Pulse Transit Time and Blood Pressure During Cardiopulmonary Exercise Tests

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Summary

Pulse transit time (PTT), the interval between ventricular electrical activity and peripheral pulse wave, is assumed to be a surrogate marker for blood pressure (BP) changes. The objective of this study was to analyze PTT and its relation to BP during cardiopulmonary exercise tests (CPET). In 20 patients (mean age 51 ± 18.4 years), ECG and finger-photoplethysmography were continuously recorded during routine CPETs. PTT was calculated for each R-wave in the ECG and the steepest slope of the corresponding upstroke in the plethysmogram. For each subject, linear and non-linear regression models were used to assess the relation between PTT and upper-arm oscillometric BP in 9 predefined measuring points including measurements at rest, during exercise and during recovery. Mean systolic BP (sBP) and PTT at rest were 128 mm Hg and 366 ms respectively, 197 mm Hg and 289 ms under maximum exercise, and 128 mm Hg and 371 ms during recovery. Linear regression showed a significant, strong negative correlation between PTT and sBP. The correlation between PTT and diastolic BP was rather weak. Bland-Altman plots of sBP values estimated by the regression functions revealed slightly better limits of agreements for the non-linear model (–10.9 to 10.9 mm Hg) than for the linear model (−13.2 to 13.1 mm Hg). These results indicate that PTT is a good potential surrogate measure for sBP during exercise and could easily be implemented in CPET as an additional parameter of cardiovascular reactivity. A non-linear approach might be more effective in estimating BP than linear regression.

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Introduction

Cardiopulmonary exercise testing (CPET) is considered the gold standard for comprehensive evaluation of exercise responses. CPET permits objective assessment of the pulmonary, cardiovascular, and skeletal muscle systems and can provide information on the pathophysiology of exercise limitation. These results can be relevant for clinical decision making including risk stratification, therapy efficacy evaluation and setting up exercise-training programs.

Although CPET is considered a multiparametric, comprehensive approach, the generated data are primarily focused on gas exchange and ventilation. Additional cardiovascular parameters in CPET might provide novel opportunities for research and clinical assessment.

Pulse transit time (PTT) is a promising, potentially useful index of arterial stiffness and cardiac output and has been proposed to be a substitute for continuous blood pressure measurement, particularly if not the absolute blood pressure values but short term changes are to be quantified (Kounalakis and Geladas 2009, Schmalgemeier *et al.* 2012, Sharwood-Smith *et al.* 2006). PTT is inversely related to BP. With increasing BP, increasing distending pressure and decreasing arterial compliance, pulse wave velocity increases and thus pulse transit time shortens (Smith *et al.* 1999). In recent years, PTT has demonstrated its capability in basic research as

well as in studies on sleep disorders, anesthesia, dialysis and psychophysiological stress (Ochiai *et al.* 1999, Contal *et al.* 2013, Kortekaas *et al.* 2012, Ahlstrom *et al.* 2005, Fechir *et al.* 2008). However, this method is not widely applied in clinical routine at present and despite long-standing research efforts, there is still a lack of systematic data on PTT during physical exercise in humans.

PTT is defined as the time required for the arterial pulse pressure wave to travel from the aortic valve to periphery (Smith *et al.* 1999). It can be estimated as the delay between the peak of the R wave in the ECG and the arrival of the corresponding pulse wave at the finger as determined by pulse oximetry. PTT can therefore be easily measured, since only simultaneous recording of ECG and photoplethysmography are required.

The objective of the present study was (1) to evaluate the feasibility of PTT measurement during routine maximal cardiopulmonary exercise testing by means of standard medical equipment and (2) to analyze the relation between blood pressure and PTT using both a linear and a non-linear approach.

Methods

Patients and measurement procedure

20 consecutive patients from a cardiopulmonary unit who were referred to our lung function laboratory for CPET were enrolled into the study. Inclusion criteria were age>18 years and a documented clinical indication for CPET. Patients with acute or life-threatening disease, congestive heart failure NYHA class IV, difference in systolic or diastolic blood pressure between arms greater 10 mm Hg and those whose blood pressure at rest exceeded 200 mm Hg, were excluded. All subjects gave informed consent, and the protocol was approved by the local ethics committee.

All participants underwent a maximal cardiopulmonary exercise testing on a semi-recumbent cycle ergometer (Ergoselect 1000, Ergoline, Bitz, Germany) using an incremental protocol at a comfortable room temperature between 20-22 °C. The initial load was 20 W and was increased by 10 W every minute until individual exhaustion. The study-protocol comprised a 10-min reference and recovery period at rest before and after exercise, respectively.

Right arm blood pressure was measured every 2 min *via* an appropriately sized cuff, using an automated

oscillometric system (Dinamap, ProCare 100, General Electric, Milwaukee, Wisconsin, USA).

Additional single channel electrocardiogram (ECG) and left-arm standard finger photoplethysmography were simultaneously recorded using a multichannel polysomnography device (SomnoLab 2, Weinmann, Germany) at 256 Hz and 32 Hz, respectively.

