This full-text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication.

Bilateral Carotid Pulse Wave Velocity: A Proof of Concept

Ishwarya S
Department of Electrical Engineering,
Indian Institute of Technology Madras
Chennai, India
ee22s058@smail.iitm.ac.in

Raj Kiran V
Healthcare Technology
Innovation Centre (HTIC), IIT Madras
Chennai, India
rajkiran.v@htic.iitm.ac.in

Rahul Manoj
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
rahul_manoj@smail.iitm.ac.in

P. M. Nabeel
Healthcare Technology
Innovation Centre (HTIC), IIT Madras
Chennai, India
nabeel@htic.iitm.ac.in

Jayaraj Joseph
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
jayaraj@ee.iitm.ac.in

2024 IEEE International Symposium on Medical Measurements and Applications (MeMeA) | 979-8-3503-0799-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/MEMEA60663.2024.10596721

***Abstract*—Stroke, a devastating cerebrovascular event caused by blood clot formation, poses a significant global health challenge. Timely detection of vulnerable plaque accumulation in the carotid arteries, which supply blood to the brain, is crucial for stroke prevention, yet diagnosing this plaque with conventional tests is difficult. The rupture of such plaque can lead to clot formation, obstructing blood flow and resulting in lasting brain damage. However, current technologies that utilize imaging are costly and require expertise, limiting their use in routine healthcare assessments. Moreover, techniques like global pulse wave velocity (PWV) measurements lack the precision to capture specific variations related to plaque presence and stiffness differences, particularly in detecting asymmetries and localized stiffness variations. To address these limitations, a novel bilateral carotid PWV measurement system is introduced, designed to overcome synchronization challenges and anatomical discrepancies by ensuring optimal probe placement and thereby reducing reliance on operator skill. A preliminary in-vivo study involving 40 subjects demonstrated promising results, with beat-to-beat PWV coefficient of variation on the left and right carotid arteries below 7% and 9%, respectively. Further exploration in larger clinical settings is warranted to fully assess the potential of bilateral PWV measurement in stroke prevention**

***Keywords*—Vascular aging, arterial stiffness, bilateral PWV, photoplethysmography.**

I. Introduction

Stroke, a devastating neurological event often initiated by the formation of blood clots in cerebral arteries, remains a significant global health concern. It frequently stems from a particular type of unstable plaque termed vulnerable plaque [1]. This plaque accumulates silently in the carotid arteries, crucial vessels that supply blood to the brain [2].

The rupture of vulnerable plaque sets off the formation of blood clots, which obstruct blood flow to the brain, leading to neurological impairment [3]. Hence, early identification and management of vulnerable plaque are pivotal in stroke prevention.

Symptoms such as transient ischemic attacks and strokes serve as warning signs of impending stroke risk, whereas asymptomatic plaque does not manifest noticeable symptoms or clinical signs [4]. They may be incidentally detected during medical imaging studies like CT scans, MRIs, or ultrasounds. Nonetheless, they still pose a stroke risk if they result in vessel narrowing or blockage over time or if they rupture, causing a thrombus or embolus to develop, remaining silent until provoked by specific factors [2]. This underscores the necessity for vigilant monitoring and risk assessment of the cardiovascular system.

The current state of technology encompasses various approaches for assessing cardiovascular health. Approaches like Carotid Artery Intravascular Ultrasound (IVUS) involve inserting a catheter with a miniaturized ultrasound probe into the artery, which is invasive and not feasible for initial screening [5]. Conversely, other modalities like MRI and Computed Tomographic Angiography (CTA) are costly and may not be available in smaller healthcare facilities [6]. Computerized recognition, segmentation and detection mechanisms have become the cornerstone of imaging based diagnostics applications [7-9]. While High-Resolution Ultrasound (HRUS) provides excellent, noninvasive images of the carotid arteries for plaque detection, its high cost and requirement for skilled technicians limit its use in primary care and small healthcare facilities [10-13]. On the other hand, global Pulse Wave Velocity (PWV) assessments may indicate plaque accumulation but lack specificity for carotid arteries [14]. Additionally, they do not give information on which side of plaque is present, as measuring it on one side may not necessarily reflect plaque presence on the other [15-16]. Consequently, a user-friendly, localized PWV device tailored for the carotids would serve as a valuable tool for identifying individuals at stroke risk due to plaque accumulation on either side, thereby enabling early intervention in primary care settings.

