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Pulse Arrival Time is Not an Adequate Surrogate for Pulse Transit Time in Terms of Tracking Diastolic Pressure

Guanqun Zhang, Da Xu, *Member, IEEE*, N. Bari Olivier, Ramakrishna Mukkamala, *Member, IEEE*

***Abstract*—We compared pulse arrival time (PAT) and pulse transit time (PTT) in terms of their ability to track diastolic pressure (DP). We performed the comparison using high fidelity, invasive arterial waveforms recorded from six dogs during multiple interventions. On average, DP ranged from 40 to 106 mmHg and therefore varied widely. PAT and PTT were able to predict DP with average root-mean-squared-errors of 9.8±5.8 mmHg and 5.7±2.0 mmHg (p = 0.02). Thus, even though PAT is simpler to measure, we can only recommend using PTT for tracking DP.**

I. Introduction

PULSE transit time (PTT) and blood pressure often show a tight relationship. Further, since PTT can be determined from proximal and distal arterial waveforms, it is easy to measure. Thus, PTT holds great promise for translating into a continuous, non-invasive, and cuff-less blood pressure monitoring solution.

A number of investigators have proposed to make the measurement process even simpler by using the ECG waveform in lieu of a proximal arterial waveform [1-7]. The resulting pulse arrival time (PAT) is equal to the sum of PTT and the pre-ejection period (PEP). However, PEP, which includes the electromechanical delay and the isovolumic contraction phase, is hardly invariant [1, 8-10]. So, PAT may not be an adequate surrogate for PTT in terms of tracking blood pressure.

A few investigators have compared PAT to PTT as markers of blood pressure. Steptoe et al. and Ochiai et al. concluded that PAT is similar to PTT for following blood pressure changes [7, 11]. However, Steptoe et al. performed their assessment over a limited blood pressure range, while Ochiai et al. did so over just one intervention at a time. By contrast, Geddes et al. and Payne et al. concluded that PAT is an inadequate marker of blood pressure [12, 13]. However, Geddes et al. only showed a qualitative result from one subject, whereas Payne et al. found that PTT was just as inadequate, perhaps due to the imperfect non-invasive arterial waveforms that were measured. Thus, further investigation of the relative adequacy of PAT for blood pressure tracking is needed.

In this study, we compared PAT and PTT, as determined from high fidelity, invasive arterial waveforms, in terms of their correspondence to wide diastolic pressure (DP) changes induced by multiple interventions. Our quantitative results over multiple subjects demonstrate that PAT is not an adequate surrogate for PTT in terms of tracking DP.

II. Methods

We previously collected data from six dogs. The data collection procedures were approved by the MSU All-University Committee on Animal Use and Care and are described in detail elsewhere [14]. Briefly, under general anesthesia, we inserted micromanometer-tipped catheters for ascending aortic and femoral artery pressure waveforms and placed surface electrodes for ECG waveforms. We then recorded the waveforms at a sampling rate of 500 Hz during a baseline period and following infusions of hemodynamic drugs, blood volume changes, and/or cardiac pacing. The Table shows the interventions performed in each dog.

We determined PAT and PTT by applying conventional detection methods to the recorded waveforms. More specifically, we computed PAT as the time delay between the R-wave of the ECG waveform and the foot of the femoral artery pressure waveform and PTT as the foot-to-foot time delay between the ascending aortic and femoral artery pressure waveforms. We then averaged each of these time delays over 15-sec intervals in order to mitigate noise.

We evaluated PAT and PTT in terms of their correspondence to DP (as averaged over the corresponding 15-sec intervals). Fig. 1 shows the evaluation procedure for each of these time delays. First, we computed the reciprocal of the time delay in order to improve the linear correlation with DP. Then, we found the line of best fit between the reciprocal of the time delay and DP per dog. Next, we predicted DP from the corresponding reciprocal of the time delay and the line of best fit (calibration). Finally, we computed the root-mean-squared-error (RMSE = $\sqrt{(\mu^2+\sigma^2)}$, where μ and σ are bias and precision) between the predicted and measured DP for each dog.

We statistically compared PAT and PTT by applying paired t-tests to their log-transformed RMSE values. A p-value < 0.05 was considered significant.

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G. Zhang is with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824 USA (e-mail: zhanggu2@msu.edu).

