Towards At-Home Applications of Pulse Wave Imaging (PWI): Investigating Optimal Sampling Parameters for Real-Time Pulse Wave Velocity (PWV) Estimation

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Introduction

Pulse Wave Imaging (PWI)[1-7]

- Quantification of central arterial mechanics can improve the **characterization** and **monitoring** of cardiovascular-related diseases including hypertension, diabetes, Alzheimer's, etc.[8]
- PWI is a **noninvasive**, **high-frame-rate**, **ultrasound imaging** method that tracks the pulse wave propagation
- PWI provides estimates of **central arterial properties** (carotid, aorta), including pulse wave velocity (PWV) at end-diastole (PWV_{ED}) and end-systole (PWV_{ES}), pulse pressure (PP), compliance, and homogeneity

Translation of PWI to At-Home and Wearable Applications

- Advancements in piezoelectric micromachined ultrasound technology (**PMUT**) have enabled the development of **at-home** and **wearable** applications of PWI[9-10]
- Current PWI technique requires offline processing (~13-18 minutes) and GPU-based computing
  - **Home-Use Requirements:** Real-time PWV and PP estimation (within 1-2 minutes of the scan)

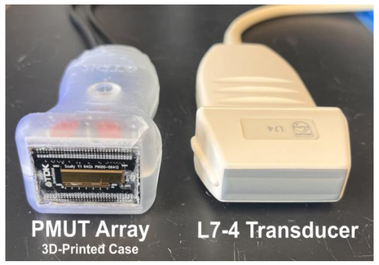
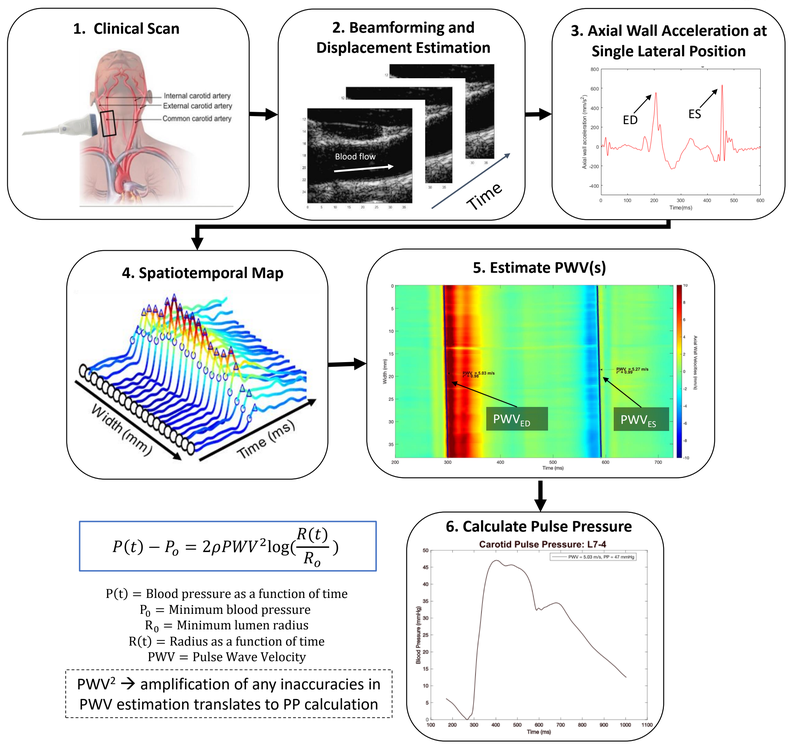


Figure 1. 3D-printed holder for PMUT array (left) compared to the conventional L7-4 linear transducer (right).

