34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Estimation of central aortic pressure waveform features derived from the brachial cuff volume displacement waveform*

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Abstract— **There is increasing interest in non-invasive estimation of central aortic waveform parameters in the clinical setting. However, controversy has arisen around radial tonometric based systems due to the requirement of a trained operator or lack of ease of use, especially in the clinical environment. A recently developed device utilizes a novel algorithm for brachial cuff based assessment of aortic pressure values and waveform (SphygmoCor XCEL, AtCor Medical). The cuff was inflated to 10 mmHg below an individual's diastolic blood pressure and the brachial volume displacement waveform recorded. The aortic waveform was derived using proprietary digital signal processing and transfer function applied to the recorded waveform. The aortic waveform was also estimated using a validated technique (radial tonometry based assessment, SphygmoCor, AtCor Medical). Measurements were taken in triplicate with each device in 30 people (17 female) aged 22 to 79 years of age. An average for each device for each individual was calculated, and the results from the two devices were compared using regression and Bland-Altman analysis. A high correlation was found between the devices for measures of aortic systolic (R^2=0.99) and diastolic (R^2=0.98) pressure. Augmentation index and subendocardial viability ratio both had a between device R^2 value of 0.82. The difference between devices for measured aortic systolic pressure was 0.5±1.8 mmHg, and for augmentation index, 1.8±7.0%. The brachial cuff based approach, with an individualized sub-diastolic cuff pressure, provides an operator independent method of assessing not only systolic pressure, but also aortic waveform features, comparable to existing validated tonometric-based methods.**

I. INTRODUCTION

As an increasing number of population studies show the importance of central aortic parameters of blood pressure as potential additive predictors of cardiovascular risk and events [1], [2], [3], there is a parallel impetus for use of such parameters in the clinical setting and as clinical markers of cardiovascular disease [4], [5]. A number of devices that estimate the aortic pressure waveform by non-invasive means use a tonometric based approach, whereby the radial artery is applanated, and a transfer function applied to estimate the aortic waveform [6], [7], [8] or use the carotid waveform calibrated to mean and diastolic brachial blood pressure values as a surrogate measure of aortic pulse pressure [8], [9].Whilst both have proven to be reliable techniques, useful in the research setting, the clinical environment poses different restrictions. Namely, a blood pressure device routinely used in the clinical setting should be user independent, easy to use with minimal operator training whilst maintaining accuracy. Tonometric applanation of the radial artery does require some training, and has, arguably, some degree of operator dependence.

New devices are being developed and entering the market using various features of the waveform derived from a brachial cuff to estimate the central aortic waveform. One such device is the SphygmoCor XCEL, which records the volume displacement waveform from the brachial cuff, with the cuff inflated to 10 mmHg below diastolic blood pressure. This signal is processed and a transfer function applied to estimate the aortic waveform.

This study examines the SphygmoCor XCEL device, comparing against the SphygmoCor tonometer based device, often quoted as the "gold standard" for non-invasive estimation on the aortic pressure waveform.

II. METHODS

30 subjects (13 female) aged 22 to 79 years of age were recruited. The Macquarie University Human Ethics Committee approved recruitment and procedures and all subjects gave informed consent.

Each subject attended the clinic at The Australian School of Advanced Medicine, where they were seated for 10 minutes before brachial blood pressure was measured, in the seated position, using a standard blood pressure measuring device (Microlife BP A100 Plus).

The SphygmoCor XCEL device was fitted, with a brachial cuff positioned in the standard position used for oscillometric measurement of blood pressure. The cuff was inflated to 10 mmHg below the individual's diastolic blood pressure for optimum recording of the brachial volume displacement waveform. This threshold for inflation pressure was obtained by taking into account the possible variation in diastolic pressure during the measurement period such that an optimal volume pulse can be obtained free of distortion due to the inflation pressure being above arterial diastolic pressure. The waveform was calibrated to systolic and diastolic values obtained by oscillometric measurement of brachial blood pressure. Proprietary digital signal processing and transfer function, programmed into the device, were applied to the calibrated brachial waveform to estimate the aortic pressure waveform.

