are analyzed to observe interparticipant compliance variations from four healthy participants, by controlling the blood flow in a way similar to the oscillometric method for BP measurement. A Bio-Z based compliance index (DBZI) is proposed that can be leveraged for continuous and unobtrusive sensing paradigms. A consecutive seven-day experiment shows that the mean and standard deviation values of the difference between the median value of the Bio-Z based beat-by-beat calculated compliance and DBZI are 0.17 and 0.20 mOhm/mmHg, respectively. This demonstrates the consistency and repeatability of the measurements. The results show that DBZI can track the Bio-Z based compliance with an error of 9.72% and 11.67%, compared to a gold standard, in terms of mean and standard deviation, respectively.**

***Index Terms*—Radial arterial compliance, bio-impedance, compliance BP relation, long-term compliance monitoring.**

I. Introduction

CARDIOVASCULAR disease (CVD) has become the leading health problem in many countries. According to the American Heart Association's report, the estimated annual direct and total cost of CVD in America in 2035 will reach $748.7 billion and $1.1 trillion, respectively [1]. Arterial compliance is an essential biomarker in the diagnosis of several types of CVD. Given that the human artery tree is an inhomogeneous system, both local and systematic arterial compliance have been found to be significant in prior studies. For example, studies show that systematic arterial compliance is strongly related to age and early diagnosis of hypertension [2] [3]. Care-providers usually take advantage of technologies like the SphygmoCor to evaluate systematic arterial compliance that requires training and can only be used in clinical settings [4]. It is challenging to conduct measurements on a daily or weekly basis. In contrast, local arterial compliance such as radial arterial compliance (RAC) may show paradoxical compliance characteristics [5]. RAC plays essential roles in a wide range of scenarios; RAC has a pathophysiological relationship with sympathetic activation in congestive heart failure patients [6]; RAC could also be used to evaluate a long-term antihypertensive treatment that can reduce radial artery wall hypertrophy in elderly patients [7]; RAC could be seen as evidence of long duration lipid-lowering therapy for familial hypercholesterolemia [8]. Local compliance measurements typically require ultrasound echo-tracking systems to obtain information like diameter and diameter change of the radial artery. These systems are bulky and need skilled technicians for use [2].

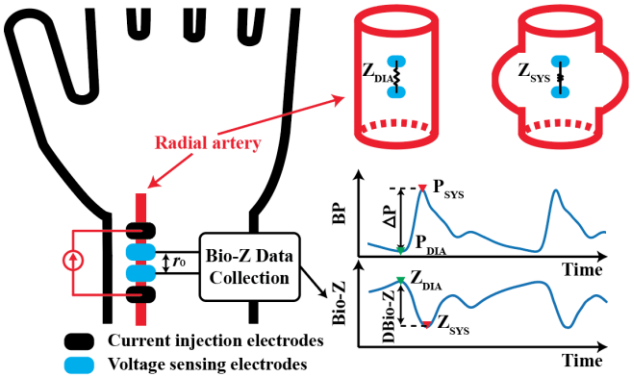


Fig. 1. Bio-Z data collected from left hand radial artery using four-terminal sensing, and examples of signal morphology of BP and Bio-Z with corresponding fiducial points.