Signal processing and data analysis

After the end of the recording, PTT was automatically calculated for each R-wave in the ECG and the steepest slope of the corresponding upstroke in the plethysmogram using an open source biosignal-processing software (ANSLAB: Autonomic Nervous System Laboratory, Version 4.0). For each resulting PTT curve, a moving average curve with an interval of 20 s was generated in order to compensate sample rate- and movement-associated noise. Nine measuring points were defined: 2 points during reference period (P1, P2), 2 points during increasing exercise (P3, P4), 1 point near maximum exercise (P5), 2 points after maximum exercise (P6, P7) and 2 points during recovery (P8, P9). Cuff-measured blood pressure (BP) values were assigned to these measuring point categories using the following rules: P1: the first available BP value during reference period; P2: the last available BP value during reference period; P3: the closest available BP value at half-maximum exercise; P4: the last available BP value during increasing exercise previous to P5; P5: the closest available BP value at maximum exercise; P6: the first available BP value after maximum exercise; P7: the second available BP value after maximum exercise; P8: the penultimate available BP value during recovery; P9: the last available BP value during recovery. At each measuring point, the cuff-measured blood pressure value was paired with the corresponding, time-synchronized PTT value, provided that both values were available.

Statistical methods

Relation between PTT and blood pressure was analyzed using linear and non-linear regression.

Linear regression was performed using the standard linear regression model to fit a linear function

$$y = mx + t$$

to the set of data pairs for each individual patient. Based on this function, relation between BP and PTT could be

expressed as follows:

$$BP = mPTT + t \text{ or } PTT = \frac{BP - t}{m}$$

For non-linear regression, we developed a simplified empiric function

$$y = c + \frac{b}{\sqrt{x - a}}$$

to fit the same data pairs. This simplified function was developed based on a more complex model derived from the Moens-Korteweg equation in which pulse wave velocity (PWV) is expressed as a function of blood density (ρ), vessel radius (r), wall thickness (h) and young elasticity modulus (E) (Hirata *et al.* 2006):

$$PWV = \sqrt{\frac{E \cdot h}{2r\rho}}$$

PTT can be expressed as a function of distance (d) and PWV as

$$PTT = \frac{d}{PWV} = \frac{d}{\sqrt{\dfrac{E \cdot h}{2r\rho}}}$$

Assuming that d remains constant, that ρ, r, and h show only small changes (Hughes *et al.* 1979) and that elasticity E is largely determined by blood pressure (Wong *et al.* 2009), we tried to express the relation between BP and PTT using the simplified formula as follows:

$$PTT = c + \frac{b}{\sqrt{BP - a}} \text{ or } BP = a + (\frac{b}{PTT - c})^2$$

In this equation, the constants a and c allows the function to shift along the two axes and the curvature is characterized by the constant b.

Linear and non-linear regression and calculation of coefficients of determination was done separately for the data sets of each individual patient.

Bland-Altman plots were performed to assess the overall agreement between the BP measured by arm cuff and the calculated BP as a function of PTT by using each patient's individual linear and non-linear function

parameters (Bland and Altman 1986). Limits of agreement were defined as average difference ± 1.96 standard deviation (SD).

Data are reported as mean±SD unless otherwise stated. A p<0.05 was considered statistically significant. All data were analyzed with GraphPad Prism (version 5, GraphPad Software, USA).

Results

Patient characteristics and CPET outcome

A total of 20 patients were included in the study and completed the protocol. Patient characteristics are shown in Table 1. The majority of patients had pulmonary diseases. A medical history of moderate or severe dyspnea on exertion, congestive heart failure or left ventricular dysfunction was not present in any of the patients. Two patients had atrial fibrillation (patients 12 and 13), one of them having a dual chamber pace maker (patient 12). In all of the patients, data were processed the same way.

Results from the exercise tests and PTT measurements are shown in Table 2 and in Figures 1-2. The mean maximum workload was 106±47 W and the mean number of evaluable BP/PTT pairs was 8.1, ranging from 5 to 9. Mean systolic BP, diastolic BP and PTT at rest were 128±16 mm Hg, 88±11 mm Hg and 366±31 ms respectively, 197±35 mm Hg, 92±14 mm Hg and 289±23 ms under maximum exercise, and 128±15 mm Hg, 83±13 mm Hg and 371±33 ms during recovery.

Linear and non-linear regression

Linear regression revealed a significant, strong negative correlation (r) between PTT and sBP in all of the 20 patients (data shown as r² in Table 3). The correlation between PTT and dBP was rather weak. In 3 patients a fall in dBP during exercise was observed, resulting in a positive correlation between PTT and dBP (patients 4, 7 and 15). For those 3 sets of data, the non-linear regression model was not applied. For all other data, the non-linear best-fit curves could be calculated and the fit was assessed by the coefficients of determination (R²). Results for R² and r² and the calculated best-fit curves are shown in Table 3 and Figures 3-4.