PWI Pipeline:



$$P(t) - P_o = 2\rho PWV^2 \log(\frac{R(t)}{R_o})$$

P(t) = Blood pressure as a function of time
P_0 = Minimum blood pressure
R_0 = Minimum lumen radius
R(t) = Radius as a function of time
PWV = Pulse Wave Velocity

PWV^2 → amplification of any inaccuracies in PWV estimation translates to PP calculation

Figure 2. Pulse Wave Imaging pipeline

Objective: To guide the development of Real-Time PWI...
- Determine the minimum number of lateral positions necessary for accurate PWV estimation
- Compare sampling strategies between data collected from the PMUT array (future at-home/wearable) and L7-4 transducer (conventional diagnostics transducer)

References

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[7] Gami et al., IEEE IUS, 2021
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Methods: Retrospective Study

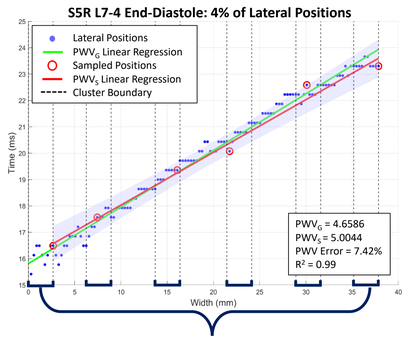
Sample Population

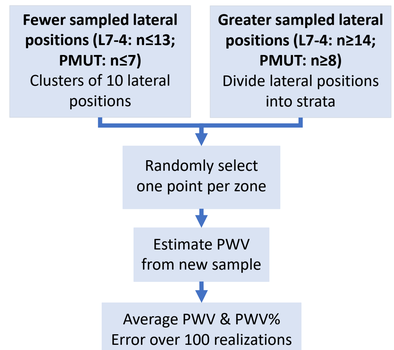
- Left and right common carotid arteries (CCA) of 6 young, normotensive patients (28 ± 3 y.o.; 3 M, 3 F) at the same location, twice, with both the L7-4 and PMUT array

	L7-4 Transducer	PMUT Array
Number of lateral positions	128	64
Subject Sample Size (Carotids Post-Rejection)	9	9
Sample Size of PWV_{ED} Estimates	39	35
Sample Size of PWV_{ES} Estimates	34	31

Sampling Technique:

- PWV from all 128 (L7-4) or 64 (PMUT) lateral positions acts as the gold standard PWV
- No outliers were down-weighted or removed from linear regressions





$$\textbf{PWV \% Error} = abs(\frac{PWV_S - PWV_G}{PWV_G}) * 100$$

- PWV_G: Gold standard PWV estimation (using all lateral positions)
- PWV_S: Sampled PWV estimation

Results: Individual Subjects

Subject 5, Right CCA (S5 R):

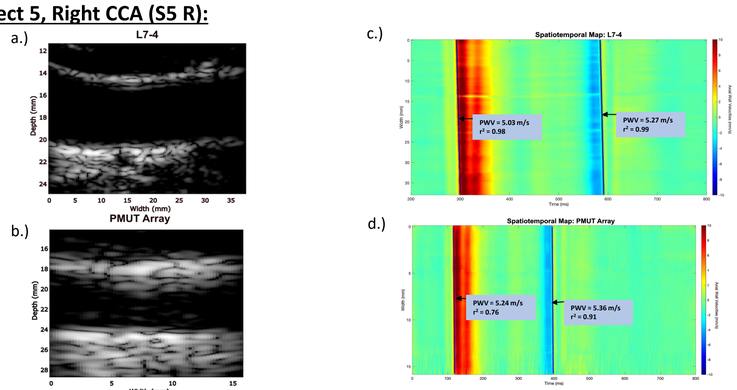


Figure 4. a-b.) B-modes of S5 R's right CCA acquired from L7-4 transducer and PMUT Array, respectively. c-d.)Spatiotemporal maps and corresponding pulse wave velocity estimates for the data collected by the L7-4 (a) and PMUT array (c)

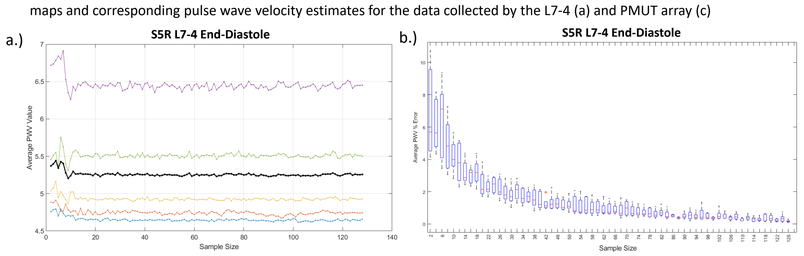


Figure 5. a.) Average estimated PWV_{ED} values from 2-128 lateral positions utilized for S5's right CCA using L7-4. Each colored line represents a different cardiac cycle and single PWV estimate; the black line represents the average of all cycles. b.) Box plots for the average PWV % error across all cardiac cycles for S5 R from utilizing 2-128 lateral positions.