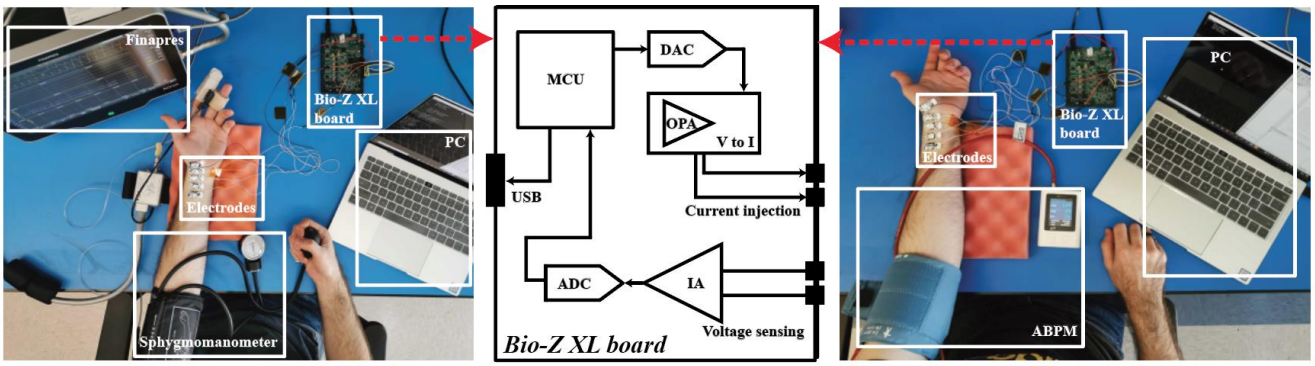
Bio-impedance (Bio-Z) is a non-invasive, yet powerful modality to measure human vitals through a pair of small-sized high-frequency alternating current (AC) injection and voltage sensing electrodes placed on the skin as shown in Fig. 1. These electrodes capture the impedance of the human body at the injected frequency. Bio-Z has been widely used to monitor human health conditions, such as to project blood

This work was supported in part by the National Science Foundation, under grant CNS-1738293 and the National Institutes of Health, under grant 1R01EB028106. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding organizations.

Xiaochen Tang is with the Department of Biomedical Engineering, Texas A&M University, College Station, TX 77843 USA.

Matija Jankovic is with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843 USA.

R. Jafari is with the Departments of Biomedical, Computer Science and Engineering, and Electrical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: rjafari@tamu.edu).



(a) (b) (c)

Fig. 2. RAC measurement system setup. (a) Compliance BP relation measurement; (b) Main components of Bio-Z XL board; (c) Compliance index (DBZI) measurement.

pressure (BP) using pulse transit time (PTT) and features extracted from real-time Bio-Z signals [9]; and to detect respiration rate, heartbeat rate, and other thoracic activities [10]. An advantage of using Bio-Z in lieu of photoplethysmography (PPG) is the ability of Bio-Z to provide more detailed observations from the artery segment, due to the deep penetration of the high-frequency signal into tissue. PPG merely captures pulsatile activities in capillaries. The Bio-Z signals carry the characteristics of the pulsatile activities within the arteries as well as the capillaries. As shown in Fig. 1, the Bio-Z signal is collected from the radial artery using the four-terminal sensing method, where the Bio-Z signal is aligned with the pulse wave, and the delta Bio-Z (DBio-Z) value represents the variation of blood volume with BP changing from diastolic to systolic in the selected artery segment. With the information of blood volume variation and BP change, we can measure arterial compliance.

The contributions of this paper can be summarized as follows: 1) a non-invasive RAC measuring method based on Bio-Z is proposed. With the proposed method, we could monitor RAC changes and identify the interparticipant RAC differences through the analysis of the compliance and BP relations. Both the distensibility-BP (represented by DBio-Z) relation and the Bio-Z based compliance-mean artery pressure (MAP) relation are analyzed. 2) A definition of DBio-Z based compliance index (DBZI) is also proposed for future long-term ambulatory RAC monitoring. The rest of this paper is organized as follows. In Section II, the proposed compliance measurement details based on Bio-Z and DBZI are introduced. The analysis of the compliance BP relation and calculated DBZI are described in Section III. Finally, the paper ends in Section IV with the concluding remarks.

II. Methods

Arterial compliance is defined as the volume change of an artery segment (diameter change) due to a given change in BP:

$$Local\ Compliance = \frac{\Delta V}{\Delta P} \quad (1)$$

where ΔV is the blood volume change for a defined artery segment, and ΔP is the corresponding change in BP. Localized arterial compliance measurement is usually governed by Equation (1), while systematic compliance is estimated using an indirect method by obtaining the pulse wave velocity (PWV) as noted in Equation (2):

$$Systematic\ Compliance = \frac{V}{\rho PWV^2} \quad (2)$$

where V is the internal volume of the artery segment, and ρ is the blood density.