D. Xu was with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824 USA. He is now with the Department of Kinesiology, University of Waterloo, Waterloo, ON, N2L3G1, Canada (e-mail: da.xu@uwaterloo.ca)

N. B. Olivier is with the Department of Small Animal Clinical Sciences, Michigan State University, East Lansing, MI 48824, USA (e-mail: olivier@cvm.msu.edu).

R. Mukkamala is with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824 USA (phone: 517-353-3120; fax: 517-353-1980; e-mail: rama@egr.msu.edu).

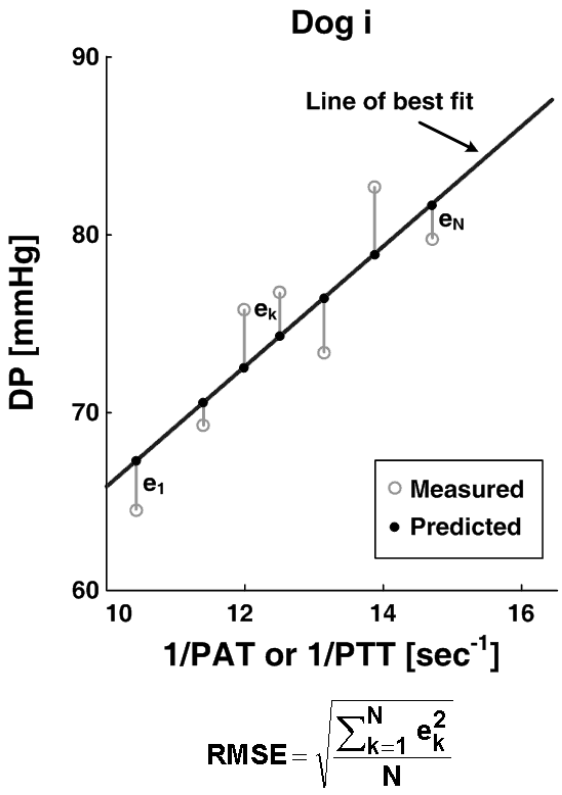

Fig. 1. Procedure for evaluating pulse arrival time (PAT) and pulse transit time (PTT) in terms of their ability to track diastolic pressure (DP).

III. Results

The Table also shows the DP range and the PAT and PTT RMSE values for each dog. On average, DP ranged from 40 to 106 mmHg and therefore varied widely. The average RMSE values were 9.8±5.8 mmHg for PAT and 5.7±2.0 mmHg for PTT. The difference in these average values reached statistical significance ($p = 0.02$). The average PAT RMSE value was 72±53% higher than its PTT counterpart. Thus, on average, PAT yielded markedly inferior correspondence to DP than PTT.

IV. Discussion

We compared PAT to PTT in terms of their ability to track DP in six dogs. In contrast to similar studies in the past (see Introduction section), we performed the comparison using high fidelity arterial waveforms obtained across multiple interventions that generally induced a wide blood pressure range and quantitatively indicated the results from all of the subjects. Further, we minimized potential confounding vasomotor tone-induced PTT changes by determining these time delays through the aorta, which is relatively sparse in smooth muscle [15].

Our results showed that PAT and PTT were able to predict DP with statistically different average RMSE values of 9.8±5.8 mmHg and 5.7±2.0 mmHg, respectively. So, on average, PAT was not only substantially less capable of tracking DP compared to PTT but was also unable to predict DP within FDA limits (bias and precision of 5 and 8 mmHg) despite the fact that the same data were utilized for both calibration and testing.

For each dog, the PAT RMSE value always exceeded the PTT RMSE value. However, the extent of the difference was quite variable in the dogs. This variability stemmed from differences in the type and number of interventions that were performed in each dog. More specifically, in dog 1, phenylephrine and nitroglycerin were infused. Fig. 2 shows that the former vasoconstrictor intervention caused PTT to decrease (due to the increase in blood pressure) and PEP to increase (due to the increase in afterload). The opposing changes in PTT and PEP blunted PAT so as to render it ineffective in predicting DP. In dogs 5 and 6, four interventions instead of just two were performed. As a result, PEP was more variable (not shown), and PAT was consequently likewise ineffective. By contrast, in dogs 2 and 4, the DP ranges were much smaller. So, consistent with the findings of Steptoe et al. [7], PAT was able to show linear correlation with DP that was not much worse than PTT. Finally, in dog 3, norepinephrine and xylazine were infused. These interventions happened to cause PEP and PTT to change in the same direction (not shown). Thus, PAT was again not that much worse than PTT.