The XCEL device was compared to the SphygmoCor tonometric device. A radial pulse was recorded using the tonometer, applanated on the wrist above the radial artery and ulna. The recorded waveform was calibrated using brachial oscillometric blood pressure measurement of systolic and

*This work was supported in part by AtCor Medical and by a grant from the Australian Research Council (MB: ARC Discovery DP110101134).

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978-1-4577-1787-1/12/$26.00 ©2012 IEEE

diastolic pressure, and a validated transfer function utilized to estimate the central, aortic pressure [7], [6]. Aortic pressure was estimated three times with each device in each individual. A dual operator study design was adopted, with the two devices being used alternatively by the two operators on each study subject.

Parameters characterizing the estimated aortic pressure waveform that were extracted for analysis were: systolic pressure, diastolic pressure, augmentation index (AIx), and subendocardial viability ratio (SEVR). The AIx is the ratio of the augmented pressure component of the pressure waveform to the pulse pressure (1). The augmented pressure component is defined by the limits of the inflection point in the pressure waveform (P_i) and the systolic peak (P_s). The SEVR is the ratio of the diastolic area of the pressure waveform to the systolic area of the waveform (2). The transition point between systole and diastole is defined by the incisura. As the AIx and SEVR require detection of fiducial points on the pressure waveform, a reliable estimation of the aortic waveform is required to accurately estimate AIx and SEVR.

$$AIx(\%) = 100(P_s - P_i)/pulse\ pressure \quad (1)$$

$$SEVR = diastolic\ area/systolic\ area \quad (2)$$

An average of each parameter for each device for each individual was calculated. These were then grouped and the results from the two devices compared using linear regression and Bland-Altman analysis [10], including paired Student's t-test between device results. All analysis was conducted in R [11].

III. Results

Grouped demographics of the recruited subjects are presented in Table I. Subjects were recruited such that adults from a wide range of ages were studied: 10 subjects below the age of 30 (6 female); 12 subjects between the ages of 30 and 60 (5 female); and 8 subjects above the age of 60 (2 female).

An example brachial volume displacement waveform, radial tonometric waveform, and respective derived central aortic waveforms is provided in Fig. 1. The fitting of the brachial cuff of the XCEL device was made according to standard fitting of an oscillometric device, and from that point forward, measurement was user independent.

Regression of the aortic diastolic values from the two devices yielded an R^2 value of 0.98 (p=0.93), and for aortic systolic values, 0.99 (p=0.15, Table II). There was a slight bias toward lower systolic values in the cuff-based device at higher systolic pressures (Fig. 2B, F), though the magnitude of this was small, no more than 4 mmHg, and on average read 0.5 mmHg higher across the whole group (Table III).

A greater bias was seen in AIx measurements (Fig. 2C), though the difference between devices was 1.8±7.0% in absolute terms. The SEVR had little bias (Fig. 2D), but a small, significant difference between devices (Table III).

TABLE I

Subject demographics

parameter	mean±standard deviation (range)
Age (years)	43±19 (22 to 79)
Sex (male/female)	17/13
Height (m)	1.72±0.09 (1.56 to 1.94)
Weight (kg)	70±12 (44 to 92)
Body mass index (kg/m^2)	23±4 (17 to 33)
Heart rate (bpm)	68±9 (50 to 90)
Brachial pressures	
Systolic pressure (mmHg)	119±16 (95 to 151)
Diastolic pressure (mmHg)	75±9 (65 to 106)
Aortic pressures	
Systolic pressure (tonometer) (mmHg)	106±16 (84 to 146)
Diastolic pressure (tonometer) (mmHg)	76±9 (66 to 107)
Systolic pressure (XCEL) (mmHg)	106±15 (84 to 143)
Diastolic pressure (XCEL) (mmHg)	76±9 (66 to 106)

tonometer=SphygmoCor tonometer device, XCEL=SphygmoCor XCEL (cuff-based) device.