A. *DBio-Z as an alternative representation of blood volume change*

According to (1), $Local\ Compliance = \frac{\Delta V}{\Delta P} = \frac{\Delta A_s r_0 \eta}{\Delta P}$, where ΔA_s is the cross-section area change of the artery segment, r_0 is the length of the chosen artery segment as shown in Fig. 1 (*i.e.,* the distance between the voltage sensing electrodes), and η is the membrane circumferential strain. Instead of using blood volume (artery diameter) change in the numerator, the Bio-Z signal is applied to represent ΔA_s by $DBio\text{-}Z = \rho_Z \frac{r_0}{\Delta A_s}$, where ρ_Z is electrical resistivity. Thus, we can obtain the compliance equation expressed in terms of *DBio-Z* as,

$$Local\ Compliance = \frac{\rho_Z r_0^2 \eta}{Z_{sys} Z_{dia}} \cdot \frac{DBio\text{-}Z}{P_{sys} - P_{dia}} \quad (3)$$

Here, $DBio\text{-}Z = Z_{dia} - Z_{sys}$, Z_{sys} and Z_{dia} are the corresponding systolic and diastolic amplitude of *Bio-Z* as shown in Fig. 1, respectively, and P_{sys} and P_{dia} are the systolic and diastolic BP, respectively.

In Equation (3), ρ_Z is assumed to remain constant in the presence of pulse waves. The Bio-Z signal in this experiment has a base impedance of around 100 Ohm, while *DBio-Z* is typically less than 100 mOhm. Experiments show that during a two-minute measurement, the base impedance usually changes by less than 1 Ohm. Given this is less than a 2% change in the base impedance, $Z_{sys} Z_{dia}$ could be seen as a constant. The value for r_0 is set to 5 mm in this measurement. For a *PWV* range from 6 m/s to 12 m/s, the pulse transit time between the voltage sensing electrodes then ranges from 0.42 ms to 0.83 ms. From the pulse wave morphology [2], the chosen artery segment could be seen as isobaric for this time

interval. Thus, the left part of (3) could be viewed as a constant $C_C = \frac{\rho_Z r_0^2 \eta}{Z_{sys} Z_{dia}}$, and we can use Equation (4) to measure the Bio-Z based arterial compliance:

$$Compliance_{Bio\text{-}Z} = C_C \frac{DBio\text{-}Z}{P_{sys} - P_{dia}} \quad (4)$$

B. Data collection for compliance BP relation analysis

The system setup used to collect data for the Bio-Z based compliance BP relation analysis is shown in Fig. 2, which is composed of a custom-designed versatile Bio-Z signal recording printed-circuit board (called Bio-Z XL board), a standard sphygmomanometer with cuff, and the Finapres® NOVA system for capturing BP continuously.

The core components of the XL board for Bio-Z signal acquisition mainly include an ARM Cortex M4 microcontroller unit (MCU), a 16-bit digital-to-analog converter (DAC) (DAC8811, Texas Instruments, USA), a precision operational amplifier (OPA) (OPA211, Texas Instruments, USA), a low noise instrumentation amplifier (IA) (AD8421, Analog Devices, USA), and the high-resolution 24-bit delta-sigma analog-to-digital converter (ADC) (ADS1278, Texas Instruments, USA). The MCU controls the DAC to generate sinusoidal AC with a programmable frequency (generating 0.9 mA peak-to-peak amplitude at 11.7 kHz in our experiments) using the operational amplifier. The generated current is sent to the current injection electrodes which are attached to the skin. The voltage sensing electrodes then capture the voltage changes due to this stimulation, and the signal is amplified (gain: 20 dB) through the instrumentation amplifier. Finally, the voltage signal is sampled by the delta-sigma ADC and sent to the PC through USB for post data processing, including de-mixing, downsampling, conversion to impedance, and *DBio-Z* extraction.