Bland-Altman plot

Bland-Altman plots on the basis of the linear function revealed limits of agreement of −13.2 to 13.1 mm Hg and −9.5 to 9.5 mm Hg for sBP and dBP,

Table 1. Patient characteristics.

Characteristic	
Number of patients	20
Age, years	51.3 ± 18.4
Male, n (%)	14 (70)
Body height, cm	175 ± 7.9
Body mass index, kg/m²	26.2 ± 5.1
Underlying disease	
Interstitial lung disease, n (%)	5 (25)
COPD	5 (25)
Pulmonary hypertension	4 (20)
Connective tissue disease	2 (10)
Congestive heart failure (NYHA I)	2 (10)
Other	2 (10)
Dyspnea (New York Heart Association Class), n (%)	
I or less	14 (70)
II	6 (30)
III	0 (0)
IV	0 (0)
Left ventricular systolic function, n (%)	
Normal	18 (90)
Mild dysfunction	2 (10)
Moderate or severe dysfunction	0 (0)
History of smoking, n (%)	14 (70)
History of hypertension, n (%)	5 (25)
Diabetes mellitus, n (%)	3 (15)
Atherosclerotic artery disease, n (%)	0 (0)
Rhythm	
Sinus rhythm, n (%)	18 (90)
Atrial fibrillation, n (%)	2 (10)
Pace maker, n (%)	1 (5)
Current medication, n (%)	
Beta-blockers	2 (10)
ACE-inhibitors or AT1b	5 (25)
Digitalis	0 (0)
Diuretics	3 (15)
Calcium channel blockers	0 (0)
Nitrates	0 (0)

Data are mean ± SD. ACE: angiotensin-converting-enzyme; AT1b: angiotensin receptor 1 blockers; COPD: chronic obstructive pulmonary disease. Left ventricular systolic function was assessed by echocardiography.

respectively. When the non-linear function was used, limits of agreement were −10.9 to 10.9 mm Hg and −8.9 to 8.9 mm Hg, respectively. We observed more scatter at

Table 2. CPET results.

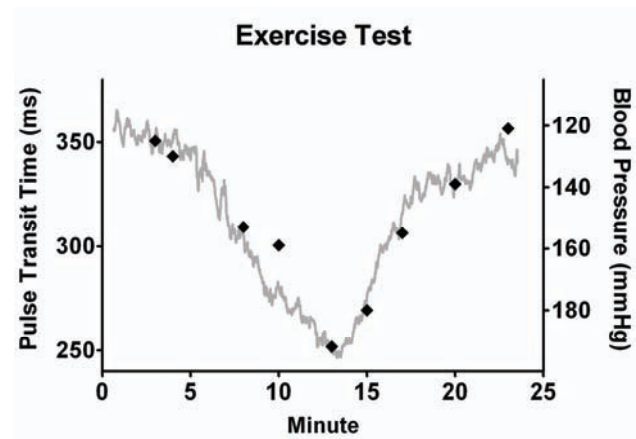| Parameter	
Maximum workload, W	106 ± 47
(% predicted)	(65 ± 22)
Anaerobic threshold workload, W	79 ± 34
Peak-VO$_2$, ml/min/kg	19.5 ± 8.1
VE/VCO$_2$	35.2 ± 6.6
Limitations to maximum exercise, n	
Dyspnea	9
Muscle (fatigue/cramps)	5
Dyspnea and muscle	3
Arthralgia	2
Others (technical)	1
Evaluable BP/PTT pairs, n	8.1 ± 1.3

Data are mean ± SD.

Fig. 1. Average pulse transit time (PTT) and corresponding arm-cuff systolic blood pressure during a cardiopulmonary cycle exercise test (Patient 10). Measuring points (from left to right): P1,P2: reference period; P3,P4: increasing exercise; P5: near maximum exercise; P6,P7: after maximum exercise; P8,P9: recovery period

the higher end of blood pressure values. Bland-Altman plots are shown in Figure 5.