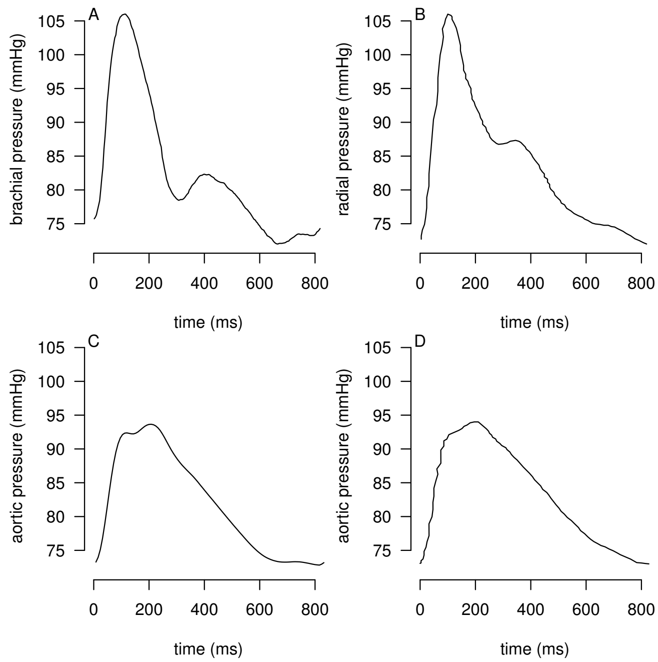

Fig. 1. An example of the waveforms acquired from the cuff based and tonometric devices. (A) Waveform acquired with a brachial cuff inflated to 60 mmHg, calibrated to oscillometric measured brachial blood pressure systolic and diastolic values (106/72 mmHg). (B) Waveform acquired with a tonometer applanating the radial artery, calibrated to oscillometric measured brachial blood pressure systolic and diastolic values (106/72 mmHg). The bottom panels display the derived aortic waveform from (C) the cuff based device and (D) the tonometer based device. Recordings are from a 37 year old male subject.

TABLE II

Linear relationship between devices

Linear regression between devices	R^2	p
$ASP_c = 0.94 \times ASP_t + 7.1$	0.99	<0.001
$ADP_c = 0.98 \times ADP_t + 1.6$	0.99	<0.001
$AIx_c = 0.62 \times AIx_t + 5.9$	0.82	<0.001
$SEVR_c = 0.89 \times SEVR_t + 0.091$	0.82	<0.001

ASP=aortic systolic pressure, ADP=aortic diastolic pressure, AIx=aortic augmentation index, SEVR=subendocardial viability ratio, c=cuff based device, t=tonometric device.