Electrodes connected to the XL board are attached to the skin at locations on top of the left wrist's radial artery using the four-terminal sensing method, as shown in Fig. 1, which has been commonly used in previous related work [11]. The Finapres® NOVA system is operated simultaneously with the XL board to record beat-by-beat BP in real-time. The standard sphygmomanometer is worn on the left arm 2 cm above the cubital fossa, which controls the blood flow in the brachial artery.

The intuition behind this experiment is that after the blood flow in the brachial artery is occluded and then reinstated gradually, the change in blood volume and pressure could be recorded simultaneously. The characteristic of the RAC could then be calculated. The detailed operation flow of the measurement is described in Procedure 1, and five repetitions of this procedure were conducted for finer curve plotting.

C. Compliance index measurement

To further facilitate the adoption of Bio-Z and RAC measurement in medical diagnostic paradigms, we introduce the *DBZI*. Instead of capturing pressure change data for each heartbeat through the Finapres® NOVA, *DBZI* uses a cuff-based BP monitor to obtain a one-time BP measurement. The mean value of *DBio-Z* is measured for two minutes, and *DBZI* is calculated using Equation (5):

$$DBZI = mean(DBio\text{-}Z)/(P_{sys} - P_{dia}) \quad (5)$$

The procedure associated with obtaining this index is

Procedure 1: Data acquisition for compliance BP relation analysis based on Bio-Z (XL board collects data for two minutes)

1: Record BP data using a continuous BP monitoring device (e.g., Finapres® NOVA);
2: Collect Bio-Z data for 20 seconds while wearing the deflated cuff;
3: Inflate the cuff to 160-180 mmHg while the pressure is monitored by a sphygmomanometer;
4: Deflate the cuff gradually at the rate of 2-3 mmHg/s until the cuff is fully deflated;
5: Keep the arm steady until the Bio-Z recording device completes the measurement;

Procedure 2: Data acquisition for *DBZI* calculation (XL board collects data for two minutes)

1: Record BP data using the cuff-based BP monitor;
2: Record *DBio-Z* using Bio-Z recording device for two minutes;
3: Calculate the *DBZI*;

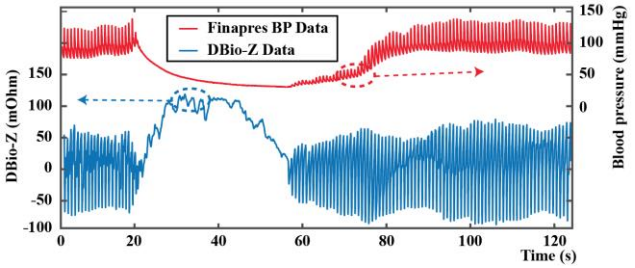


Fig. 3. An example of aligned *DBio-Z* and BP data collected using Bio-Z XL board and Finapres® NOVA system.

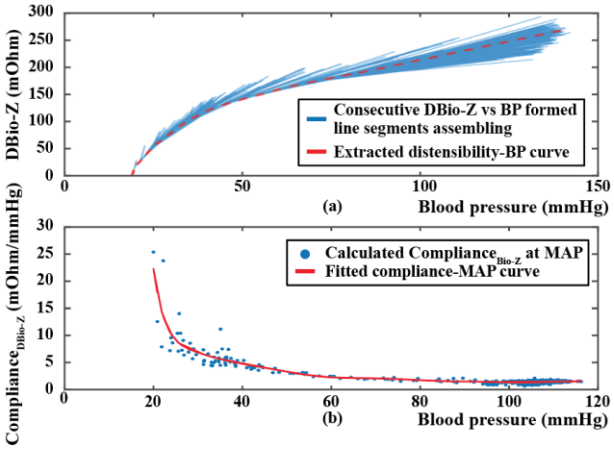


Fig. 4. Example compliance BP relations that are generated by data collected following procedure 1 from one participant. (a) Distensibility-BP relation, (b) compliance-MAP relation.

similar, but simpler and more convenient than the data collection for compliance BP relation analysis and is described in Procedure 2.

