

Estimating Left Ventricular Contractility through Carotid Artery Distension: A Portable Device Utilizing A-Mode Ultrasound and Surrogate Marker Analysis

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Abstract—Non-invasive assessment of left ventricular (LV) function is crucial for early diagnosis and management of cardiovascular diseases. The Acceleration Time (AT) to Ejection Time (ET) ratio, is a measurement used to assess the contractility of the left ventricle (LV) of the heart. This study explores the feasibility of a novel device for a surrogate estimation of the AT/ET ratio using carotid artery distension dynamics. In this in-vivo study, 17 healthy young male participants were recruited. A custom-designed device combining A-mode ultrasound and a pocket Doppler was used to acquire simultaneous measurements of carotid artery distension and blood flow velocity. The pocket Doppler aided in identifying critical events in the carotid artery flow waveform, serving as reference points for analyzing the second derivative of the carotid distension waveform obtained by the A-mode component. This facilitated the estimation of surrogate AT, ET, and the AT/ET ratio from carotid artery dynamics. The study demonstrated a strong correlation between surrogate markers and reference measurements. The surrogate AT measured from carotid distension showed a significant correlation ($r = 0.81$, $p < 0.05$) with the reference AT obtained from LVOT flow. Similarly, the surrogate ET derived from carotid distension exhibited a strong correlation ($r = 0.83$, $p < 0.05$) with the reference ET from LVOT. Importantly, the surrogate AT/ET ratio estimated from carotid artery dynamics displayed a significant correlation ($r = 0.8$, $p < 0.05$) with the reference AT/ET ratio measured using the gold-standard LVOT flow waveform. This study suggests that the combined A-mode ultrasound and pocket Doppler device has the potential to serve as a non-invasive tool for estimating key LV function parameters, including the clinically relevant AT/ET ratio, through analysis of carotid artery distension. Further research with a larger and more diverse population is warranted to validate this approach for broader clinical applications.

Keywords— Acceleration Time, Ejection Time, Carotid distension, Doppler, Left Ventricular Outflow Tract, A-mode Ultrasound

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I. INTRODUCTION

Assessing left ventricular (LV) function is crucial in diagnosing and monitoring cardiovascular diseases. A critical indicator of LV contractility is the AT/ET ratio, which increases with aortic valve stenosis [1]. Conventionally, this evaluation relies on echocardiography, particularly pulsed-wave Doppler (PW Doppler) recordings of the Left Ventricular Outflow Tract (LVOT) velocity. However, this method has its constraints. Conventional echocardiography, although valuable, presents several challenges. Firstly, it is subject to operator-dependent variability, which can affect its reliability. Additionally, the requirement for specialized equipment and trained personnel restricts its utility in resource-limited settings and for continuous monitoring purposes [2]. Furthermore, accessibility may be limited in regions lacking advanced medical facilities. Cost is another significant limitation, particularly in areas with limited resources, potentially impeding access to this essential diagnostic tool for many individuals. Moreover, echocardiography's reliance on sound waves for imaging renders it susceptible to limitations such as obscured image quality due to patient factors like obesity or lung disease [3]. Finally, the operator's skill and experience play an important role in the accuracy and reproducibility of measurements, further emphasizing the technique's dependency on personnel expertise.

The pursuit of non-invasive alternatives for assessing LV function has prompted an investigation into surrogate markers. Given its proximity to the aorta, the carotid artery effectively transmits pressure and flow waves generated by the heart [4]. Through various non-invasive techniques, these waveforms offer promising methods for monitoring LV function. The temporal attributes of the carotid artery diameter align with those of the local transmural pressure waveform. Utilizing pulse wave (PW) analysis on the pulsatile carotid artery diameter acquired through ultrasound presents an intriguing alternative [5].

This study introduces an innovative method to non-invasively assess left ventricular ejection dynamics, with a particular emphasis on the crucial parameter known as the Acceleration Time to Ejection Time Ratio (AT/ET). The Acceleration Time (AT) signifies the duration from the onset of systole to the peak systolic velocity, indicating the speed at which blood accelerates out of the left ventricle (LV). Incorporating information from both the acceleration phase and the entire systolic duration, the AT/ET ratio offers a potentially more robust indicator of LV contractility compared to Ejection Time (ET) alone. The AT/ET ratio, indicative of ejection dynamics through the valve, stands out as a convenient, angle-independent, and consistently reproducible parameter [6]. Our proposed device integrates A-mode ultrasound for measuring carotid artery distension waveform and a pocket Doppler for concurrently assessing carotid blood flow velocity. This combined system offers numerous benefits. Firstly, it is non-invasive, removing the requirement for specialized equipment or trained personnel. Secondly, combining these measurements provides a holistic view of left ventricular function, capturing both anatomical and hemodynamic data. Additionally, its portability enables potential applications in point-of-care settings or for continuous monitoring purposes.