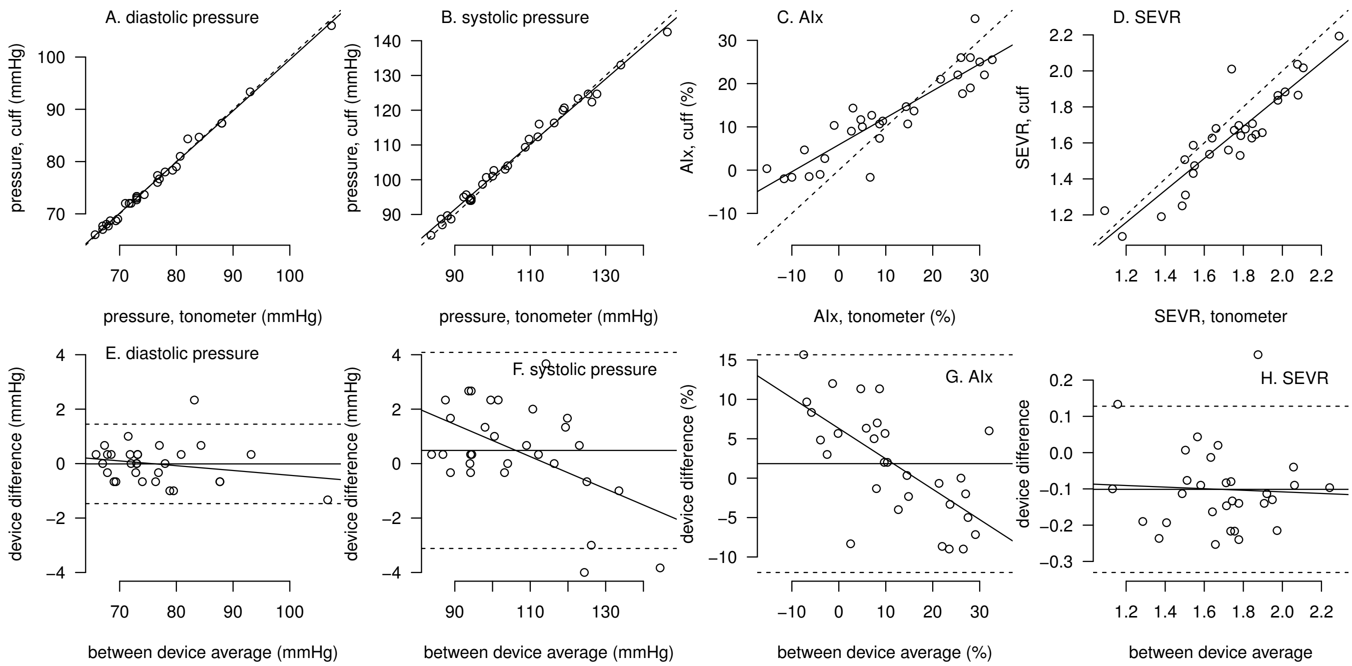

Fig. 2. The relationship between the cuff based and tonometric device for estimated aortic (A) systolic pressure, (B) diastolic pressure, (C) augmentation index (AIx), and (D) subendocardial viability ratio (SEVR) and their corresponding difference between devices (E-H). The linear regression for A-D are given in Table II. In the lower panels (E-H), the dashed lines encapsulate the area within two times the standard deviation of the mean of the difference. The mean and standard deviation of the differences are provided in Table III.

TABLE III

DIFFERENCE BETWEEN DEVICES

parameter	difference			p
aortic systolic pressure	0.5	±	1.8 mmHg	0.15
aortic diastolic pressure	-0.01	±	0.5 mmHg	0.93
aortic AIx	1.8	±	7.0 %	0.15
SEVR	-0.10	±	0.12	<0.001

IV. DISCUSSION

The brachial cuff volume displacement waveform was easily obtained with conventional placement of the cuff in the standard, upper arm position. The waveform was stable if the subject stayed relatively still (Fig. 1), though the waveform was prone to movement artefact if subjects moved their body or arm considerably.

In device design, a variety of cuff pressures were trialled, including sub-diastolic, mean pressure, and supra-systolic values. Supra-diastolic values of cuff pressure either eliminated the diastolic component of the waveform or introduced additional artefact due to partially or fully obliterating the artery being interrogated. Therefore, a sub-diastolic value of cuff pressure was chosen as this permitted capturing of features during the entire pulse. A value of 10 mmHg was chosen to permit small, short term changes in diastolic pressure whilst still having a cuff pressure below that diastolic value.

Estimated systolic and diastolic values of central aortic pressure using the cuff based device did not differ greatly from those estimated using the tonometer based method. There was a small trend toward underestimation of aortic systolic pressures by the cuff based device (Fig. 2B, F), though this underestimation did not exceed 4 mmHg in the subjects sampled.

The cuff based device showed a slight underestimation of SEVR compared to values derived with the tonometer based device. AIx estimated with the cuff based device was centred about the mean given by the tonometer based device. However, there was a trend toward overestimation of low AIx values, and underestimation of high AIx values. That is, a flattening of the spread across the subjects sampled. This may be of some concern in population studies using the device, especially when comparing measurements to existing data collected with devices such as the SphygmoCor tonometer based device. This result may also be considered in the discussion around the general accuracy of estimation of central aortic AIx [12], [13], regardless of the non-invasive technique used.

There were no discernible differences between the pulses acquired in males and females using the cuff based device, though the sample size in this study is underpowered for any thorough analysis and further work would be required to investigate this.

In this study, a comparison was drawn between two non-invasive devices for estimation of aortic pressure. No effort has been made to validate these against an invasive measure of the aortic pressure waveform. By comparing one non-invasive device against another, this study does not rule out a similar bias in measurement of both devices compared to an invasive measure of aortic pressure. The validation of the cuff based device relies on the previous studies confirming the accuracy of the tonometer based device, compared to invasive measures [6], [7], [14].

