HHS Public Access

Author manuscript

IEEE Trans Biomed Eng. Author manuscript; available in PMC 2019 November 01.

Published in final edited form as:

IEEE Trans Biomed Eng. 2018 November ; 65(11): 2384–2391. doi:10.1109/TBME.2018.2797239.

Ballistocardiogram-Based Approach to Cuff-Less Blood Pressure Monitoring: Proof-of-Concept and Potential Challenges

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Abstract

Objective: The goal was to propose and establish the proof-of-concept of an ultra-convenient cuff-less blood pressure monitoring approach based on the ballistocardiogram.

Methods: The proposed approach monitors blood pressure by exploiting two features in the whole-body, head-to-foot ballistocardiogram measured using a force plate: the time interval between the first ("I") and and second ("J") major waves ("I-J interval") for diastolic pressure, and the amplitude between the J and third major ("K") waves ("J-K ampulitude") for pulse pressure. The efficacy of the approach was examined in 22 young healthy volunteers, by investigating the diastolic pressure monitoring performance of pulse transit time, pulse arrival time, and ballistocardiogram's I-J interval, and the systolic pressure monitoring performance of pulse transit time and I-J interval in conjunction with ballistocardiogram's J-K amplitude.

Results: The I-J interval was comparable to pulse transit time and pulse arrival time in monitoring diastolic pressure, and the J-K amplitude could provide meaningful improvement to pulse transit time and I-J interval in monitoring systolic pressure.

Conclusion: The ballistocardiogram may contribute toward ultra-convenient and more accurate cuff-less blood pressure monitoring.

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This material is based upon work supported by the National Institutes of Health under Grant EB018818.

Significance: The proposed approach has potential to complement the pulse transit time technique for cuff-less blood pressure monitoring in two ways. First, it may be integrated with pulse transit time to enable independent monitoring of diastolic and systolic pressures via the J-K amplitude. Second, it may even enable diastolic and systolic pressure monitoring from the ballistocardiogram alone.

Keywords

ballistocardiogram; ballistocardiography; blood pressure; cuff-less blood pressure monitoring; pulse transit time; hypertension

I. INTRODUCTION

HYPERTENSION is one of the most prevalent chronic diseases in the Unites States and around the world. Hypertension can be treated with lifestyle changes and medication therapy, but the primary issue associated with hypertension management is that its presence is frequently missed. Unobtrusive and ubiquitous blood pressure (BP) monitoring technology could improve hypertension management and control, but such a technology has not been mature enough to be deployed at present. In fact, most existing non-invasive BP monitoring techniques widely used in healthcare and research (e.g., auscultation [1], oscillometry [2], [3], volume clamping [4], [5], and applanation tonometry [6], [7]) suffer from limited convenience due to the requirement for an inflatable cuff.

To realize more convenient and deployable BP monitoring technologies, cuff-less BP monitoring is being widely investigated. Much of the reported techniques are built upon the principle of pulse wave velocity and pulse transit time (PTT) [8]. PTT is the time required for a BP wave to travel from one arterial site to another. An increase in BP results in a decrease in PTT, as artery stiffens with an increase in BP, increasing the velocity of travel of the BP wave. Hence, PTT is often inversely correlated with BP. Further, PTT may be simply measured as the time interval between proximal and distal arterial waveforms. Thus, PTT carries the major advantage of possibly offering passive BP monitoring without using any inflatable cuff.

Despite its convenience relative to the cuff-based techniques, PTT-based cuff-less BP monitoring technology may further be improved both in terms of accuracy and convenience. First, many PTT techniques frequently employ a *single* BP surrogate (that is, a PTT or pulse arrival time (PAT)) to monitor *both* diastolic (DP) and systolic (SP) pressures. However, given that these BP levels are not perfectly correlated with each other [9], the accuracy of PTT-based techniques may be improved by employing independent BP surrogates indicative of multiple BP levels. Second, although much advance has been made in the PTT/PAT instrumentation technologies [8], many existing techniques require the placement of two sensors on the body (e.g., electrocardiogram (ECG) as the proximal arterial waveform and a distal arterial waveform, e.g., photoplethysmogram (PPG) for PAT). Thus, the convenience of PTT-based BP monitoring techniques may be improved by reducing, or even eliminating, the sensors that must be placed on the body.