III. Results

The data was collected under IRB approved by Texas A&M University (IRB2017-0086D). Five trials of Bio-Z data following Procedure 1 were collected from four healthy participants (age range: 21-41) while seated on a chair at rest. All participants had no underlying health conditions including the absence of pressure-related pathologies, and provided written consent before they participated in the study. A summary of their information can be found in Table 1.

TABLE I. Participant Demographics

Age (years)	30.8 ± 7.5
Weight (kg)	91.9 ± 13.4
Height (cm)	183.7 ± 8.5
Male	4
BMI (kg/m^2)	27.1 ± 2.0

The data is presented as mean ± standard deviation.

A. Compliance and BP relation measurement

Sample raw data collected for the experiment in Procedure 1 is shown in Fig. 3. After the timing alignment, pairs of *DBio-Z* and ΔP data can be extracted beat-by-beat. We plot the distensibility-BP relation in Fig. 4(a), which illustrates the relationship between arterial inner volume and BP change, and gives us insight into the elasticity of the artery under different BP. The compliance-MAP relation shows the fitted curve of calculated amplitude of $Compliance_{Bio\text{-}Z}$ at each measured MAP point as depicted in Fig. 4(b).

Because arterial compliance is inversely proportional to BP^2 [12], different diastolic BP may introduce variations in the baseline of the compliance. Further, considering the error introduced by electrode placement, a Bio-Z and diastolic pressure based empirical normalization factor (NF) is applied to reduce the errors as shown in Equation (6):

$$NF = mean(DBio\text{-}Z_{base}, Bio\text{-}Z_{base})/(P_{dia}^2) \quad (6)$$

Where $DBio\text{-}Z_{base}$ and $Bio\text{-}Z_{baseline}$ are the mean value of *DBio-Z* and baseline *Bio-Z* collected from a two-minute measurement prior to the initiation of the first iteration of Procedure 1. During this two-minute period the participants were seated, and the Bio-Z and BP were recorded without any manipulation of blood flow in the brachial artery. As shown in Fig. 5, an experiment consisting of six measurements is performed with participant 3 following Procedure 1 within five days, which is used to investigate our hypothesis that human RAC does not change significantly with a uniform health condition over a short period of time. After applying the normalization factor, the six distensibility-BP and compliance-MAP relations show similar morphologies and trends, which supports our hypothesis. By applying the normalization factor to mitigate the effects of electrode placement and BP changes, we can monitor the RAC variations through these relation analyses.

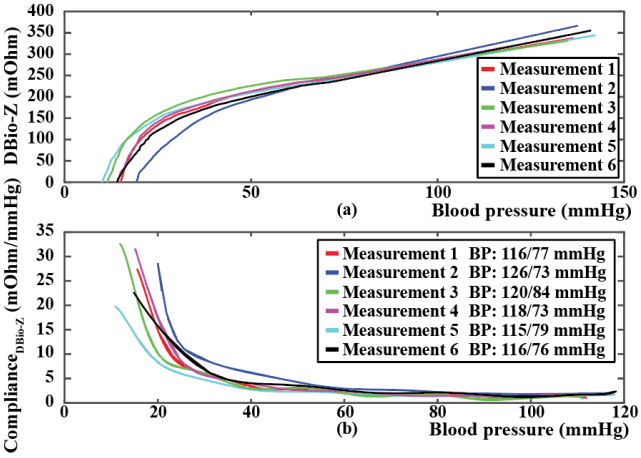


Fig. 5. Compliance BP relations with the proposed normalization factor, which are generated from 6 measurements from participant 3 following Procedure 1. (a) Distensibility-BP relation, (b) compliance-MAP relation.