Discussion

The present study demonstrates that the measurement of PTT, using a standard pulse oximeter and a single lead ECG, is feasible during cardiopulmonary exercise tests under routine conditions and that the results produced by this simple method correlate well with the sBP measured by the arm cuff-
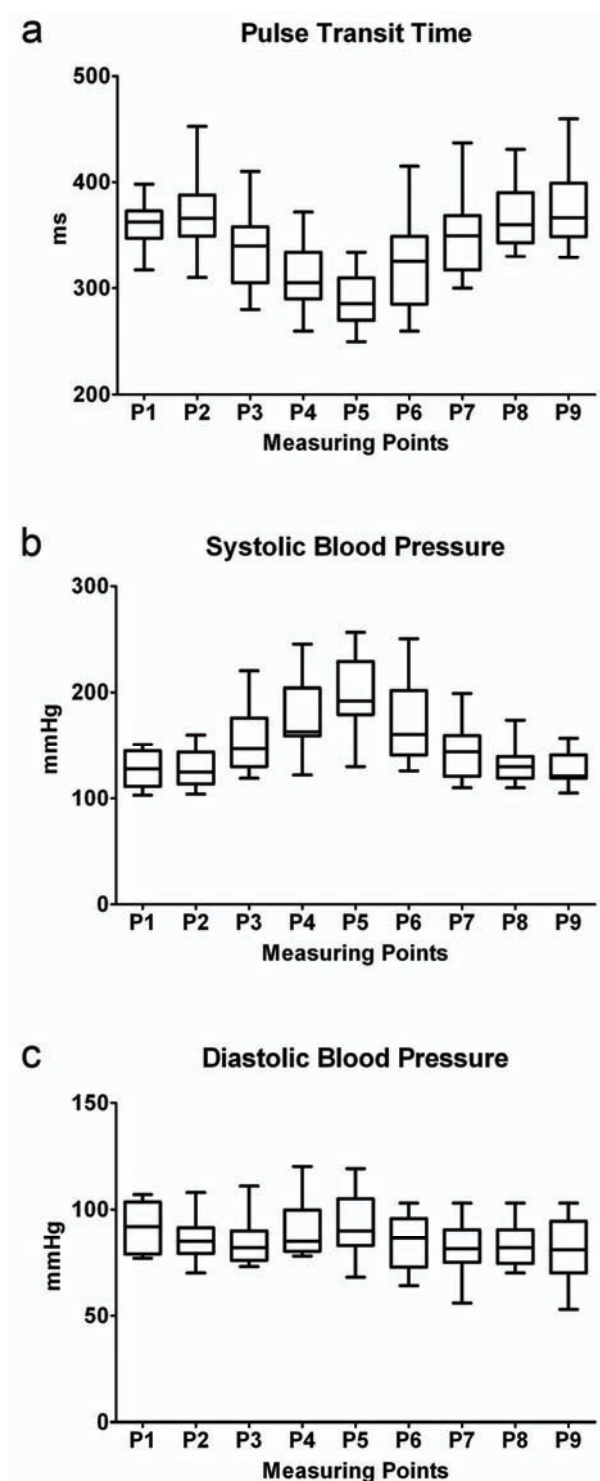
Fig. 2. Box plot of PTT (**a**) and corresponding sBP (**b**) and dBP (**c**) values at measuring points P1 to P9. The line through the box indicates the median, the box represents the interquartile range, and the whiskers represent the full range of values.

method. Similar studies that have been conducted before, focused on the development of particular blood pressure monitoring devices and used special software or methods that were matter of a patent (Gesche et al. 2012, Lass et al. 2004, Masè et al. 2011). In the present study,

particular emphasis was placed on the utilization and development of methods that are simple, readily available, easily reproducible and not dependent on a specific product. For technical reasons, blood pressure, ECG and photoplethysmography was recorded with additional devices in this study, but the ultimate goal should be to implement software to calculate PTT in the commonly used CPET ergometers, based on the build-in standard ECG and pulse oximeter. Our results demonstrate that this objective could basically be achieved.

In the present study, linear and non-linear regression was performed to assess the relationship between PTT and blood pressure. In a number of previous studies, linear relationships between PTT and blood pressure have been reported, while other authors described non-linear relations, and a number of approaches have been developed to find a more realistic model for this relationship based on non-linear functions (Callaghan et al. 1986, Geddes et al. 1981, Gesche et al. 2012, Lass et al. 2004, Muehlsteff et al. 2006, Payne et al. 2006, Porta et al. 2006, Schmalgemeier et al. 2012, Yamashina et al. 2003). To our knowledge, this is the first study to compare the linear and the non-linear approach based on the same set of data in human subjects. For obvious reasons, the linear model has some major limitations, because it assumes negative PTT values when blood pressure increases as well as negative blood pressure at higher PTT values. Thus we created a more realistic, non-linear model assuming asymptotic behavior at higher PTT and BP values. Both the linear and the non-linear model fitted the observed data sets well. Because of the obvious limitations of the linear model and the known pitfalls of regression analysis, comparisons of the two models were not performed using theoretical statistical approaches. Instead, the overall ability to predict BP values from PTT was analyzed using Bland-Altman plots of the calculated BP values using both the linear and the non-linear approach (Bland and Altman 1986). In this analysis, we observed slightly better limits of agreements for the non-linear model than for the linear model. This indicates that when multipoint calibration is used, a non-linear model can be considered more effective in estimating BP compared to a linear model and should therefore be preferred. However, despite its limitations, the linear model might still be an alternative option when non-linear regression analysis is not available, but the obvious issues of this model at high BP and PTT values have to be taken into account.