The forthcoming sections describe the methodology of the study. Section II describes the study design and functionality of our innovative A-mode ultrasound and pocket Doppler device. Subsequently, we will present our experimental setup and the data collection process. Section III describes the results section, comparing the surrogate markers for the AT/ET ratio obtained from our device with the reference values acquired through LVOT Pulsed Wave Doppler. Finally, the discussion section will thoroughly analyze our findings, address limitations, and explore potential clinical applications of this novel approach for non-invasive LV contractility assessment.

II. MATERIALS AND METHODS

A. Study Design and Protocol

This research employed a cross-sectional design to assess the practicality and precision of an innovative method for

non-invasively evaluating LV function. This method utilizes surrogate markers obtained from carotid artery waveforms, measured using a combined A-mode ultrasound and pocket Doppler device. This study recruited 17 young, healthy male participants to investigate the relationship between surrogate markers and reference LVOT measurements. Focusing on young males minimized confounding factors, gender-related hemodynamics, and arterial properties variations. Inclusion criteria include age 21 to 29, male gender, and the absence of cardiovascular disease or other severe medical disorders as validated by a medical questionnaire. Participants provided written informed permission, and the study was approved by the IIT Madras Institute review boards (IEC/2021-01/JJ/07), which was by the Helsinki Declaration of 1975, as updated in 2013. Anthropometric measurements were conducted on all participants, encompassing height, weight, and age, utilizing a standardized stadiometer and weighing scale. Body Mass Index (BMI) was measured from the height and weight data using the formula $BMI = \text{weight (kg)} / \text{height (m)}^2$. Resting brachial blood pressure (BP) and heart rate (HR) were assessed following a standardized procedure. Participants were positioned supine for a minimum of 5 minutes in a quiet, temperature-controlled environment to minimize potential influences of activity or anxiety on BP and HR readings. BP was measured using a clinical-grade automated cuff-based oscillometric device placed on the left arm at the brachial artery site (SunTech®247TM, SunTech Medical, Halma, UK).

B. LVOT AT/ET Measurement

A portable wireless ultrasound device (Clarius PAHD3) was utilized to capture the LVOT waveform, serving as the reference standard for assessing critical parameters of LV function, namely AT and ET. The technician positioned the PAHD3 phased array scanner probe through the apical five-chamber window to ensure optimal signal acquisition, providing a clear visualization of the LV outflow tract as shown in Fig.1.(a). AT was defined as the duration between the onset of flow over the LVOT and the peak velocity moment [7]. LV ejection time (ET) was determined by the