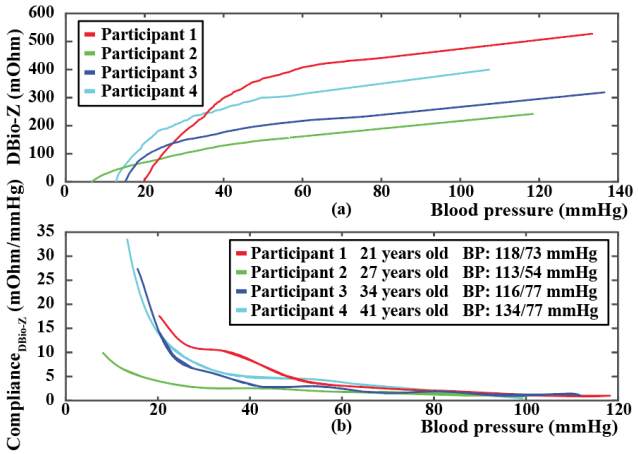


Fig. 6. Compliance BP relations for 4 participants following Procedure 1. (a) Distensibility-BP relation, (b) compliance-MAP relation.

Fig. 6 shows the distensibility-BP and compliance-MAP relations for four participants, with each participant completing measurements as specified by Procedure 1. We observe apparent differences among four participants which indicates the interparticipant variability in RAC. The largest $Compliance_{Bio\text{-}Z}$ values calculated from (4) imply the steepness of the rising slope of the distensibility-BP relation. From participant 1 to participant 4, the largest $Compliance_{Bio\text{-}Z}$ values are 36.40, 14.90, 32.56, and 33.35 mOhm/mmHg, respectively, which conforms to the participants' morphologies of the distensibility-BP relations as shown in Fig. 6 (a).

B. Compliance index measurement

The findings of the seven-day *DBZI* recording experiment are shown in Fig. 7. Compared to concurrent $Compliance_{Bio\text{-}Z}$ measurements conducted by the Finapres® NOVA and calculated for each beat, the mean and standard

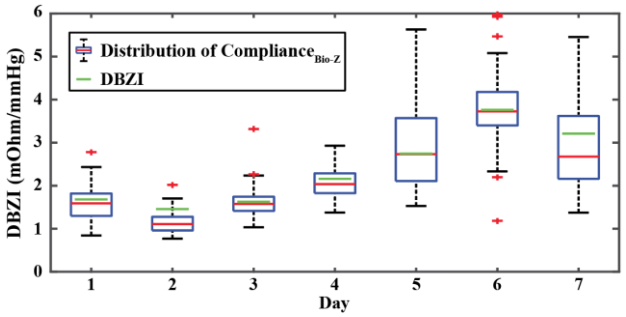


Fig. 7. 7-day consecutive measurements of *DBZI*, and distributions of $Compliance_{Bio\text{-}Z}$ simultaneously measured by Finapres® NOVA for comparison.

deviation of the difference between the median of the distribution of $Compliance_{Bio\text{-}Z}$ and *DBZI* are 0.17 and 0.20 mOhm/mmHg, respectively. These results show that *DBZI* can track the slight compliance variation with an error of 9.72% and 11.67% in mean and standard deviation, respectively. *DBZI* provides an effective method for capturing arterial compliance while ensuring ease of deployment and use.

IV. Conclusion

In this paper, a non-invasive RAC measuring method using Bio-Z is proposed. Distensibility-BP and compliance-MAP relations are analyzed using *DBio-Z*, instead of reliance on measuring blood volume changes, and are used to evaluate arterial compliance. The results show consistent morphologies and trends in the compliance BP relations for single participant continuous RAC measurements, and identifiable differences in an experiment with four participants. A compliance index is also proposed for more convenient long-term monitoring of RAC, and the results show that the *DBZI* can track small RAC changes. Given the RAC experiment is carried out with only four healthy participants, we are limited in approaching more sophisticated findings. Validation of RAC consistency on more participants would be beneficial. We plan to include more participants with various health and physical conditions in our future research.