In our recent work, we discovered that the principal mechanism responsible for the genesis of the ballistocardiogram (BCG) waves is the interaction between the aortic BP waves: the BCG waves are generated by the ascending aortic (formed by the aortic inlet (P_0) and arch (P_1) BP waves) and descending aortic (formed by the aortic arch (P_1) and outlet (P_2) BP waves) BP gradients [10] (Fig. 1). The physical insight obtained from this discovery yields two features in the BCG waveform that can potentially enable ultra-convenient cuff-less BP monitoring. First, noting that the onsets of aortic inlet and outlet BP waves approximately correspond to the initiation of the first major wave (called the I wave) and the peak of the second major wave (called the J wave) in the BCG, respectively, the time interval between the initiation of the I wave and the peak of the J wave (called the "I-J interval" hereafter) represents aortic PTT, a well-known surrogate of DP (Fig. 1). Second, noting that the aortic inlet and arch BP waves remain at the systolic level while the aortic outlet BP wave increases from its diastolic to systolic level (i.e., by pulse pressure (PP)) during the down-stroke from the J wave to the third major wave in the BCG (called the K wave), the amplitude between the peaks of the J and K waves (called the "J-K amplitude" hereafter) represents aortic outlet (which may correspond to a site near the femoral artery [10]) PP (Fig 1). This discovery resulted in a hypothesis that the BCG I-J interval and J-K amplitude could be used to monitor BP (in particular, DP and SP independently), either in conjunction with PTT or based on the BCG alone.

In this paper, we proposed and established the proof-of-concept of an ultra-convenient cuff-less BP monitoring approach based on the BCG by leveraging the above discovery on the BCG. The approach employs the BCG's I-J interval and J-K amplitude as surrogates of DP and PP, respectively. It has potential to complement the conventional PTT technique in two ways. First, it may be integrated with PTT to enable independent monitoring of DP and SP via the J-K amplitude. Second, it may even enable DP and SP monitoring from the BCG alone. Experimental results from 22 young healthy volunteers illustrated that the I-J interval was comparable to PTT and PAT in monitoring DP, and the J-K amplitude could provide meaningful improvement to PTT and I-J interval in monitoring SP.

This paper is organized as follows. Section 2 describes the experimental data and data analysis methods. Section 3 presents the results. Section 4 summarizes the opportunities and challenges for ultra-convenient BP monitoring implied by the present work.

II. METHODS

A. Experimental Data

We used experimental data collected from our previous study, described in detail in our prior report [11]. Here, we succinctly summarize the essential details relevant to this work.

Under the Institutional Review Board approval obtained from the Georgia Institute of Technology and Michigan State University as well as written informed consent, we recruited and performed procedures in 22 young heathy volunteers (age 22±4 years; gender 19 males and 3 females; height 177±11 cm; weight 75±1 kg) in accordance with the guidelines provided by the Review Boards at both institutions.

For the present study, we used five physiological waveforms obtained in each subject: (1) a BCG measured using a high-resolution force plate (9260AA6, Kystler Group, Winterthur, Switzerland); (2) a blood volume waveform from the instep of a foot ("foot PPG") measured using a PPG sensor array in an adjustable strap installed on the force plate [12]; (3) an ECG measured using 3 gel electrodes in Lead II configuration and interfaced to a wireless amplifier (BNEL50, Biopac Systems, Goleta, CA, USA); (4) a finger blood volume waveform ("finger PPG") measured using a transmission-mode PPG clip (8000AA, Nonin Medical, Plymouth, MN, USA) placed on an index finger and interfaced to a wired amplifier (PPG100C, Biopac systems, Goleta, CA, USA); and (5) a reference brachial BP waveform measured using a finger cuff embedded with a PPG sensor on the middle finger of the same hand to implement the volume clamp method (ccNexfin, Edwards Lifesciences, Irvine, CA, USA). These devices were interfaced to a laptop computer using a data acquisition unit (MP150, Biopac Systems, Goleta, CA, USA) to synchronously record all the waveforms at 2 kHz sampling rate (Fig. 2(A)).

We collected the data during three hemodynamic interventions (Fig. 2(B)). Each subject stood still for 1 min for an initial baseline state (R1). Then, the subject underwent the mental arithmetic intervention (MA) for 1 min, in which the subject repeatedly added the digits of a three-digit number and added the sum to the original number. Followed by standing still for 1 min for a second baseline state (R2), the subject underwent the cold pressor intervention (CP) for 1 min, in which the subject immersed free hand into 4ºC water for 1 min. Followed by standing still for 2 min for a third baseline state (R3), the subject underwent the exercise intervention, in which the subject got off the force plate, performed a stair climbing exercise for 1 min, and returned to the force plate for a post-exercise state (PE). We made recordings throughout these states.