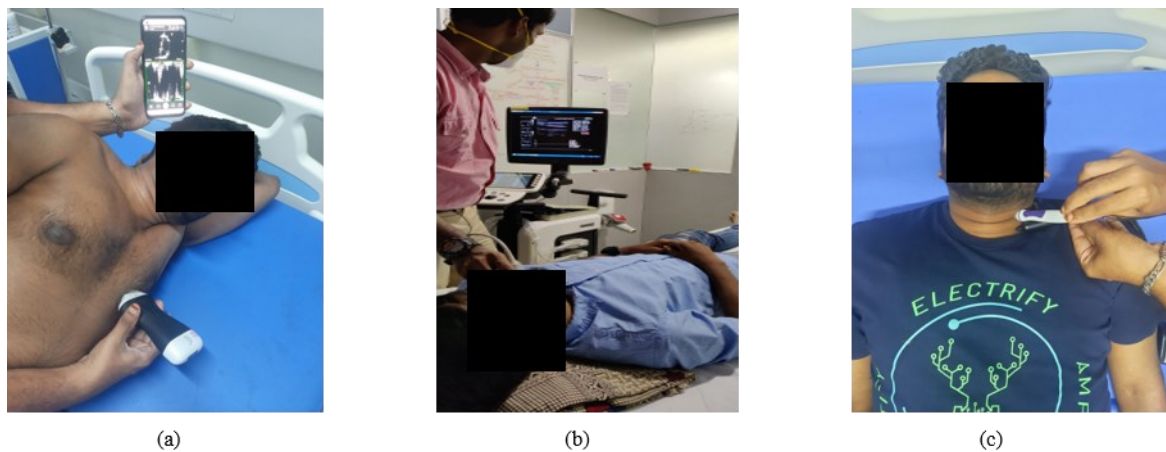


Fig.1. (a) LVOT flow measurement using portable ultrasound device (PAHD3), (b) Carotid Duplex Mode flow measurement using ultrasound imaging system and (c) Simultaneous probe placement of pocket doppler and A-mode ultrasound transducer

total systolic blood flow interval, encompassing the aortic valve's opening and closing [8].

C. Carotid Flow AT/ET Measurement

A duplex ultrasound imaging device equipped with a linear probe was utilized to capture the carotid artery flow waveform (Sonix Touch+, BK Medicals, US). The positioning of the probe on the common carotid artery, proximal to its bifurcation, ensured optimal visualization of the carotid artery lumen while minimizing potential interference from branching vessels. Leveraging the duplex mode of the ultrasound device facilitated simultaneous visualization of both carotid artery anatomy and blood flow

within the vessel, aiding the technician in identifying landmarks on the carotid artery wall for subsequent B-mode imaging analysis as shown in Fig.1.(b). Carotid flow AT was defined as the interval between the onset of carotid flow over the artery and the moment of peak systolic velocity. ET represented the total duration of systolic blood flow.

D. Surrogate AT/ET Measurement

The device incorporates a single-channel, A-mode ultrasound transducer featuring a 5 MHz centre frequency, chosen to strike a balance between penetration depth and resolution, thus enabling precise measurement of carotid artery wall motion. With a spatial angle of 1.3 degrees, the