Table 3. Coefficients of determination r² and R² of linear and non-linear regression for each individual patient.

| Patient	Number of data pairs	r² Linear regression		R² Non-linear regression	
		sBP	dBP	sBP	dBP
1	8	0.95	0.12	0.97	0.23
2	8	0.87	0.70	0.87	0.78
3	9	0.96	0.73	0.97	0.73
4	8	0.93	0.58	0.95	
5	8	0.97	0.53	0.98	0.54
6	7	0.98	0.22	0.98	0.36
7	7	0.89	0.38	0.97	
8	9	0.98	0.61	0.99	0.62
9	9	0.92	0.07	0.97	0.32
10	9	0.94	0.55	0.94	0.55
11	8	0.96	0.55	0.96	0.55
12	8	0.93	0.76	0.96	0.79
13	9	0.87	0.46	0.87	0.46
14	9	0.92	0.33	0.92	0.33
15	8	0.93	0.03	0.95	
16	7	0.92	0.27	0.94	0.48
17	7	0.93	0.14	0.93	0.14
18	9	0.93	0.46	0.93	0.53
19	6	0.98	0.01	0.98	0.30
20	9	0.96	0.04	0.97	0.05
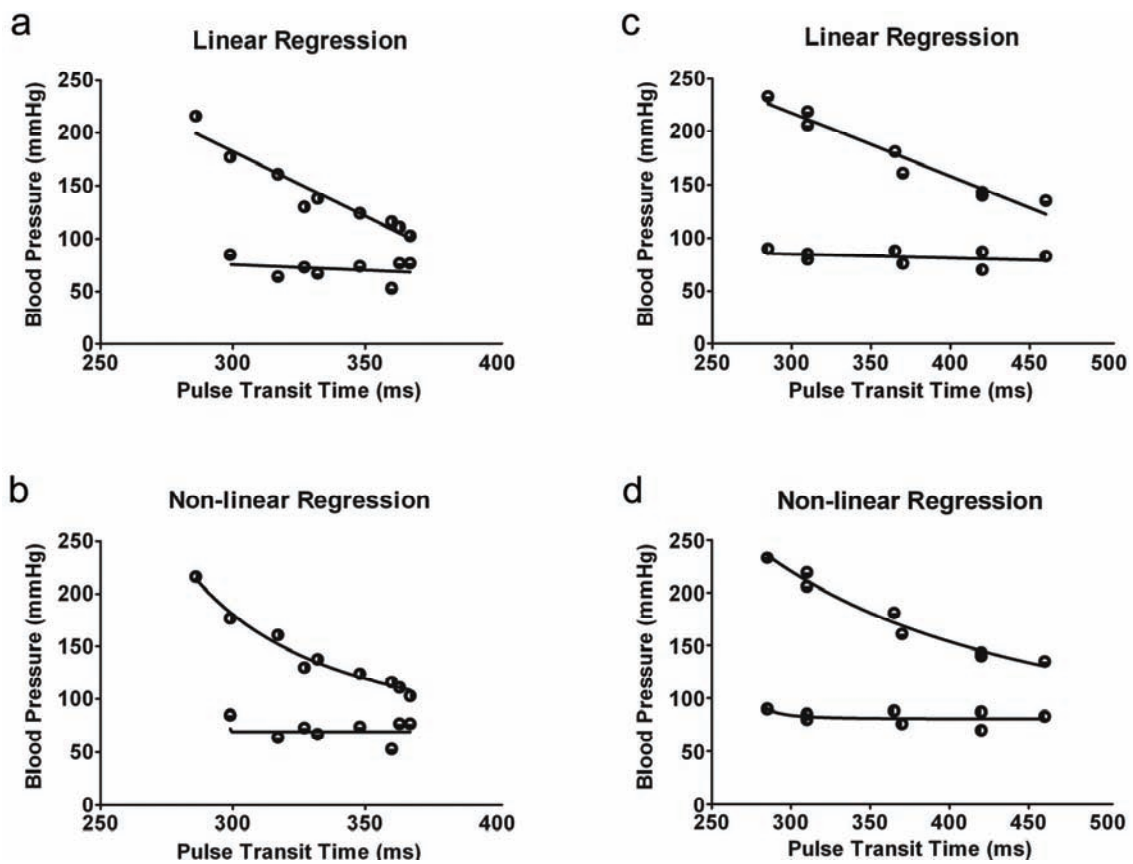
Fig. 3. Two examples of relation between PTT and blood pressure using linear and non-linear regression (**a** and **b**: Patient 9; **c** and **d**: Patient 1). Upper curve: sBP; lower curve: dBP
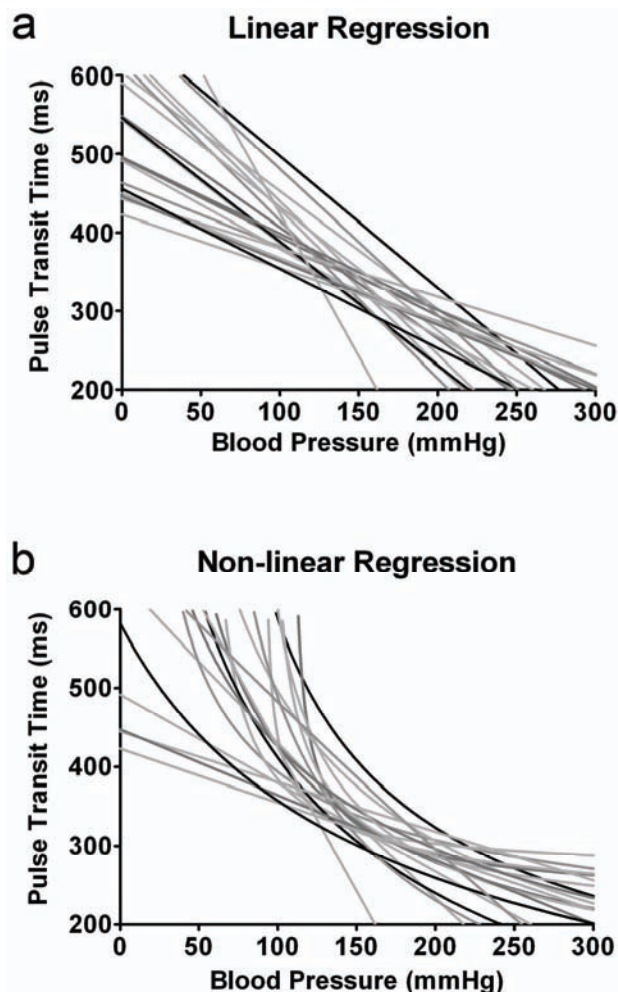
Fig. 4. Plot of the 20 regression function estimates derived from the 20 individual data sets of sBP and PTT, generated either by linear (**a**) or non-linear regression (**b**).