In theory, PAT and PTT should correspond best to DP, because they are conventionally determined from the waveform feet. However, it would be remiss of us not to mention that some previous studies have shown that PAT paradoxically corresponds to systolic pressure (SP) better than DP [13, 16]. Our future work will accordingly involve comparisons of PAT and PTT in terms of tracking SP as well as mean blood pressure (MAP). However, at this point, we can at least conclude that PAT is generally not an adequate surrogate for PTT in terms of tracking DP.

TABLE
Results of PAT and PTT per dog

Dog	Interventions	DP Range [mmHg]	RMSE [mmHg]	
			PAT	PTT
1	Phenylephrine, Nitroglycerin	34 – 129	11.6	4.7
2	Dobutamine, Esmolol	52 – 75	6.4	6.1
3	Norepinephrine, Xylazine	42 – 116	6.3	5.2
4	Hemorrhage, Saline	44 – 73	3.8	2.9
5	Phenylephrine, Nitroglycerin, Verapamil, High rate pacing	41 – 142	10.8	6.3
6	Dobutamine, Esmolol, Vasopressin, Low rate pacing	29 – 103	20.1	8.9
Average	–	40 -106	9.8±5.8	5.7±2.0

RMSE is the root-mean-squared-error between DP predicted by PAT or PTT and measured DP.

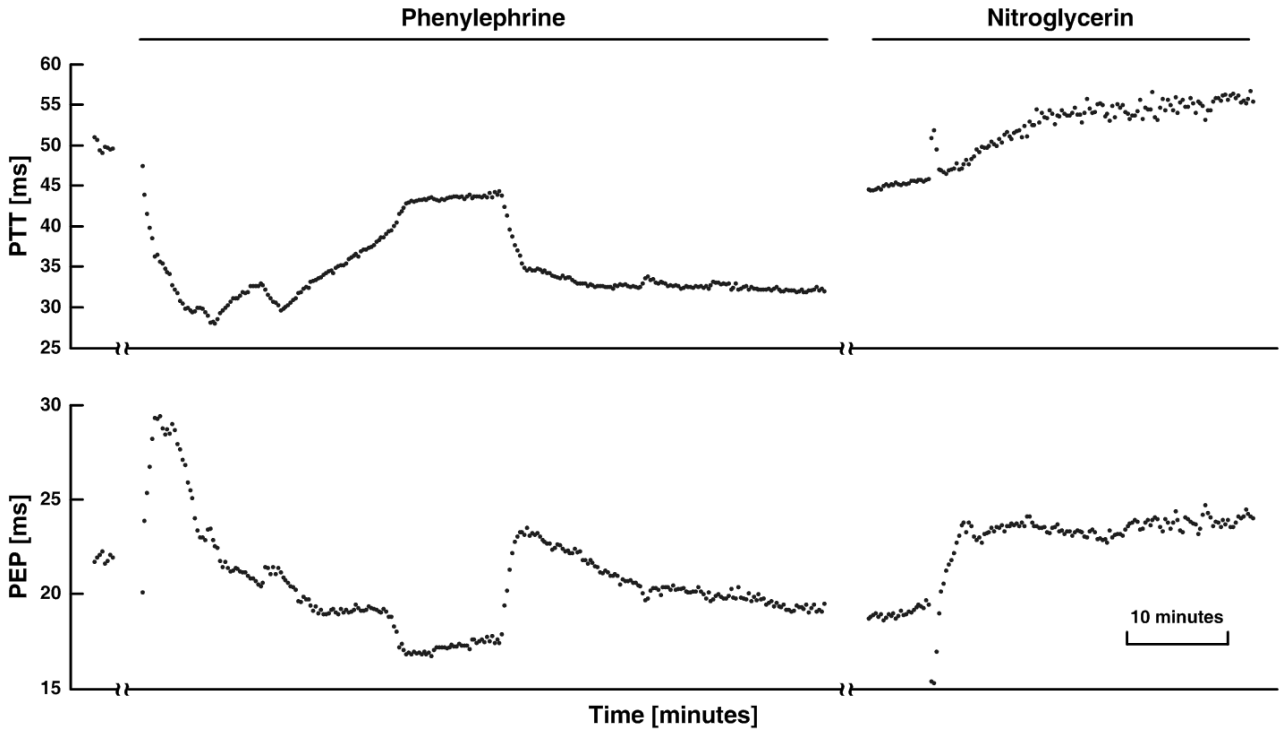

Fig. 2. PTT and the pre-ejection period (PEP) as functions of time in dog 1.