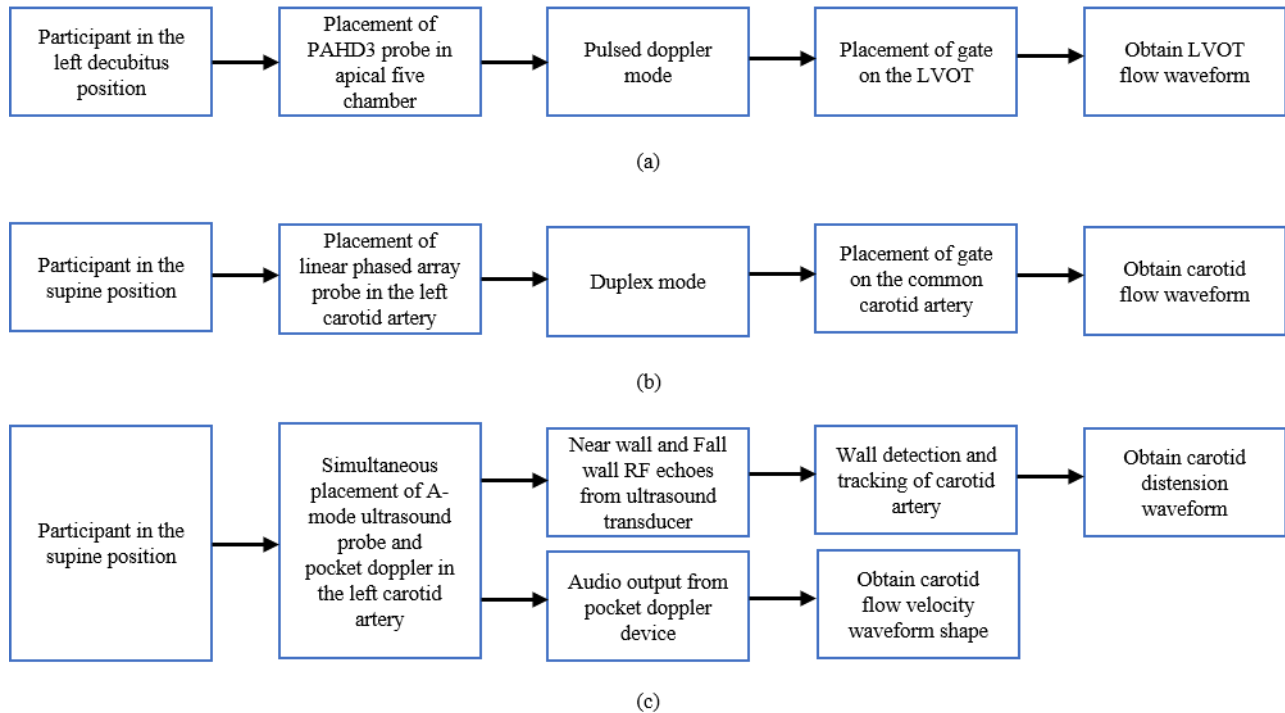


Fig.2. Block diagram representation of study measurement procedure (a) Reference LVOT flow waveform (b) Reference carotid duplex mode flow waveform and (c) Surrogate carotid distension and pocket doppler flow simultaneous waveform

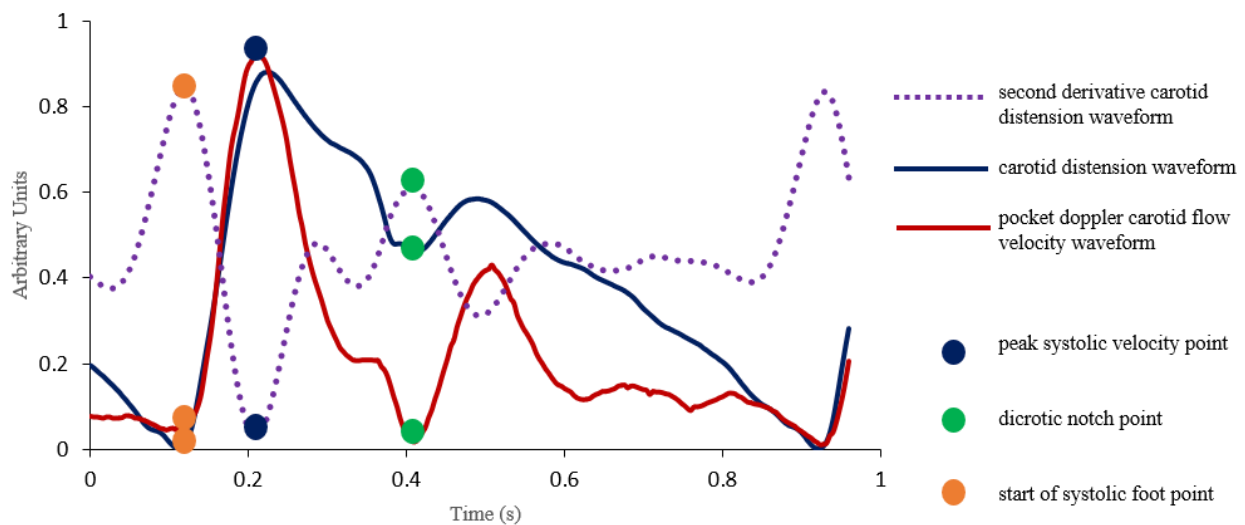


Fig.3. Simultaneous representation of carotid distension, pocket doppler carotid velocity and second derivative of carotid distension waveform of a participant showing fiducial points extraction

transducer focuses the ultrasound beam for accurate signal acquisition. Its axial resolution of 360 μm ensures high fidelity in detecting subtle changes in carotid artery diameter. Measuring a compact 5 mm diameter, the transducer facilitates comfortable probe placement on the participant's neck. A high sampling rate of 80 MHz ensures rapid changes in carotid artery wall movement are captured with minimal distortion, while a scan depth of 40 mm allows sufficient penetration to reach the far wall of the common carotid artery in most individuals. Application-specific measurement software was developed for the A-mode ultrasound component using LabVIEW 2019 (32-bit, National Instruments Co., Austin, Texas, United States). This software provides real-time visualization of the acquired A-mode signals and facilitates data analysis [9], [15]. The software uses intelligent signal processing algorithms to detect carotid artery dimensions within the A-mode waveforms [10], [18]. The device also integrates the EMCO D580, a commercially available handheld continuous wave Doppler device consisting of a fixed 8 MHz transducer as shown in Fig.1.(c). This component facilitates the measurement of carotid blood flow velocity across the entire cardiac cycle. For the proper probe angulation, we employ a real-time signal quality index displayed as a bar for user feedback. This ensures perpendicular insonation by guiding probe positioning until a signal quality above 90% is achieved from both near and far wall echoes [16]. Once the desired signal quality is achieved then the wall tracking algorithm happens. Our device leverages a single instrument platform housing both the A-mode ultrasound transducer and a Doppler transducer. Single microcontroller which controls both the acquisition of RF carotid echoes and carotid doppler by generating a single trigger pulse [17], ensures the synchronization between RF carotid echoes carotid blood flow detected by the Doppler probe.