In response to this demand, we have developed a bilateral PWV measurement designed to comprehensively evaluate arterial health. By measuring PWV in both carotid arteries, it

This research was partially supported by Science and Engineering Research Board (SERB), Department of Science and Technology (DST) and Indian Institute of Technology (IIT) Madras under Institute of Eminence (IoE) funding from the Ministry of Human Resource Development (MHRD), Government of India.

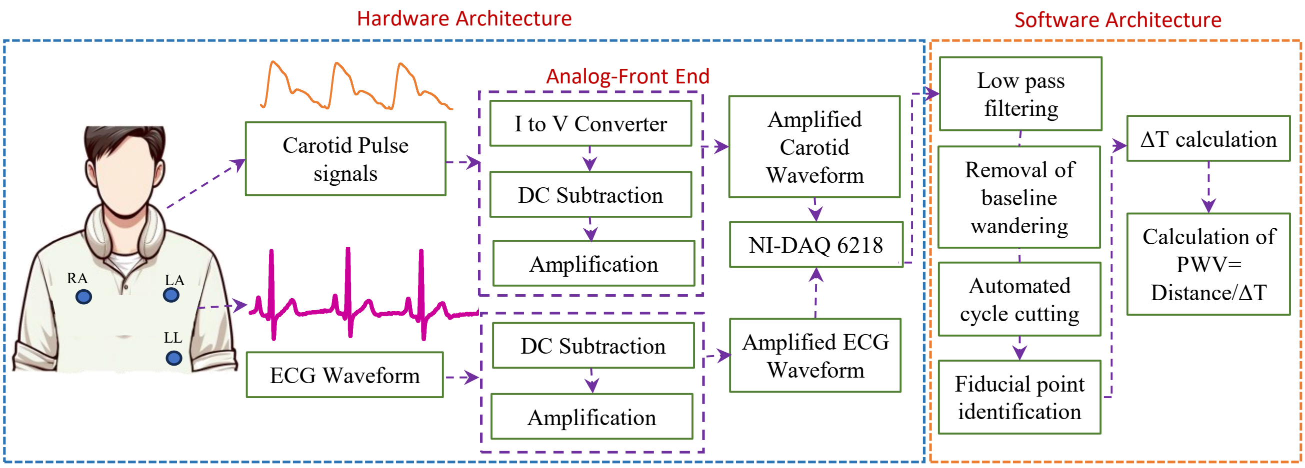

Fig. 1. Measurement system block diagram comprising of the hardware and software architecture

adeptly identifies potential disparities or localized vulnerabilities in arterial rigidity between the left and right sides [17]. While this device does not singularly pinpoint plaque presence, it flags the irregularities within the arteries. Our main objective with this device is to provide an initial assessment that is noninvasive and relatively straightforward, capable of detecting notable discrepancies in PWV between the left and right carotid arteries. Such variances may hint at conditions like stenosis on one side, potentially linked with precarious plaque [15]. This device can thus serve as a screening instrument to pinpoint individuals at elevated risk. Subsequent evaluation can be done utilizing specific plaque characterization techniques such as Carotid Artery Intravascular Ultrasound (IVUS) or MRI. The developed device incorporates a custom-designed sensor system to measure pulse signals from both sides of the carotid artery along with ECG readings. To accommodate anatomical variations and ensure accurate probe placement, meticulous attention was given to the ergonomic design of the device, thus reducing the dependency on operator expertise. This study primarily focuses on the repeatability of the system and its in-vivo feasibility. Section II provides an intricate overview of the instrumentation, encompassing both hardware and software architecture. The detailed in-vivo assessment protocol is outlined in Section III, while Section IV presents the corresponding results, concluding with a delineation of future research directions.

II. Measurement System

A. Design of the transducer

The developed bilateral PWV device comprises the photoplethysmography (PPG) based sensor module to capture signals from both the carotid artery and an ECG module. ECG signals were captured using an Analog Front End (AD8232), renowned for its high Common Mode Rejection Ratio (CMRR) and signal gain. The PPG sensing module uses a quad-LED configuration. The choice of a Quad-LED configuration aimed at maximizing the surface area and optimizing light penetration angles to enhance the understanding of the effect of blood volume changes in the signal [18]. This approach sought to improve the fidelity of the captured pulse waveform, offering more accurate information about pulsatile dynamics. The strategic placement of multiple LEDs aimed to mitigate specificity issues by averaging signals across different illumination pathways, preventing potential interference from specific structures or vessels [18]. Employing a Quad-LED setup was aimed at maximizing surface area and optimizing light penetration angles to better understand blood volume fluctuations, enhancing pulse waveform fidelity for precise pulsatile dynamic analysis. The arrangement of LEDs aimed to address specificity concerns by averaging signals across varied illumination pathways, thus mitigating potential interference from specific structures or vessels.