The study involves only 30 subjects across a wide range of ages and blood pressures, with an equal distribution between males and females. This was a large enough sample to detect some differences between the two devices. However, a larger sample size may provide further information on the accuracy of the cuff based device, especially with respect to analysis of waveform parameters such as AIx and SEVR.

This study compares the SphygmoCor XCEL device with the SphygmoCor tonometer based device. In a similar manner, validation studies have been carried out on other cuff based devices for central aortic parameter estimation, such as techniques using nominal set [15], oscillometric [16] and supra-systolic cuff pressure [17] cuff pressure for pulse detection. As cuff based devices have come to market, they traditionally have estimated only aortic systolic and diastolic values, though there is a trend toward incorporation of other indices related to waveform geometry, such as AIx. The current study investigates not only aortic systolic and diastolic values in the SphygmoCor XCEL device, but also parameters of waveform shape, specifically, AIx and SEVR. These parameters are dependent on the estimation and detection of fiducial points on the aortic waveform, and therefore reliable estimation of the waveform shape, not just the peak and trough, is required. The additional information provided from aortic waveform features has additive clinical significance. AIx, for example, is a known risk factor for cardiovascular disease and events in the young compared to the elderly [18], and SEVR can provide an index of myocardial perfusion [19].

V. Conclusion

The volume displacement waveform from the brachial cuff, inflated to 10 mmHg below the individual's diastolic pressure, can be used to estimate the central, aortic pressure waveform in so far as features such as the systolic and diastolic peaks, augmentation index, and subendocardial viability ratio. The estimation of aortic peak values and waveform features from the brachial cuff waveform is comparable to existing tonometric-based methods.

References

[1] B. Dahlöf, R. B. Devereux, S. E. Kjeldsen, S. Julius, G. Beevers, U. de Faire, F. Fyhrquist, H. Ibsen, K. Kristiansson, O. Lederballe-Pedersen, L. H. Lindholm, M. S. Nieminen, P. Omvik, S. Oparil, and H. Wedel, "Cardiovascular morbidity and mortality in the Losartan Intervention For Endpoint reduction in hypertension study (LIFE): a randomised trial against atenolol." *Lancet*, vol. 359, no. 9311, pp. 995–1003, Mar. 2002.

[2] B. Williams, P. S. Lacy, S. M. Thom, K. Cruickshank, A. Stanton, D. Collier, A. D. Hughes, H. Thurston, and M. O'Rourke, "Differential impact of blood pressure-lowering drugs on central aortic pressure and clinical outcomes: principal results of the Conduit Artery Function Evaluation (CAFE) study." *Circulation*, vol. 113, no. 9, pp. 1213–25, Mar. 2006.

[3] M. J. Roman, R. B. Devereux, J. R. Kizer, E. T. Lee, J. M. Galloway, T. Ali, J. G. Umans, and B. V. Howard, "Central pressure more strongly relates to vascular disease and outcome than does brachial pressure: the Strong Heart Study," *Hypertension*, vol. 50, no. 1, pp. 197–203, 2007.

[4] M. F. O'Rourke and A. Adji, "Noninvasive studies of central aortic pressure." *Current hypertension reports*, vol. 14, no. 1, pp. 8–20, Feb. 2012.

[5] A. P. Avolio, M. Butlin, and A. Walsh, "Arterial blood pressure measurement and pulse wave analysis–their role in enhancing cardiovascular assessment." *Physiological measurement*, vol. 31, no. 1, pp. R1–47, Jan. 2010.

[6] J. E. Sharman, R. Lim, A. M. Qasem, J. S. Coombes, M. I. Burgess, J. Franco, P. Garrahy, I. B. Wilkinson, and T. H. Marwick, "Validation of a generalized transfer function to noninvasively derive central blood pressure during exercise." *Hypertension*, vol. 47, no. 6, pp. 1203–8, 2006.