E. Data Processing

Measurements of AT and ET involved tracing Pulse wave Doppler signals from LVOT and carotid artery across three consecutive beats, and the values were averaged to yield a single value per patient. The recorded flow waveform underwent post-analysis utilizing MATLAB software. The A-mode ultrasound probe is positioned on the common carotid artery, with LabVIEW software controlling the data acquisition process, capturing radiofrequency (RF) echoes reflected from the carotid artery walls. The software transforms these RF echoes through a validated algorithm into a time-domain representation of the carotid artery diameter, depicting its distension and recoil across the cardiac cycle. Automated algorithms integrated into the software identify pivotal points on the carotid diameter waveform, corresponding to critical events like the onset of systole and the dicrotic notch for subsequent estimation of acceleration time (AT) and ejection time (ET). The second derivative of the carotid distension waveform was calculated to precisely identify fiducial points such as the foot of the systole and dicrotic notch. This process included employing a Savitzky-Golay filter with a polynomial degree of 4 and 28 side points. Utilizing the Savitzky-Golay filter effectively reduces noise while retaining the key characteristics of the waveform, ensuring accurate detection of these crucial points. Concurrently, the pocket Doppler continually records blood

flow velocity within the carotid artery, providing data for AT and ET calculation.

AT serves as an indicator of blood acceleration during systole, and it is computed in this study as the time interval between the first peak of the second derivative of the carotid distension waveform, representing the onset of systole and the first local minimum point on the second derivative of the distension waveform. Surrogate ET, serving as a substitute marker for LV ejection time is derived from the second derivative of the carotid distension waveform. The interval between two peaks on the second derivative waveform is utilized, with the first peak indicating the onset of systole and the third peak corresponding to the dicrotic notch as depicted in Fig.3. Furthermore, AT and ET are also determined from the continuous carotid flow velocity waveform obtained through the pocket Doppler. This enables the calculation of conventional AT (time from systolic onset to peak systolic velocity) and total systolic duration (ET) for comparison with the surrogate markers.

F. Statistical Analysis

Data analysis will primarily involve linear regression analysis to evaluate the agreement between surrogate markers (AT/ET ratio) derived from the novel device and reference values obtained from LVOT PW Doppler (reference AT/ET ratio). Additionally, visual representations using box and whisker plots will compare the distribution of surrogate markers with reference AT/ET values, enabling comparison of central tendency, variability, and potential outliers between the groups. Statistical significance will be determined with a significance level set at $\alpha = 0.05$, where a p-value less than 0.05 ($p < 0.05$) will denote statistical significance.

III. RESULTS AND DISCUSSIONS

A. In-vivo Measurements

TABLE I presents a comprehensive summary of the demographic characteristics of the study cohort. Seventeen healthy young male participants actively participated in this in-vivo study, successfully acquiring all necessary data for analysis. This data included measurements of carotid artery distension waveform, Left Ventricular Outflow Tract (LVOT) flow velocity waveform using standard echocardiography, carotid artery flow waveform using

TABLE I. CHARACTERISTICS OF STUDY POPULATION (N=17)

Parameter	Mean \pm SD	Range
Age	25 \pm 2.68	21 – 29
Height (cm)	173 \pm 6.9	160 – 186
Weight (kg)	68.9 \pm 13.13	48 – 96
BMI (kg/m^2)	22.88 \pm 3.74	16.54 – 30.30
Heart Rate (bpm)	67.12 \pm 7.49	57 – 81
Systolic Blood Pressure (mmHg)	115 \pm 14	98 – 141
Diastolic Blood Pressure (mmHg)	70 \pm 8	57 – 89
Mean Arterial Pressure (mmHg)	84 \pm 9	72 – 103
LVOT AT/ET ratio	0.27 \pm 0.03	0.22 – 0.31
Carotid flow AT/ET ratio	0.26 \pm 0.03	0.22 – 0.33
Carotid distension AT/ET ratio	0.28 \pm 0.02	0.24 – 0.31
Pocket doppler carotid flow AT/ET ratio	0.27 \pm 0.03	0.23 – 0.34