B. Data Analysis

From each subject record, we determined the following BP surrogates. For DP, we determined (1) the force plate-based PTT ("BCG PTT") as the time interval between the BCG I wave (indicating the initiation of the mechanical ejection of the heart [10]) and the foot PPG trough; (2) the conventional PAT ("PAT") as the time interval between the ECG R wave and the finger PPG trough; and (3) the BCG I-J interval (indicating the aortic PTT [10]) as the time interval between the I and J waves in the BCG. For PP, we determined the BCG J-K amplitude (indicating the distal PP [10]). Details follow.

First, we band-pass filtered the BCG and PPG waveforms using a 1st-order Butterworth filter with 0.5 Hz and 10 Hz cutoff frequencies [13]. Second, we extracted the ECG R wave from each beat using the popular Pan-Tompkins method [14]. Third, we identified BCG and PPG beats via the ECG gating. Fourth, we smoothed the BCG waveform using an exponential moving average filter to suppress movement artifacts [15]. Fifth, we extracted BCG and PPG features of interest from each beat as follows. We extracted the BCG J wave as the local maximum within 100 ms to 300 ms after the ECG R wave. We extracted the BCG I and K waves as the local minima before and after the J wave, respectively, that are nearest to the J wave. We extracted the PPG trough by applying the intersecting tangent method [16], [17] to the PPG beat. Sixth, we extracted the reference DP, SP, and PP associated with each beat as

the minimum and maximum of the finger-cuff BP waveform as well as the difference between the two in the ECG-gated BP beat. Finally, we determined the BP surrogates using the features thus extracted (Fig. 3). In addition, we further suppressed the beat-to-beat fluctuations in the BCG I-J interval and J-K amplitude due to motion artifacts by smoothing the respective beat-to-beat sequences and removing outliers.

To analyze and compare the efficacy of the BP surrogates, we segmented each subject record into six periods: three baselines (R1, R2, R3) and three interventions (MA, CP, PE). In each period, we averaged the reference BPs and BP surrogates over five beat intervals. Then, we identified the five-beat intervals where DP and PP attained extremum (minimum for baseline periods and maximum for intervention periods). Then, we extracted six pairs of reference BPs-BP surrogates associated with (1) DP extremum intervals and (2) PP extremum intervals from each of the 22 subject record for subsequent analysis (see Discussion for details).

We analyzed and compared the efficacy of the BP surrogates as follows. First, we examined the correlation between the BP surrogates and the reference BPs. In each subject, we calibrated (1) the BCG PTT, PAT, and the BCG IJ interval to DP; (2) the BCG J-K amplitude to PP; and (3) the pairs of BCG PTT-BCG J-K amplitude and BCG I-J interval-BCG J-K amplitude as well as PAT to SP, all based on the univariate and multivariate linear regression analysis. Then, we computed the correlation coefficients between the reference and calibrated BPs. Second, we computed the rootmean-squared errors (RMSE) between the reference and calibrated BPs in each subject as a measure of the best-case BP monitoring accuracy associated with each BP surrogate(s). We compared the correlation coefficients and RMSEs thus obtained using the paired t-test as follows. First, we compared BCG PTT, PAT, and BCG I-J interval in monitoring DP. Second, we compared BCG PTT, PAT, and the BCG PTTBCG J-K amplitude pair in monitoring SP. Third, we likewise compared BCG I-J interval, PAT, and the BCG I-J interval-BCG J-K amplitude pair in monitoring SP. In all these comparisons, we used a significance level of $p<0.016$ after the Bonferroni correction factor of 3 (=0.05/3).

III. RESULTS

Fig. 4 shows the group average (mean±SE) reference DP and SP, reference PP, BCG PTT and PAT, BCG I-J interval, BCG J-K amplitude, and pre-ejection period for the six (A) DP extremum intervals and (B) PP extremum intervals (i.e., R1, R2, R3, MA, CP, PE). In the DP extremum intervals, a maximum change in DP, PP, and SP of 21 mmHg, 13 mmHg, and 31 mmHg was observed. In the PP extremum intervals, a maximum change in DP, PP, and SP of 14 mmHg, 19 mmHg, and 28 mmHg was observed. Maximum change in SP was similar in both extremum intervals. However, maximum PP change in the DP extremum intervals (68% of the PP extremum intervals; Fig. 4(A)) and maximum DP change in the PP extremum intervals (67% of the DP extremum intervals; Fig. 4(B)) were quite different from the corresponding changes in the other extremum intervals.