References

[1] S. S. Virani, A. Alonso, E. J. Benjamin, M. S. Bittencourt, C. W. Callaway, A. P. Carson, A. M. Chamberlain, A. R. Chang, S. Cheng, F. N. Delling and others, "Heart disease and stroke statistics—2020 update: a report from the American Heart Association," *Circulation,* vol. 141, p. e139–e596, 2020.

[2] L. A. Bortolotto, O. Hanon, G. Franconi, P. Boutouyrie, S. Legrain and X. Girerd, "The aging process modifies the distensibility of elastic but not muscular arteries," *Hypertension,* vol. 34, p. 889–892, 1999.

[3] R. R. Townsend, I. B. Wilkinson, E. L. Schiffrin, A. P. Avolio, J. A. Chirinos, J. R. Cockcroft, K. S. Heffernan, E. G. Lakatta, C. M. McEniery, G. F. Mitchell and others, "Recommendations for improving and standardizing vascular research on arterial stiffness: a scientific statement from the American Heart Association," *Hypertension,* vol. 66, p. 698–722, 2015.

[4] M. Butlin and A. Qasem, "Large artery stiffness assessment using SphygmoCor technology," *Pulse,* vol. 4, p. 180–192, 2016.

[5] G. E. McVeigh, C. W. Bratteli, D. J. Morgan, C. M. Alinder, S. P. Glasser, S. M. Finkelstein and J. N. Cohn, "Age-related abnormalities in arterial compliance identified by pressure pulse contour analysis: aging and arterial compliance," *Hypertension,* vol. 33, p. 1392–1398, 1999.

[6] G. Grassi, C. Giannattasio, M. Failla, A. Pesenti, G. Peretti, E. Marinoni, N. Fraschini, S. Vailati and G. Mancia, "Sympathetic modulation of radial artery compliance in congestive heart failure," *Hypertension,* vol. 26, p. 348–354, 1995.

[7] X. Girerd, C. Giannattasio, C. Moulin, M. Safar, G. Mancia and S. Laurent, "Regression of radial artery wall hypertrophy and improvement of carotid artery compliance after long-term antihypertensive treatment in elderly patients," *Journal of the American College of Cardiology,* vol. 31, p. 1064–1073, 1998.

[8] C. Giannattasio, A. A. Mangoni, M. Failla, S. Carugo, M. L. Stella, P. Stefanoni, G. Grassi, C. Vergani and G. Mancia, "Impaired radial artery compliance in normotensive subjects with familial hypercholesterolemia," *Atherosclerosis,* vol. 124, p. 249–260, 1996.

[9] B. Ibrahim and R. Jafari, "Cuffless blood pressure monitoring from an array of wrist bio-impedance sensors using subject-specific regression models: Proof of concept," *IEEE transactions on biomedical circuits and systems,* vol. 13, p. 1723–1735, 2019.

[10] K. Sel, B. Ibrahim and R. Jafari, "ImpediBands: Body coupled bio-impedance patches for physiological sensing proof of concept," *IEEE Transactions on Biomedical Circuits and Systems,* vol. 14, p. 757–774, 2020.

[11] J. Chen, L. Xu, Z. Cao and H. Zhou, "Four-terminal imaging using a two-terminal electrical impedance tomography system," *IEEE Transactions on Instrumentation and Measurement,* vol. 63, p. 432–440, 2013.

[12] R. Mukkamala, J.-O. Hahn, O. T. Inan, L. K. Mestha, C.-S. Kim, H. Töreyin and S. Kyal, "Toward ubiquitous blood pressure monitoring via pulse transit time: theory and practice," *IEEE Transactions on Biomedical Engineering,* vol. 62, p. 1879–1901, 2015.