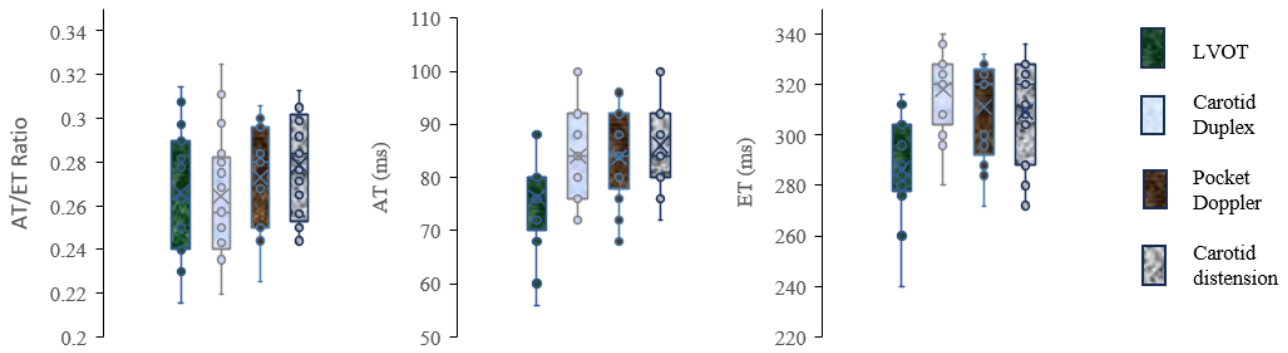


Fig.4. Distribution of measured markers AT/ET, AT and ET using box and whisker plots

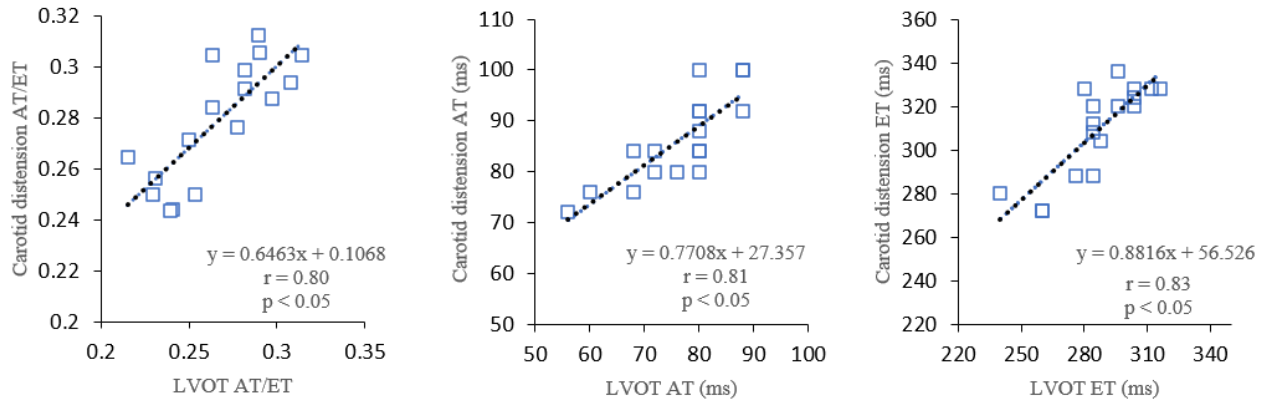


Fig.5. Comparison of Reference LVOT measurements with the carotid distension measurements using linear regression plot

duplex mode, and carotid artery flow velocity waveform using a pocket Doppler.

B. Measurement Reliability

A consistently high signal-to-noise ratio (SNR) exceeding 20 dB was achieved for A-mode frames captured from carotid artery locations. Echo frames exhibited well-defined near and far walls, enabling precise tracking using ARTSENS algorithms and accurate carotid artery distension waveform extraction [11]. Surrogate markers such as AT and ET were derived from the second derivative of the carotid distension waveform, demonstrating excellent repeatability with a coefficient of variation below 8%. Fig.3. illustrates the data from a single participant, depicting the concurrent acquisition of carotid distension and its second derivative alongside the pocket Doppler velocity waveform for one cardiac cycle. Consistently across all participants, the peak flow point identified by the pocket Doppler in the carotid flow velocity waveform coincided with the local minimum point observed in the second derivative of the carotid distension waveform as shown in Fig.3. This observation contrasts with previous studies, which typically identify the flow peak time near the inflection point (zero crossing) of the second derivative waveform or the local minimum of the first derivative waveform [12]. Additionally, in young participants, the obtained waveform is typically Type-C, wherein the flow peak occurs after the systolic peak distension [13]. However, in this investigation, the local minimum point of the second derivative, which aligns more closely with the flow peak, was utilized for surrogate marker estimation.