BCG PTT, PAT, and BCG I-J interval all correctly changed in the opposite direction to DP changes in both the DP extremum and PP extremum intervals. BCG PTT and BCG IJ

interval changed more consistently to DP than PAT in terms of the degree of change in the DP extremum intervals, while PAT changed more consistently with DP than BCG I-J interval in the PP extremum intervals. This may be attributed to the difference in the behavior of pre-ejection period in the two extremum intervals (Fig. 4; PEP responded to MA and PE more clearly in the PP extremum intervals than in the DP extremum intervals due to larger cardiac contractility (i.e., PP) change in the former; as well, it did not increase in CP in the former due to smaller afterload (i.e., DP) change). BCG J-K amplitude correctly changed in the same direction to PP changes in the PP extremum intervals (Fig. 4(B)) but not in the DP extremum intervals (Fig. 4(A)). It was also observed that J-K amplitude under-responded to CP (Fig. 4(B)). These may be explained by the fact that the reference PP was measured at the brachial level, whereas J-K amplitude represents aortic outlet (near the femoral artery [10]) PP, which may not change as much as brachial PP in response to the local vasoconstriction at the finger level induced by CP.

Fig. 5 shows the group average correlation coefficients (r values) between the reference DP and SP versus the corresponding surrogates for the six (A) DP extremum intervals and (B) PP extremum intervals. First, BCG I-J interval was comparable to BCG PTT and PAT in monitoring DP. In the DP extremum intervals, BCG I-J interval showed correlation coefficient for DP higher than PAT (by 19%) but lower than BCG PTT (by 11%). In the PP extremum intervals, BCG I-J interval showed correlation coefficient for DP lower than both BCG PTT and PAT but the differences were not significant. Second, the BCG PTT-BCG J-K amplitude pair was superior to BCG PTT and PAT in monitoring SP: multivariate linear regression of BCG PTT and BCG J-K amplitude to SP yielded higher correlation coefficients than BCG PTT (by 6% and 36% in the DP and PP extremum intervals; $p<0.005$) and PAT (by 26% and 10% in the DP and PP extremum intervals; $p<0.005$ in the DP extremum intervals). Third, the BCG I-J interval-BCG J-K amplitude pair was superior to BCG I-J interval alone and comparable to PAT in monitoring SP: in both the DP and PP extremum intervals, multivariate linear regression of BCG I-J interval and J-K amplitude to SP outperformed BCG I-J interval alone (by 9% and 46% in the DP and PP extremum intervals; $p<0.015$) and PAT (by 20% and 1% in the DP and PP extremum intervals). The improvement in the r values for SP contributed by the BCG J-K amplitude was more prominent in the PP extremum intervals than in the DP extremum intervals. Interestingly, PAT performed well for SP in the PP extremum intervals than in the DP extremum intervals, due to the (1) larger PP change in the former than in the latter that may indicate larger increase in cardiac contractility in MA and PE associated with the former (Fig. 4) and (2) smaller mean BP change that may indicate smaller increase in afterload in CP associated with the former (not shown), both of which leads to an increase in PEP when BP increases.

Fig. 6 presents the group average best-case RMSEs between the reference DP and SP versus the corresponding calibrated DP and SP surrogates for the six (A) DP extremum intervals and (B) PP extremum intervals. In regards to DP, BCG I-J interval resulted in good DP RMSEs that were comparable to the RMSEs associated with BCG PTT and PAT in both DP and PP extremum intervals. In regards to SP, multivariate linear regression of BCG PTT and BCG J-K amplitude yielded smaller RMSEs than BCG PTT (by 12% and 28% in the DP and PP extremum intervals; $p<0.002$) and PAT (by 25% and 19% in the DP and PP extremum intervals; $p<0.015$ in the DP extremum intervals). Further, multivariate linear

regression of BCG I-J interval and J-K amplitude to SP yielded good SP RMSEs that were smaller than BCG I-J interval alone (by 28% and 14% in the DP and PP extremum intervals; $p<0.01$) and PAT (by 16% and 10% in the DP and PP extremum intervals). Consistently to the r values, the improvement in the RMSEs for SP contributed by the BCG J-K amplitude was more prominent in the PP extremum intervals than in the DP extremum intervals. Finally, the BCG PTT-BCG J-K amplitude pair outperformed the BCG I-J interval-BCG J-K amplitude pair in monitoring SP, but the difference was not significant.