The photodetector (PD) selected has a broad spectral range, encompassing the infrared region, and with an active surface area of 7.5mm^2. The decision on the PD's surface area was made by carefully balancing considerations that increasing the surface area of the photodetector (PD) may hinder the detection of the AC component of the PPG signal while reducing PD size could diminish the magnitude of the reflected signal. The LED and the detector were spaced 6 mm apart, with a black isolator to prevent direct coupling. The probe incorporates a custom PCB housing the LED and detector, with a silicone sealant ensuring skin coupling. Electrical connectivity was facilitated via a 3-core shielded cable from the analog front end.

The developed sensor module was housed in a custom-designed neckband with three adjustable compartments on each side, accommodating different neck sizes. The analog front end processed photoplethysmography signals by subtracting DC components and amplifying AC components, ensuring reliable acquisition of pulse signals.

B. Acquisition Hardware

Photoplethysmography signals typically encompass AC components reflecting arterial blood volume and flow changes alongside DC components representing total blood volume in the measurement area [17-19]. Given that the AC component is less than 0.2% of the DC amplitude, it is essential to subtract the DC component and amplify the AC component [19]. A custom-made analog front end was employed to ensure the reliable acquisition of pulse signals. The photodiode, responsive to light intensity, generates a current signal, which is then converted into a voltage signal through a trans-impedance amplifier. A first-order RC filter with a cutoff frequency of 0.2 Hz was utilized to extract DC

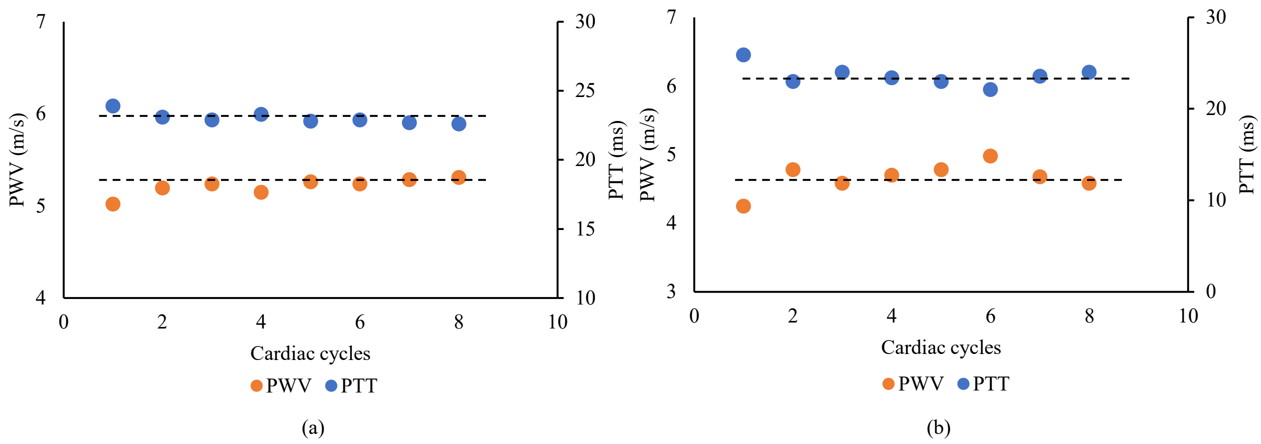

Fig 2 (a) Beat to Beat PTT and PWV obtained from left side of the artery (b) Beat to Beat PTT and PWV obtained from right side of the artery

components from the PPG signal [20]. The DC signal was subtracted and the AC signal was amplified at a gain of 50dB.

A preamplifier was used for ECG signals, followed by DC filtering and amplification. The resultant signal was then level-shifted to range from 0 to 3.3V. All voltage signals, including ECG and carotid pulse waveforms from the analog front end, were acquired using a National Instruments (NI) 6218 Data Acquisition (DAQ) system at a high sampling rate of 10 kHz.