Fig. 5. Bland-Altman plots demonstrating the overall agreement between the sBP measured by arm cuff and the calculated sBP as a linear (**a**) or non-linear function (**b**) of PTT in all 20 sets of data by using each patient's individual linear and non-linear function parameters. The outer lines indicate the limits of agreement, the inner line represents the mean difference.

In most of the patients we observed better coefficients of determination for sBP than for dBP, which is in agreement with the results of previous studies (Gesche *et al.* 2012, Lass *et al.* 2004, Muehlsteff *et al.* 2006, Payne *et al.* 2006). A possible explanation of these findings is that sBP as well as PTT are similarly dependent on both vascular function and ventricular contraction (Payne *et al.* 2006).

Previous studies have demonstrated strong relations between PTT and sBP in healthy subjects during exercise (Gesche *et al.* 2012, Lass *et al.* 2004, Masè *et al.* 2011), and the results of our study suggest that the feasibility of PTT measurement as well as the strong PTT-sBP relation during CPET is similar in exercise-limited patients with clinical indication for CPET.

Using the methods shown in this study, PTT might therefore allow continuous estimation of sBP during CPET, provided that intermittent arm-cuff BP measurements are simultaneously performed for
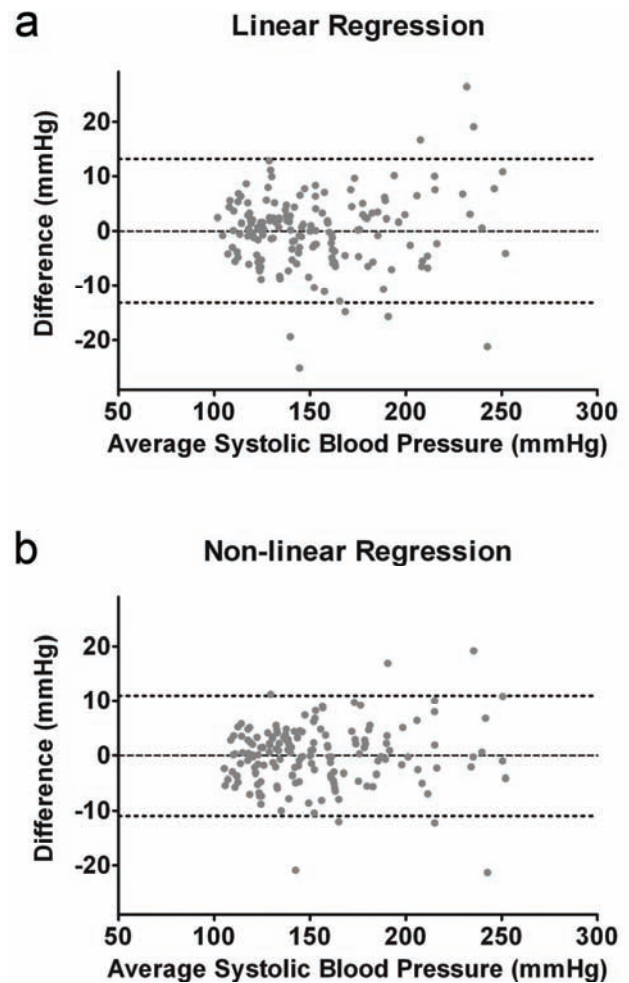
multipoint calibration. As an additional cardiovascular parameter during CPET, this surrogate measure of continuous sBP might have the potential to provide novel opportunities for future research.