C. Distribution of AT and ET over devices

Reference measurements showed AT values ranging from 56 to 88 milliseconds (ms), ET durations spanning from 240 to 316 ms, and AT/ET ratios varying between 0.21 and 0.31, aligning with previous research suggesting a threshold of >0.32 for potential aortic stenosis [14]. Notably, all participants were healthy young individuals with expected AT/ET ratios. Surrogate markers derived from the second derivative of the carotid distension waveform displayed similar distributions, with surrogate AT values ranging from 72 to 100 ms, surrogate ET durations ranging from 272 to 336 ms, and surrogate AT/ET ratios varying between 0.24 and 0.31, closely resembling reference values obtained from LVOT flow. The distribution of AT, ET, and AT/ET ratio measured using various techniques, including LVOT flow, carotid duplex mode, pocket Doppler, and carotid distension, is illustrated in Fig.4.

D. Association and Agreement between Measurements

Correlation analysis unveiled strong positive associations between surrogate and reference measurements. Surrogate acceleration time (AT), extracted from the second derivative of the carotid distension waveform, exhibited a significant correlation ($r = 0.81$, $p < 0.05$) with the reference AT obtained from LVOT flow. Surrogate ejection time (ET), derived from carotid artery dynamics, demonstrated a robust correlation ($r = 0.83$, $p < 0.05$) with the reference ET measured from LVOT flow. The surrogate AT/ET ratio estimated from carotid distension displayed a substantial correlation ($r = 0.8$, $p < 0.05$) with the reference AT/ET ratio derived from the gold-standard LVOT flow assessment as illustrated in Fig.5. Bland

Altman plot depicted in Fig.6 shows the agreement between the LVOT AT/ET and Carotid distension AT/ET and there is no random and systematic errors observed.

E. Study Limitations and Future Plan

The limited sample size and the restriction to healthy young males in our study constrain the applicability of our results. Further investigation is necessary to confirm the validity of our approach across a broader and more diverse population, encompassing individuals with differing degrees of aortic stenosis severity. Moreover, additional research is warranted to evaluate the device's efficacy in various clinical settings and to ascertain its potential integration into standard clinical protocols. Recent advancements in artificial intelligence, particularly computer vision and machine learning, have revolutionized image analysis through powerful automated recognition, segmentation, and detection methods [19] - [22]. This trend highlights the growing need for further development in automated ultrasound technologies. In our study, we employed A-mode ultrasound for the measurement of the AT/ET ratio, which does not involve image analysis. Future research that integrates automation with A-mode techniques could offer significant advantages in terms of efficiency, accuracy, and consistency of measurements.

IV. CONCLUSION

This study delved into the feasibility of utilizing a novel device that combines A-mode ultrasound and pocket Doppler for the non-invasive estimation of the AT/ET ratio. Our examination, involving 17 healthy young male participants, revealed substantial correlations between surrogate AT, ET, and the AT/ET ratio derived from carotid artery distension and the reference values obtained from standard echocardiographic LVOT flow assessment. These results suggest that the developed device has the potential to serve as an effective non-invasive tool for estimating key LV function parameters. However, further research involving a more extensive and diverse population is imperative to validate the efficacy of this approach and explore its broader clinical applications.

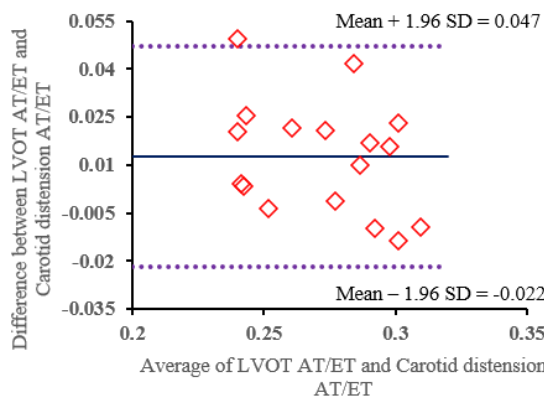


Fig.6. Bland Altman plot showing the agreement between LVOT AT/ET and Carotid Distension AT/ET.

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