C. Acquisition software

A customized LabVIEW program was developed to facilitate the simultaneous recording of electrocardiogram (ECG) and bilateral carotid pulse waveforms. The acquired raw signals were stored in a database for subsequent analysis. The processing software systematically handled the concurrent ECG and bilateral carotid pulse signals.

To enhance the quality of carotid signals, a 4^{th}-order Butterworth low-pass filter with a cutoff frequency of 10 Hz was applied. Since the expected range of blood pulse signal frequency in humans is from 0.7 Hz to 3 Hz, the low-pass filter was realized with 10 Hz cutoff frequency, thus allowing the fundamental and at least two harmonics while eliminating the out-of-band noise. Similarly, ECG signals underwent digital filtering with a 4th-order Butterworth low-pass filter featuring a cutoff frequency of 40 Hz. Following filtering, the acquired cycles underwent normalization and baseline wandering removal. Using an ECG-based reference, individual cycles were extracted through a cycle-cutting technique. The software evaluated each cycle's quality by assessing the repeatability of distinctive morphologies within the cycle and analyzing upward and downward slopes (ranging from 0 to 100). Key points in the carotid waveform were identified using the intersecting tangent method [21].

For each cardiac cycle, the software calculated the Pulse Transit Time (PTT) between the R peak of the ECG and the intersecting point in the carotid pulse signal. The software computed the average PTT over 10 cycles. The distance from the heart to the carotid arteries was determined by placing the phonocardiogram on the chest and identifying the point with the highest amplitude of sound signals as the heart's location. From there, the distance to the sternal notch was calculated without direct contact. Furthermore, the distances to the left

TABLE I DESCRIPTIVE STATISTICS

Parameters	**Number/ Mean ± SD**
Subjects (male/female)	49 (29/11)
Age (years)	24 – 29
Body mass index (kg/m^2)	22.70 ± 4.13
Brachial Ps (mmHg)	108.5 ± 18.5
Brachial Pd (mmHg)	71.9 ± 9.1
PWV measured on left side	3.82 ± 0.9
PTT measured on left side (ms)	41 ± 1
PWV measured on right side (m/s)	4.6 ± 1.3
PTT measured on right side (ms)	35 ± 9

and right carotid arteries were measured from the sternal notch and added to the calculated distance.

The PWV was calculated as the ratio of the distance between the heart and the carotid to the PTT. The saving the results for future analysis

III. IN-VIVO ASSESSMENT

An in-vivo study was conducted involving 40 healthy volunteers (age: 24 ± 5.2 years; gender: 29 males and 11 females; BMI: 22.70 ± 4.13 kg/m2), all free from cardiovascular diseases, to assess the repeatability and cardiovascular diseases Participants were opportunistically recruited, and written informed consent was obtained. The study adhered to protocols outlined in the Helsinki Declaration of 2003, and ethical approval was granted by the institutional review board at the Indian Institute of Technology, Madras ((IEC/2021-01/JJ/07)..

The participants were instructed to avoid strenuous physical activity for 12 hours, caffeine, and tobacco before 2 hours of the study. The examination involved interviewer-administered questionnaires to collect demographic data, medical history, and lifestyle information. The study was conducted in a quiet, temperature-controlled room. Upon entering the study room, participants were fitted with three lead electrodes and instructed to lie in the supine position for 5 minutes. Anthropometric measurements were recorded, and