Fig. 7 presents the correlation and Bland-Altman plots for (A) BCG PTT and BCG I-J interval versus DP in the DP extremum intervals and (B) BCG PTT-BCG J-K amplitude pair and BCG I-J interval-BCG J-K amplitude pair versus SP in the PP extremum intervals. Both DP and SP surrogates were highly correlated with their reference counterparts. The confidence intervals (DP: 11.9 mmHg for BCG PTT and 14.6 mmHg for BCG I-J interval; SP: 15.6 mmHg for BCG PTTBCG J-K amplitude pair and 17.5 mmHg for BCG I-J interval-BCG J-K amplitude pair) appeared adequate: the values were within the acceptable precision limits predicted in our prior work for hypertension screening accuracy comparable to auscultation (8 mmHg for DP and 12 mmHg for SP) [18].

Fig. 8 presents the correlation and Bland-Altman plots for (A) BCG J-K amplitude versus PP and (B) SP derived as the sum of DP calibrated from BCG I-J interval and PP calibrated from BCG J-K amplitude versus SP, both in the PP extremum intervals. BCG J-K amplitude showed good correlation to PP ($r=0.69+/-0.05$ and $RMSE=5.0+/-0.3$ mmHg). This notable correlation was the basis for accurate monitoring of SP based on the sum of two univariate linear regressions (i.e., BCG I-J interval to DP and BCG J-K amplitude to PP) ($r=0.68+/-0.06$ and $RMSE=9.7+/-0.6$ mmHg; Fig. 8(B)), as well as based on multivariate linear regression of BCG I-J interval-BCG J-K amplitude pair to SP (Fig. 7(B)).

IV. DISCUSSION

We sought to examine the feasibility of establishing cuffless BP monitoring technologies based on the BCG. To this aim, we leveraged the physical meaning of the BCG waves we unveiled in our prior work [10] to explore the efficacy of the IJ interval and J-K amplitude in the BCG waveform as surrogates of DP and PP to complement the conventional PTT-based cuff-less BP monitoring technique. Overall, the results suggested that (1) the BCG J-K amplitude may be integrated with PTT to enable independent monitoring of DP and SP, and that (2) the BCG I-J interval and J-K amplitude may enable ultra-convenient DP and SP monitoring from the BCG alone.

A. Efficacy of BCG in Blood Pressure Monitoring

BCG I-J interval and J-K amplitude together could monitor DP and PP. Specifically, I-J interval showed good correlation with DP ($r=0.70\pm0.03$ in the DP extremum intervals; Fig. 4(A)), and J-K amplitude showed good correlation with PP ($r=0.69\pm0.05$ in the PP extremum intervals; Fig. 4(B)). It is important to emphasize that these correlations are theoretically supported by the BCG mechanism, as described in our prior work [10]: that (1) the initiation of I wave indicates the rise in the ascending aortic BP; (2) the peak of J wave indicates the rise in the aortic outlet BP (thus, I-J interval is proportional to aortic PTT); and

(3) the peak of K wave corresponds to the peak of aortic outlet BP (thus, J-K amplitude is proportional to aortic outlet PP). In fact, I-J interval was comparable to PAT as surrogate of DP in both DP and PP extremum intervals (Fig. 5–6). Additionally, J-K amplitude offered significant value to BCG PTT in monitoring SP (Fig. 5–6) more accurately. In addition, multivariate linear regression of I-J interval and J-K amplitude to SP was superior to I-J interval alone and PAT as surrogate of SP in both extremum intervals (Fig. 5–6). Notably, the fact that the improvement in the quality of SP monitoring due to J-K amplitude was more prominent in the PP extremum intervals than in the DP extremum intervals suggests that the role of J-K amplitude in monitoring SP becomes crucial when DP and SP are not highly correlated and SP cannot be monitored accurately solely based on DP. Yet in any case, J-K amplitude generally appears to introduce added value in accurate monitoring of SP, because multivariate linear regressions of BCG PTT and J-K amplitude as well as I-J interval and J-K amplitude were significantly superior to BCG PTT and I-J interval alone, respectively, in both correlation (Fig. 5) and RMSE (Fig. 6), consistently in both DP and PP extremum intervals.