Results: L7-4 vs PMUT Array

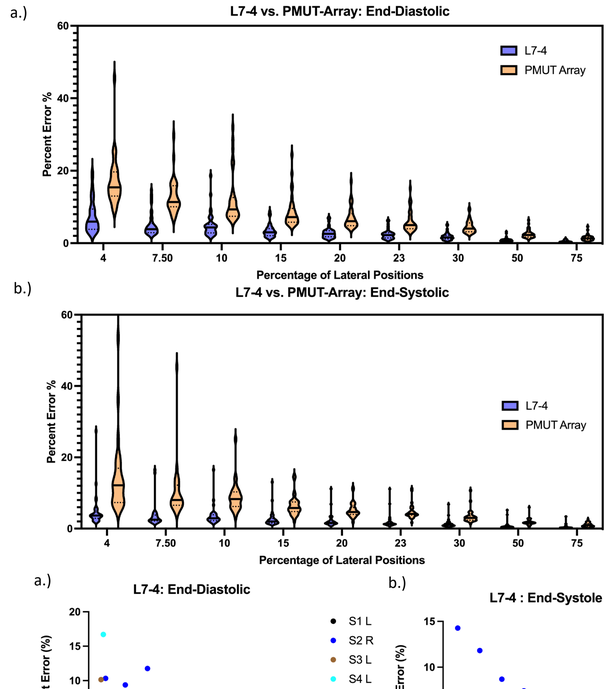


Figure 6. a-b.) Violin plots of PWV % error across all cardiac cycles for all percentages of lateral positions utilized for PWV estimation. a.) Compares the distribution between L7-4 (n=39) and PMUT array (n=34) scans for PWV_{ED} and b.) compares the L7-4 (n=34) and PMUT array (n= 31) for PWV_{ES} . Center black bars represent the median for each percentage group.

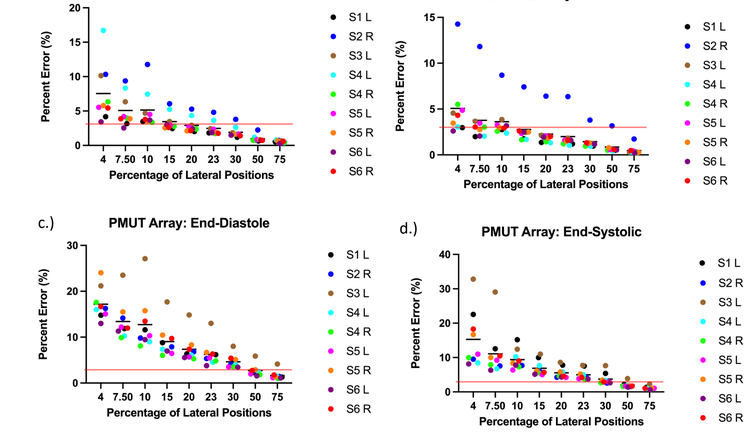


Figure 7. a-d.) The PWV% error values for all cardiac cycles per carotid artery (n=9) were averaged and plotted from the L7-4 (a-b) and PMUT array (c-d) . The black bars represent the mean PWV % error across all subjects for each percentage group of lateral positions utilized for PWV estimation. Red lines are located at 3% error.

Conclusions

Minimum Percentage of Lateral Positions for PWV Error < 3%	L7-4 Transducer	PMUT Array
PWV_{ED}	20-23% (26-30 positions)	47-63% (30-40 positions)
PWV_{ES}	15-23% (20-30 positions)	40-53% (26-34 positions)

- PWV estimations using the PMUT array will give similar results to L7-4 when averaged over multiple cardiac cycles—however, real-time estimation will require a higher percentage of lateral positions for PWV estimation when using PMUT.
- **Future work:**
  - Increase patient population and variability (larger age-range, include subjects with vascular disease, etc.), development of live quality standards to improve the selection of lateral positions in cluster-bands

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