However, estimation of continuous systolic blood pressure is not the only potential application of PTT measurement. A recent study demonstrated that the PTT-BP relationship at rest is altered in patients with severe chronic heart failure (Wagner *et al.* 2010). The relation between PTT and BP during CPET that can be characterized for the individual patient using the techniques shown in this study, might give additional information about the individual cardiovascular and autonomic response to physical exercise. Future clinical studies might address the model parameters estimated by linear or non-linear regression, as well as the estimated asymptotes in the non-linear model, or the calculated

PTTs at specific, virtual BP values to assess the condition and the reactivity of the cardiovascular and autonomous nervous system for each individual patient.

Based upon the evidence to date, PTT is an interesting research tool, but its potential use in clinical practice needs to be further explored. Definitive clinical conclusions regarding the interpretation of PTT and decision making must be based on evidence from diagnostic studies, but at present these data are limited. Moreover, before clinical use, accepted standards and recommendations have to be established which apply to the particular application of PTT and the clinical setting.

Our study was limited in some respects. We used an automated, intermittent, non-invasive, oscillometric system for blood pressure measurement. Auscultatory devices or continuous invasive blood pressure monitoring, which is the gold standard for blood pressure measurement, might have led to slightly different results. In addition, due to intermittent blood pressure measurement, the assessment of PTT-BP relation was limited to 9 pairs of data for each patient in our study. Continuous blood pressure measurement, including non-invasive methods as the volume clamp technique would have provided a large sample of beat-to-beat PTT-BP data, which could have allowed to estimate the strength of the relationship and the goodness of fit with more precision (Lass *et al.* 2004). However, all methods of blood pressure measurements have known limitations and could have caused bias (Ward and Langton 2007). Interference from movement during exercise could have affected BP values measured by the oscillometric method as well as PTT values derived from finger-photoplethysmography in our study, but influence on overall outcome seemed to be tolerable and was not systematically evaluated in this setting. For the same reason, the role of room temperature, contact force of the photoplethysmographic sensor and other factors that might have influenced finger pulse waveforms or PTT was not systematically evaluated in our study. In order to obtain a continuous photoplethysmography signal without interruption, arm cuff blood pressure had to be measured at the opposite arm, which might also have influenced our findings. Bias and limits of agreement in our study, which has been conducted during physical exercise, can not easily be compared to those for the validation of blood pressure measuring devices, which typically use strict protocols at rest, as the ANSI/AAMI

SP10-2002 protocol or the European Society of Hypertension International Protocol revision 2010 (O'Brien *et al.* 2010). Another limitation of the present study is, that it was not designed for anthropometric or disease specific statistical analyses. Further studies are warranted to explore the effects of patient and disease characteristics on PTT and on its relation to blood pressure during exercise. Reproducibility of the individual function parameters has not been investigated in this study and might be addressed in future research.

In conclusion, the results of this study show that measurement of PTT is feasible during CPET under clinical conditions and could provide additional information on individual cardiovascular reactivity during exercise. Linear regression produced generally high levels of correlation between PTT and systolic blood pressure, even though our analysis demonstrated that a more realistic, non-linear model tended to produce slightly better results in the estimation of blood pressure than linear regression. Measurement of PTT during CPET can be considered an easy-to-use method, which can potentially be used for continuous monitoring of systolic blood pressure when combined with simultaneous intermittent arm-cuff BP readings for multipoint calibration as demonstrated in the present study. Further studies on PTT-BP relation during exercise might broaden its value as a diagnostic tool in cardiopulmonary exercise tests. Implementation of PTT calculation in the commonly used CPET ergometers, based on the build-in standard ECG and pulse oximeter recordings, would allow PTT to be a widely available measurement tool for research and potential future clinical application.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

Abbreviations

BP	Blood pressure
CPET	Cardiopulmonary exercise test
dBP	Diastolic blood pressure
PTT	Pulse transit time
PWV	Pulse wave velocity
sBP	Systolic blood pressure

References

AHLSTROM C, JOHANSSON A, UHLIN F, LÄNNE T, ASK P: Noninvasive investigation of blood pressure changes using the pulse wave transit time: a novel approach in the monitoring of hemodialysis patients. *J Artif Organs* **8**: 192-197, 2005.

BLAND JM, ALTMAN DG: Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* **327**: 307-310, 1986.

CALLAGHAN FJ, GEDDES LA, BABBS CF, BOURLAND JD: Relationship between pulse-wave velocity and arterial elasticity. *Med Biol Eng Comput* **24**: 248-254, 1986.

CONTAL O, CARNEVALE C, BOREL J-C, SABIL A, TAMISIER R, LÉVY P, JANSSENS J-P, PÉPIN J-L: Pulse transit time as a measure of respiratory effort under non-invasive ventilation. *Eur Respir J* **41**: 346-353, 2013.

FECHIR M, SCHLERETH T, PURAT T, KRITZMANN S, GEBER C, EBERLE T, GAMER M, BIRKLEIN F: Patterns of sympathetic responses induced by different stress tasks. *Open Neurol J* **2**: 25-31, 2008.