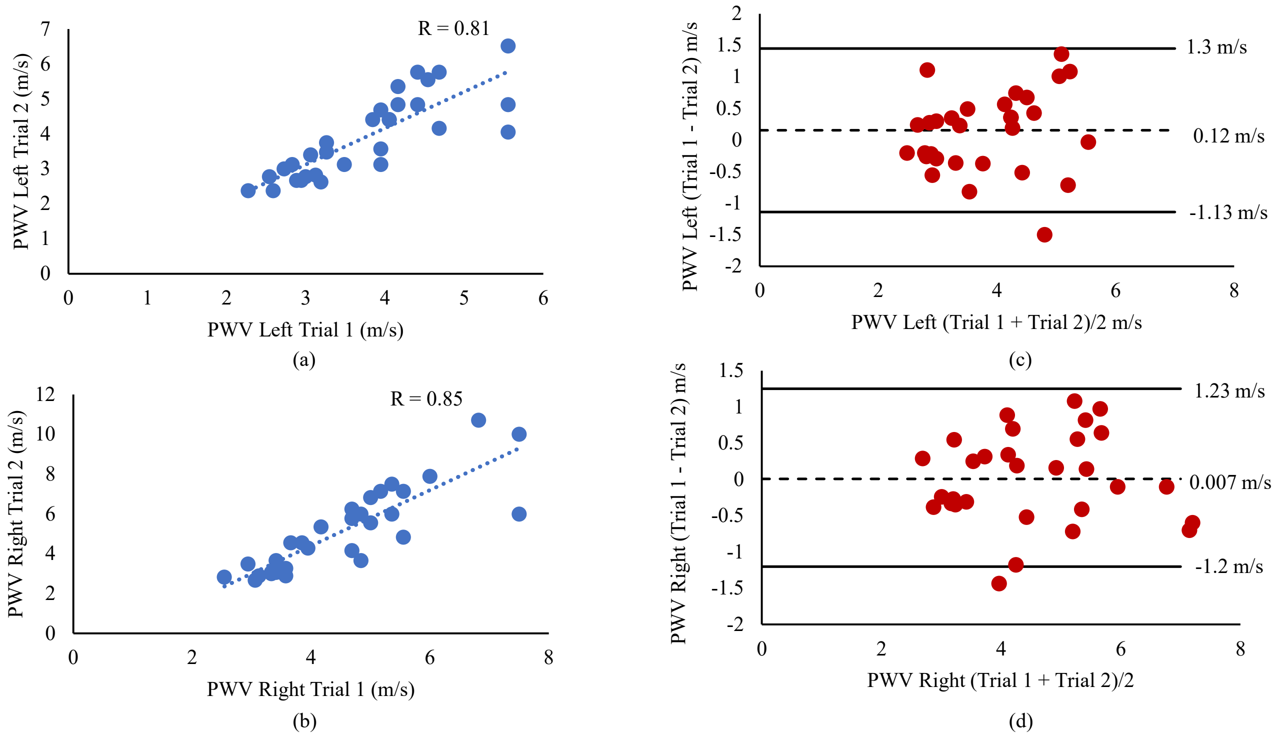

Fig 3 (a) and (b) Illustrate the regression plots comparing the two trials on the left and right side respectively, (c) and (d) corresponding Bland-Altman plots.

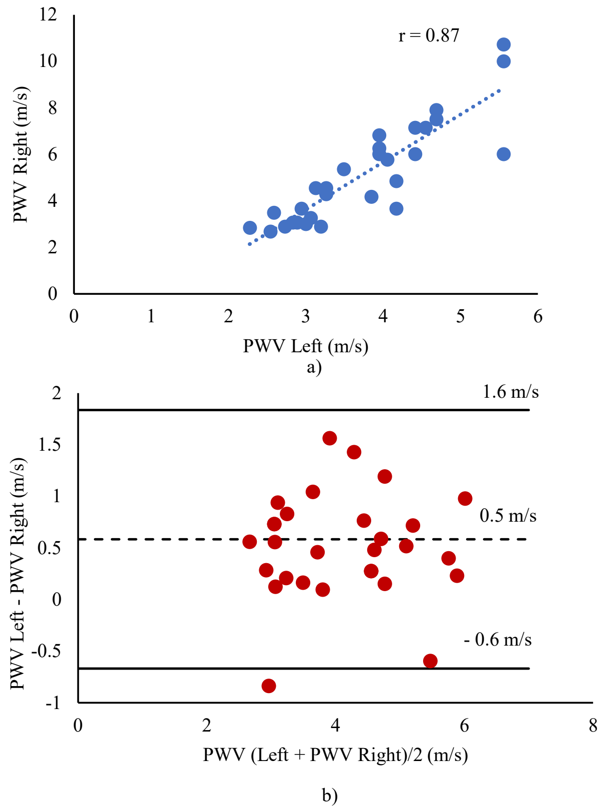

Fig 4 (a) Illustrate the regression plots comparing left and the right side of the artery (b) corresponding Bland-Altman plot.

brachial blood pressure (BP) was measured using the SunTech 721 BP monitor. Subsequently, a photoplethysmography (PPG) sensor was positioned on the carotid artery. Once high-fidelity signals were obtained, the software calculated the PWV on both the left and right carotid arteries.