It must be emphasized that SP can be monitored accurately as the sum of DP monitored from BCG I-J interval and PP monitored from BCG J-K amplitude (Fig. 8). However, SP monitoring based on multivariate linear regression of BCG I-J interval and J-K amplitude outperformed the combination of two univariate linear regressions (i.e., BCG I-J interval to DP and BCG J-K amplitude to PP); the former was superior to the latter both in terms of correlation and RMSE ($r<0.005$). This may be attributed to the fact that multivariate linear regression can directly optimize SP accuracy, whereas the combination of two univariate linear regressions merely optimizes DP and PP accuracy but not necessarily SP accuracy. The superiority of multivariate linear regression may also be attributed to the fact that BCG's I-J interval and J-K amplitude are approximate surrogates of DP and PP: I-J interval and J-K amplitude are easily identifiable features in the BCG, which are correlated with aortic PTT and aortic outlet PP in a population-based and approximate sense. Therefore, I-J interval and J-K amplitude may not be strongly correlated with DP and PP in all subjects. In this regard, multivariate linear regression may provide extra degrees of freedom in optimizing SP accuracy, relative to the combination of two univariate linear regressions, against the variability in the fidelity of I-J interval and J-K amplitude as surrogates of DP and PP, by directly correlating I-J interval and J-K amplitude to SP.

Lastly, considering that these BCG features are selected as BP surrogates with solid physical basis, the correlations are likely to generalize.

B. Opportunities for Cuff-Less Blood Pressure Monitoring

The results obtained from this study present a few important opportunities for innovating cuff-less BP monitoring. First, we showed that the BCG may enable independent and accurate monitoring of DP and SP. To date, PTT and PAT measured at the diastolic level (e.g., detected using the trough of the PPG waveform) have been used as ad-hoc surrogates of both DP and SP with limited physical basis [19]–[26]. Despite success in some prior work [21], [22], it is likely that such brute-force use of PTT and PAT may yield poor efficacy, especially when DP and SP are not closely correlated (in fact, it is well known that the

correlation between DP and SP is not perfect [9]). In contrast, the proposed BCG-based approach can exploit mechanistically identified DP (I-J interval) and PP (J-K amplitude) surrogates to complement conventional PTT technique or even allow for independent and accurate tracking of DP and SP based on the BCG alone. Second, we showed that BCG alone may suffice in monitoring BP. Practically, this suggests that BP can be monitored in an ultra-convenient way: in contrast to the conventional PTT and PAT techniques requiring the measurement of proximal and distal physiological signals (e.g., ECG and finger PPG for a PAT), the BCG-based approach may not require placement of any sensors on the body (e.g., a force plate embedded on the floor of checkout lines in the grocery stores and a weighing scale in the gyms), or in wearable settings, may require a single BCG sensor (e.g., an arm band or a wrist band equipped with an accelerometer) to implement cuff-less BP monitoring. As far as the convenience is concerned, the current work may be viewed as a leap from our prior work on BCG PTT, which required the measurement of foot PPG in addition to the BCG [11]. Also, equipped with ultra-convenience and comparable accuracy to PAT, the BCG-based approach may evolve into a viable alternative to complement or replace widely pursued PAT in the cuff-less BP monitoring domain. These opportunities may further be pursued to realize more convenient and accurate cuff-less BP monitoring technologies.

C. Potential Challenges

Nevertheless, this study also presents potential challenges. The most prominent challenge is related to the generalizability of BCG I-J interval and J-K amplitude for monitoring DP and PP. Specifically, BCG I-J interval and J-K amplitude are approximate surrogates of DP and PP, and their efficacy in monitoring DP and PP may be influenced by the variability in the aortic geometry (e.g. size) and mechanical properties (e.g., stiffness) as well as other factors (e.g., pathology, aging, and breathing, which distort and mask BCG waves [27]) that are known to alter the relationship between aortic inlet (P_0), arch (P_1), and outlet (P_2) BP. Despite the advantage of BCG I-J interval and J-K amplitude (that they may be obtained easily from the BCG for ultra-convenient BP monitoring), future work to rigorously investigate the generalizability of BCG I-J interval and J-K amplitude as BP surrogates is required to understand opportunities and hurdles related to the proposed approach.