REFERENCES

[1] D. B. Newlin, "Relationships of Pulse Transmission Times to Pre-Ejection Period and Blood-Pressure," *Psychophysiology,* vol. 18, pp. 316-321, 1981.

[2] C. F. Wippermann, D. Schranz, and R. G. Huth, "Evaluation of the Pulse-Wave Arrival Time as a Marker for Blood-Pressure Changes in Critically Ill Infants End Children," *J Clin Monitor,* vol. 11, pp. 324-328, Sep 1995.

[3] J. D. Lane, L. Greenstadt, D. Shapiro, and E. Rubinstein, "Pulse Transit-Time and Blood-Pressure - an Intensive Analysis," *Psychophysiology,* vol. 20, pp. 45-49, 1983.

[4] P. A. Obrist, K. C. Light, J. A. Mccubbin, J. S. Hutcheson, and J. L. Hoffer, "Pulse Transit-Time - Relationship to Blood-Pressure and Myocardial Performance," *Psychophysiology,* vol. 16, pp. 292-301, 1979.

[5] M. Y. M. Wong, C. C. Y. Poon, and Y. T. Zhang, "An Evaluation of the Cuffless Blood Pressure Estimation Based on Pulse Transit Time Technique: a Half Year Study on Normotensive Subjects," *Cardiovasc Eng,* vol. 9, pp. 32-38, Mar 2009.

[6] C. C. Young, J. B. Mark, W. White, A. Debree, J. S. Vender, and A. Fleming, "Clinical-Evaluation of Continuous Noninvasive Blood-Pressure Monitoring - Accuracy and Tracking Capabilities," *J Clin Monitor,* vol. 11, pp. 245-252, Jul 1995.

[7] A. Steptoe, H. Smulyan, and B. Gribbin, "Pulse-Wave Velocity and Blood-Pressure Change - Calibration and Applications," *Psychophysiology,* vol. 13, pp. 488-493, 1976.

[8] D. Newlin and R. W. Levenson, "Voluntary Control of Pulse Transmission Time to the Ear," *Psychophysiology,* vol. 17, pp. 581-585, 1980.

[9] D. B. Newlin and R. W. Levenson, "Pre-Ejection Period - Measuring Beta-Adrenergic Influences Upon the Heart," *Psychophysiology,* vol. 16, pp. 546-553, 1979.

[10] A. P. Xenakis, V. M. Quarry, and D. H. Spodick, "Immediate Cardiac Response to Exercise - Physiologic Investigation by Systolic-Time Intervals at Graded Work Loads," *Am Heart J,* vol. 89, pp. 178-185, 1975.

[11] R. Ochiai, J. Takeda, H. Hosaka, Y. Sugo, R. Tanaka, and T. Soma, "The relationship between modified pulse wave transit time and cardiovascular changes in isoflurane anesthetized dogs," *J of Clin Monitor and Comp,* vol. 15, pp. 493-501, Dec 1999.

[12] L. A. Geddes, M. H. Voelz, C. F. Babbs, J. D. Bourland, and W. A. Tacker, "Pulse Transit-Time as an Indicator of Arterial Blood-Pressure," *Psychophysiology,* vol. 18, pp. 71-74, 1981.

[13] R. A. Payne, C. N. Symeonides, D. J. Webb, and S. R. J. Maxwell, "Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure," *J Appl Physiol,* vol. 100, pp. 136-141, Jan 2006.

[14] G. Swamy, N. B. Olivier, and R. Mukkamala, "Calculation of Forward and Backward Arterial Waves by Analysis of Two Pressure Waveforms," *IEEE T Bio-Med Eng,* vol. 57, pp. 2833-2839, Dec 2010.

[15] D. A. Mcdonald, "Regional Pulse-Wave Velocity in Arterial Tree," *J Appl Physiol,* vol. 24, pp. 73-&, 1968.

[16] H. J. Baek, K. K. Kim, J. S. Kim, B. Lee, and K. S. Park, "Enhancing the estimation of blood pressure using pulse arrival time and two confounding factors," *Physiol Meas,* vol. 31, pp. 145-157, Feb 2010.