Statistical Analysis

All variables were expressed as mean and standard deviation, while the coefficient of variation, calculated as the ratio of the mean to the standard deviation, served as an indicator of beat-to-beat precision. Linear regression and Bland-Altman analysis were employed to compare measurements between the left and right sides. Statistical significance of any differences in measurements was assessed using a paired t-test, with the results presented in terms of p-values. A significance level of $\alpha = 0.05$ was applied to all tests, where a p-value < 0.05 indicated rejection of the null hypothesis and confirmed statistical significance. For data analysis, SAS® OnDemand for Academics was utilized, providing a robust platform for conducting the necessary statistical assessments and ensuring the reliability of the results.

IV. Results and Discussions

A. *Subject Characteristics*

PWV measurements were successfully conducted for all 80 trials, involving 40 participants with two trials each. Table I provides a comprehensive overview of the recruited cohort's descriptive characteristics, encompassing anthropometric measurements, blood pressure data, and aortic stiffness information.

B. *Reliability of the signals*

The entire procedure, from patient data entry to report generation, was efficiently completed by the operator within 5 minutes. The device demonstrated the capability to acquire high-fidelity cycles from both the left and right sides of the carotid artery, exhibiting signal-to-noise ratios (SNR) of 30dB and 32dB, respectively. These SNR values are adequate for ensuring reliable PWV measurements.

The beat-to-beat PWV obtained from a specific participant (age: 23 years, body mass index (BMI): 24.86 kg/m2, SBP/DBP: 123/85, HR: 82 bpm) is illustrated for both the left and right sides of the artery in Fig. 2. This visualization further underscores the device's capability to capture and analyze arterial stiffness with precision and consistency.

C. Repeatability of bilateral PWV measurement

The repeatability of Pulse Wave Velocity (PWV) measurements between the two trials on the left and right carotid artery wasto be excellent. The coefficient of variation was less than 7% for the left side and 9% for the right side. Figs 3 (a) and 3 (b) illustrate the correlation between the two trials of measurement on left and right side arteries, respectively. The intra-class correlation coefficient (ICC) for left side was 0.85 ($p < 0.05$) and right side was 0.92 ($p < 0.05$), indicating excellent repeatability. The system demonstrates strong repeatability, as indicated by comparison with existing literature, even though measurements were conducted for cfPWV[22][23][24]. The obtained repeatability values align well with those of other PWV measurement like cfPWV. The Bland–Altman analysis in Figs 3 (c) and Figs 3 (d) indicated that the confidence intervals comparing between two trials of PWV ranged from 1.3 to -1.13 m/s with a mean bias of 0.12 m/s for left side and from 1.23 to -1.2 m/s with a mean bias of 0.007 for right side. The ergonomic design of the transducer enhances carotid pulse measurement repeatability by ensuring consistent placement, stabilizing the device, and minimizing external interference. Providing standardized pressure and reducing soft tissue artifact, it improves signal quality and user compliance. This approach, maintaining a stable sensor-to-skin contact, fosters reliable pulse wave signals, contributing to repeatable measurements.

D. Left and right carotid measurement

The study focused on analyzing the variations of PWV between the left and right sides. The results highlight a significant difference in PWV values between the right and left carotid arteries (Left: 3.82 ± 0.9 m/s; Right: $4.6 + 1.3$ m/s; $P > 0.001$), with the right carotid artery showing higher values. Further, the pulse transit time (PTT) of the left and right sides were 41 ± 11 ms and $35 + 9$ ms, respectively. The Blant-Altman analysis conducted indicated a mean bias of 0.5 m/s, with a confidence interval ranging from -0.6 m/s to 1.6 m/s.

The observed difference in pulse wave velocity (PWV) of 0.5 m/s is consistent with what is typically considered normal for healthy individuals, as indicated by existing literature [25]. Differences less than 0.5 m/s is likely within the expected range of variation, while increased discrepancies should be subject to further investigation, particularly when accompanied by other cardiovascular risk factors. Minor variations in PWV between the left and right carotid arteries are generally deemed normal, attributed to anatomical differences. Nevertheless, larger differences may serve as indicators of potential issues such as plaque buildup, artery twisting, or measurement variations. The results demonstrate that the device effectively captures the expected PWV patterns in line with existing literatures.