GEDDES LA, VOELZ MH, BABBS CF, BOURLAND JD, TACKER WA: Pulse transit time as an indicator of arterial blood pressure. *Psychophysiology* **18**: 71-74, 1981.

GESCHE H, GROSSKURTH D, KÜCHLER G, PATZAK A: Continuous blood pressure measurement by using the pulse transit time: comparison to a cuff-based method. *Eur J Appl Physiol* **112**: 309-315, 2012.

HIRATA K, KAWAKAMI M, O'ROURKE MF: Pulse wave analysis and pulse wave velocity: a review of blood pressure interpretation 100 years after Korotkov. *Circ J* **70**: 1231-1239, 2006.

HUGHES DJ, BABBS CF, GEDDES LA, BOURLAND JD: Measurements of Young's modulus of elasticity of the canine aorta with ultrasound. *Ultrason Imaging* **1**: 356-367, 1979.

KORTEKAAS MC, NIEHOF SP, VAN VELZEN MHN, GALVIN EM, HUYGEN FJPM, STOLKER RJ: Pulse transit time as a quick predictor of a successful axillary brachial plexus block. *Acta Anaesthesiol Scand* **56**: 1228-1233, 2012.

KOUNALAKIS SN, GELADAS ND: The role of pulse transit time as an index of arterial stiffness during exercise. *Cardiovasc Eng* **9**: 92-97, 2009.

LASS J, MEIGAS K, KARAI D, KATTAI R, KAIK J, ROSSMANN M: Continuous blood pressure monitoring during exercise using pulse wave transit time measurement. In: *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, IEEE, San Francisco, 2004, pp 2239-2242.

MASÈ M, MATTEI W, CUCINO R, FAES L, NOLLO G: Feasibility of cuff-free measurement of systolic and diastolic arterial blood pressure. *J Electrocardiol* **44**: 201-207, 2011.

MUEHLSTEFF J, AUBERT XL, SCHUETT M: Cuffless estimation of systolic blood pressure for short effort bicycle tests: the prominent role of the pre-ejection period. In: *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, IEEE, New York, 2006, pp 5088-5092.

O'BRIEN E, ATKINS N, STERGIOU G, KARPETTAS N, PARATI G, ASMAR R, IMAI Y, WANG J, MENGDEN T, SHENNAN A: European Society of Hypertension International Protocol revision 2010 for the validation of blood pressure measuring devices in adults. *Blood Press Monit* **15**: 23-38, 2010.

OCHIAI R, TAKEDA J, HOSAKA H, SUGO Y, TANAKA R, SOMA T: The relationship between modified pulse wave transit time and cardiovascular changes in isoflurane anesthetized dogs. *J Clin Monit Comput* **15**: 493-501, 1999.

PAYNE RA, SYMEONIDES CN, WEBB DJ, MAXWELL SRJ: Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure. *J Appl Physiol* **100**: 136-141, 2006.

PORTA A, GASPERI C, NOLLO G, LUCINI D, PIZZINELLI P, ANTOLINI R, PAGANI M: Global versus local linear beat-to-beat analysis of the relationship between arterial pressure and pulse transit time during dynamic exercise. *Med Biol Eng Comput* **44**: 331-337, 2006.

SCHMALGEMEIER H, BITTER T, BARTSCH S, BULLERT K, FISCHBACH T, ECKERT S, HORSTKOTTE D, OLDENBURG O: Pulse transit time: validation of blood pressure measurement under positive airway pressure ventilation. *Sleep Breath* **16**: 1105-1112, 2012.

SHARWOOD-SMITH G, BRUCE J, DRUMMOND G: Assessment of pulse transit time to indicate cardiovascular changes during obstetric spinal anaesthesia. *Br J Anaesth* **96**: 100-105, 2006.

SMITH RP, ARGOD J, PÉPIN JL, LÉVY PA: Pulse transit time: an appraisal of potential clinical applications. *Thorax* **54**: 452-457, 1999.

WAGNER DR, ROESCH N, HARPES P, KÖRTKE H, PLUMER P, SABERIN A, CHAKOUTIO V, OUNDJEDE D, DELAGARDELLE C, BEISSEL J, GILSON G, KINDERMANN I, BÖHM M: Relationship between pulse transit time and blood pressure is impaired in patients with chronic heart failure. *Clin Res Cardiol* **99**: 657-664, 2010.

WARD M, LANGTON JA: Blood pressure measurement. *Contin Educ Anaesth Crit Care Pain* **7**: 122-126, 2007.

WONG MY, PICKWELL-MacPHERSON E, ZHANG YT: The acute effects of running on blood pressure estimation using pulse transit time in normotensive subjects. *Eur J Appl Physiol* **107**: 169-175, 2009.

YAMASHINA A, TOMIYAMA H, ARAI T, KOJI Y, YAMBE M, MOTOBE H, GLUNIZIA Z, YAMAMOTO Y, HORI S: Nomogram of the relation of brachial-ankle pulse wave velocity with blood pressure. *Hypertens Res* **26**: 801-806, 2003.