[7] C. H. Chen, E. Nevo, B. Fetics, P. H. Pak, F. C. P. Yin, L. Maughan, D. A. Kass, and W. L. Maughan, "Estimation of central aortic pressure waveform by mathematical transformation of radial tonometry pressure. Validation of generalized transfer function." *Circulation*, vol. 95, no. 7, pp. 1827–36, Apr. 1997.

[8] P. Salvi, G. Lio, C. Labat, E. Ricci, B. Pannier, and A. Benetos, "Validation of a new non-invasive portable tonometer for determining arterial pressure wave and pulse wave velocity: the PulsePen device." *Journal of hypertension*, vol. 22, no. 12, pp. 2285–93, Dec. 2004.

[9] L. M. Van Bortel, E. J. Balkestein, J. J. van der Heijden-Spek, F. H. Vanmolkot, J. a. Staessen, J. a. Kragten, J. W. Vredeveld, M. E. Safar, H. a. Struijker Boudier, and a. P. Hoeks, "Non-invasive assessment of local arterial pulse pressure: comparison of applanation tonometry and echo-tracking." *Journal of hypertension*, vol. 19, no. 6, pp. 1037–44, Jun. 2001.

[10] J. M. Bland and D. G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement." *Lancet*, vol. 1, no. 8476, pp. 307–10, Feb. 1986.

[11] R Development Core Team, "R: A Language and Environment for Statistical Computing," 2012. [Online]. Available: http://www.r-project.org/

[12] C. H. Chen, C. T. Ting, A. Nussbacher, E. Nevo, D. A. Kass, P. Pak, S. P. Wang, M. S. Chang, and F. C. Yin, "Validation of carotid artery tonometry as a means of estimating augmentation index of ascending aortic pressure." *Hypertension*, vol. 27, no. 2, pp. 168–75, Feb. 1996.

[13] V. Melenovsky, B. a. Borlaug, B. Fetics, K. Kessler, L. Shively, and D. a. Kass, "Estimation of central pressure augmentation using automated radial artery tonometry." *Journal of hypertension*, vol. 25, no. 7, pp. 1403–9, Jul. 2007.

[14] A. L. Pauca, M. F. O'Rourke, and N. D. Kon, "Prospective evaluation of a method for estimating ascending aortic pressure from the radial artery pressure waveform." *Hypertension*, vol. 38, no. 4, pp. 932–7, Oct. 2001.

[15] S. S. Hickson, M. Butlin, J. Broad, A. P. Avolio, I. B. Wilkinson, and C. M. McEniery, "Validity and repeatability of the Vicorder apparatus: a comparison with the SphygmoCor device." *Hypertension Research*, vol. 32, no. 12, pp. 1079–85, 2009.

[16] S. Wassertheurer, J. Kropf, T. Weber, M. van der Giet, J. Baulmann, M. Ammer, B. Hametner, C. C. Mayer, B. Eber, and D. Magometschnigg, "A new oscillometric method for pulse wave analysis: comparison with a common tonometric method." *Journal of human hypertension*, vol. 24, no. 8, pp. 498–504, Aug. 2010.

[17] M. W. Rajzer, W. Wojciechowska, M. Klocek, I. Palka, M. Brzozowska-Kiszka, and K. Kawecka-Jaszcz, "Comparison of aortic pulse wave velocity measured by three techniques: Complior, SphygmoCor and Arteriograph." *Journal of hypertension*, vol. 26, no. 10, pp. 2001–2007, Oct. 2008.

[18] C. M. McEniery, Yasmin, K. M. Maki-Petaja, B. J. McDonnell, M. Munnery, S. S. Hickson, S. S. Franklin, J. R. Cockcroft, and I. B. Wilkinson, "The impact of cardiovascular risk factors on aortic stiffness and wave reflections depends on age: the Anglo-Cardiff Collaborative Trial (ACCT III)." *Hypertension*, vol. 56, no. 4, pp. 591–597, Oct. 2010.

[19] J. I. Hoffman and G. D. Buckberg, "The myocardial supply:demand ratio - a critical review." *The American journal of cardiology*, vol. 41, no. 2, pp. 327–32, Feb. 1978.