V. Limitations

This preliminary study aimed to assess the feasibility and repeatability of the developed device and to see the difference between left and right carotid Pulse Wave Velocity (PWV). However, it is crucial to acknowledge the study's limitations, primarily focusing on its exclusive inclusion of healthy participants. The decision to use a healthy cohort was deliberate, serving the purpose of investigating the feasibility of measuring bilateral PWV with the developed device and ensuring repeatability.

While the study successfully demonstrated the repeatability and consistency of obtained normal values with existing literature, caution must be exercised in generalizing these findings to the broader population, particularly those with underlying health conditions. Recognizing the importance of extending this research to diverse populations, a future large-scale study is warranted. Such an undertaking would provide a more comprehensive understanding of the device's performance across various health states, enabling the validation of its effectiveness in clinical settings.

VI. Conclusion

The bilateral PWV device was developed and the measurement feasibility and repeatability was tested on 40 participants. The results show good beat to beat repeatability between trials. The right side shows higher PWV than the left side. The average difference between the right and the left carotid was 0.7 m/s. The study conducted in this work demonstrated the reliability of the device, as it performed highly (ICC > 0.85). However, while the study successfully demonstrated repeatability and consistency of obtained normal values with existing literature, caution must be exercised when generalizing these findings to the broader population, particularly those with underlying health conditions. Recognizing the importance of extending this research to diverse populations, a future large-scale study is warranted. Such an undertaking would provide a more comprehensive understanding of the device's performance across various health states, enabling the validation of its effectiveness in clinical settings.

VII. References

[1] N. Nighoghossian, L. Derex, and P. Douek, "The Vulnerable Carotid Artery Plaque," *Stroke*, vol. 36, no. 12, pp. 2764–2772, Dec. 2005.

[2] S.-T. Weng *et al.*, "Detecting vulnerable carotid plaque and its component characteristics: Progress in related imaging techniques," *Front. Neurol.*, vol. 13, Sep. 2022.

[3] Zamani, and D. Russell, "Unstable carotid artery plaque: new insights and controversies in diagnostics and treatment," *Croat. Med. J.*, vol. 57, no. 4, pp. 311–320, Aug. 2016.

[4] M. M. Mughal, M. K. Khan, J. K. DeMarco, A. Majid, F. Shamoun, and G. S. Abela, "Symptomatic and asymptomatic carotid artery plaque," *Expert Rev. Cardiovasc. Ther.*, vol. 9, no. 10, pp. 1315–1330, Oct. 2011.

[5] V. Fernández-Alvarez *et al.*, "Novel Imaging-Based Biomarkers for Identifying Carotid Plaque Vulnerability," *Biomolecules*, vol. 13, no. 8, p. 1236, Aug. 2023.

[6] K. Dakis *et al.*, "Carotid Plaque Vulnerability Diagnosis by CTA versus MRA: A Systematic Review," *Diagnostics*, vol. 13, no. 4, p. 646, Feb. 2023.

[7] Mulay, Supriti, et al. "Liver segmentation from multimodal images using HED-mask R-CNN." *Multiscale Multimodal Medical Imaging: First*

International Workshop, MMMI 2019, Held in Conjunction with MICCAI 2019, Shenzhen, China, October 13, 2019, Proceedings 1. Springer International Publishing, 2020.

[8] Mulay, Supriti, et al. "Early detection of retinopathy of prematurity stage using deep learning approach." *Medical Imaging 2019: Computer-Aided Diagnosis.* Vol. 10950. SPIE, 2019.

[9] Banerjee, Samik, et al. "Semantic segmentation of microscopic neuroanatomical data by combining topological priors with encoder–decoder deep networks." *Nature machine intelligence* 2.10 (2020): 585-594.

[7] N. Ottakath *et al.*, "Ultrasound-Based Image Analysis for Predicting Carotid Artery Stenosis Risk: A Comprehensive Review of the Problem, Techniques, Datasets, and Future Directions," *Diagnostics*, vol. 13, no. 15, p. 2614, Aug. 2023.

[8] K. V Raj, J. Joseph, N. P. M, and M. Sivaprakasam, "Automated measurement of compression-decompression in arterial diameter and wall thickness by image-free ultrasound," Comput. Methods Programs Biomed., vol. 194, p. 105557, Oct. 2020

[9] R. Kiran V., N. P.M., J. Joseph, M. I. Shah, and M. Sivaprakasam, "Evaluation of Local Pulse Wave Velocity using an Image Free Ultrasound Technique," in 2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Jun. 2018, pp. 1–6

[10] DC-WCNN: A Deep Cascade of Wavelet Based Convolutional Neural Networks for MR Image Reconstruction," in 2020 IEEE 17th International Symposium on Biomedical Imaging (ISBI), Apr. 2020.

[11] T. Pereira, C. Correia, and J. Cardoso, "Novel Methods for Pulse Wave Velocity Measurement," *J. Med. Biol. Eng.*, vol. 35, no. 5, pp. 555–565, Oct. 2015.

[12] J. Joseph et al., "ARTSENS ® Pen—portable easy-to-use device for carotid stiffness measurement: technology validation and clinical-utility assessment," Biomed. Phys. Eng. Express, vol. 6, no. 2, p. 025013, Feb. 2020.

[13] . J. M. Poorneshwaran, S. Santhosh Kumar, K. Ram, J. Joseph, and M. Sivaprakasam, "Polyp Segmentation using Generative Adversarial Network," in 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Jul. 2019.

[14] B. T. Jensen *et al.*, "The Association of Bilateral Pulse Wave Velocity and Inter-Arm Systolic Blood Pressure Difference in Apparently Healthy Individuals," *FASEB J.*, vol. 32, no. S1, Apr. 2018, doi: 10.1096/fasebj.2018.32.1_supplement.714.2.

[15] A. S. Larson, W. Brinjikji, L. Savastano, E. Scharf, J. Huston, and J. C. Benson, "Left-sided carotid arteries have a higher prevalence of intraplaque hemorrhage than right-sided: An asymmetric conundrum," *Neuroradiol. J.*, vol. 33, no. 6, pp. 494–500, Dec. 2020.

[16] D. Ramane and A. Shaligram, "Optimization of multi-element LED source for uniform illumination of plane surface," *Opt. Express*, vol. 19, no. S4, p. A639, Jul. 2011.

[17] R. K. V., N. P.M., J. Joseph, and M. Sivaprakasam, "Methodological and Measurement Concerns of Local Pulse Wave Velocity Assessment," in 2019 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Jun. 2019, pp. 1–6.

[18] Arathy R, Nabeel P.M, J. Joseph, M. Sivaprakasam, and V. Awasthi, "An accelerometer probe for local pulse wave velocity measurement," in 2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA), May 2017, pp. 426–431

[19] A. Shyam, V. Ravichandran, S. P. Preejith, J. Joseph, and M. Sivaprakasam, "PPGnet: Deep Network for Device Independent Heart Rate Estimation from Photoplethysmogram," in 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Jul. 2019, pp. 1899–1902

[20] J. K. Kim and J. M. Ahn, "Design of an optimal preamplifier of photoplethysmogram for age-related vascular stiffening evaluation," *Int. J. Eng. Res. Technol.*, vol. 12, no. 10, pp. 1639–1646, 2019.

[21] I. B. Wilkinson *et al.*, "ARTERY Society guidelines for validation of noninvasive haemodynamic measurement devices: Part 1, arterial pulse wave velocity," *Artery Res.*, vol. 4, no. 2, pp. 34–40, 2010, doi: 10.1016/j.artres.2010.03.001.

[22] P. M. Nabeel, K. V. Raj, and J. Joseph, "Image-free ultrasound for local and regional vascular stiffness assessment: The ARTSENS Plus," J *Hypertens.*, vol. 40, no. 8, pp. 1537–1544, Aug. 2022.

[23] C. J. Huck *et al.*, "Vascular Health and Risk Management Noninvasive measurements of arterial stiffness : Repeatability and interrelationships with endothelial function and arterial morphology measures Noninvasive measurements of arterial stiffness : Repeatability and interrelationships with endothelial function and arterial morphology measures," 2022..

[24] T. G. Papaioannou *et al.*, "Assessment of differences between repeated pulse wave velocity measurements in terms of 'bias' in the extrapolated cardiovascular risk and the classification of aortic stiffness : Is a single PWV measurement enough ?," vol. 26, no. 10, pp. 594–602, 2011.

[25] M. Dzeko, C. D. Peters, K. D. Kjaergaard, J. D. Jensen, and B. Jespersen, "Aortic pulse wave velocity results depend on which carotid artery is used for the measurements," *J. Hypertens.*, vol. 31, no. 1, pp. 117–122, Jan. 2013,

[26] Methodological and Measurement Concerns of Local Pulse Wave Velocity Assessment," in 2019 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Jun. 2019