The other prominent challenge is related to the calibration of BCG surrogates (i.e., I-J interval in ms and J-K amplitude in g) to BP in mmHg. Specifically, our results clearly indicate that maximum changes in DP do not occur concurrently with maximum changes in PP. In fact, the degree of change in BCG I-J interval was smaller in the PP extremum intervals than in the DP extremum intervals (Fig. 4). In addition, BCG J-K amplitude did not exhibit a meaningful behavior in the DP extremum intervals, perhaps due to small changes in PP (Fig. 4(A)). This in turn led to degraded correlation coefficients for I-J interval in the PP extremum intervals and J-K amplitude in the DP extremum intervals (Fig. 5). However, it must be noted that the degraded correlation between BCG I-J interval versus DP in the PP extremum intervals as well as between BCG J-K amplitude versus PP in the DP extremum intervals is mainly due to the relatively smaller changes in the BP levels (and accordingly, the corresponding features; Fig. 4). Indeed, RMSE associated with BCG I-J interval in monitoring DP was larger in the DP extremum intervals (6.8+/−0.6 mmHg) than in the PP extremum intervals (5.1+/−0.5 mmHg), and RMSE associated with BCG J-K amplitude in

monitoring PP was comparable in the two intervals (5.9+/−0.4 mmHg in DP extremum intervals and 5.0+/−0.3 mmHg in PP extremum intervals). Interestingly, this issue helped us in rigorously investigating the efficacy of BCG-based BP monitoring approach: (1) we could analyze the DP extremum intervals to assess I-J interval as a DP surrogate, and likewise the PP extremum intervals to assess J-K amplitude as a PP surrogate; and (2) we could analyze both extremum intervals to assess BCG PTT and BCG I-J interval in conjunction with BCG J-K amplitude as SP surrogates in situations where the change in SP is dominated by DP as well as by PP. However, this issue can complicate the calibration of these surrogates to the corresponding BPs, because the acquisition of BCG surrogates across a wide DP and PP ranges is essential in order to achieve accurate calibration of BCG I-J interval and J-K amplitude to DP and PP, respectively, which are robust against measurement errors and other uncertainties. Future work on the development of novel BCG to BP calibration techniques is thus required to overcome this issue.

D. Study Limitations

This study has a few limitations that must be addressed in the follow-up studies. First, this study was conducted only in young healthy subjects. Future work must be conducted to validate the proposed approach in diverse subjects with wider age range and pathology. Second, this study used brachial BP (derived from volume clamp method applied to a finger) as the reference, while BCG I-J interval and J-K amplitude represent aortic PTT and aortic outlet PP. Noting that DP is almost uniform in large arteries, the use of brachial DP as the reference for I-J interval is easily justified. On the other hand, considering that brachial PP and aortic outlet PP may not always be perfectly correlated (although they are expected to exhibit high correlation), the use of brachial PP as the reference for J-K amplitude may not always be ideal. Future work may consider the use of femoral BP as the reference BP. Third, the substantial BCG filtering used in this study may have altered BCG wave amplitudes. Yet, its impact on the study findings may be minimal because consistent BCG filtering was employed in both calibration and post-calibration analysis. In addition to BCG filtering due to signal processing, the body may have filtered the force BCG from the aorta mechanically and altered the BCG waveform. Future work must investigate such possible mechanical filtering and its impact on BCG. Fourth, the approach is built on a 1-axis BCG measured in standing posture, potentially limiting its utility in subjects who cannot stand straight. Considering that the BCG has 3-axis components [28] and that its morphology is influenced by posture [29], it is worthwhile to investigate the generalization of the approach by exploiting 3-axis BCG and allowing for diverse postures to maximize its value. This being said, time-dependent trends of uncalibrated BCG I-J interval and J-K amplitude may still be useful as predictors of cardiovascular risk, by virtue of their close relationships to aortic PTT and PP, which are widely accepted cardiovascular risk predictors [30].

V. CONCLUSIONS

We demonstrated that BCG may contribute toward ultraconvenient and more accurate cuff-less BP monitoring. It can complement conventional PTT technique for independent monitoring of DP and SP, and it may even enable BP monitoring based on the BCG alone. Future work must be directed to more ubiquitous and convenient cuff-less BP monitoring

using wearable BCG sensors as well as robust and efficient calibration of multiple BCG/PTT features to BP.

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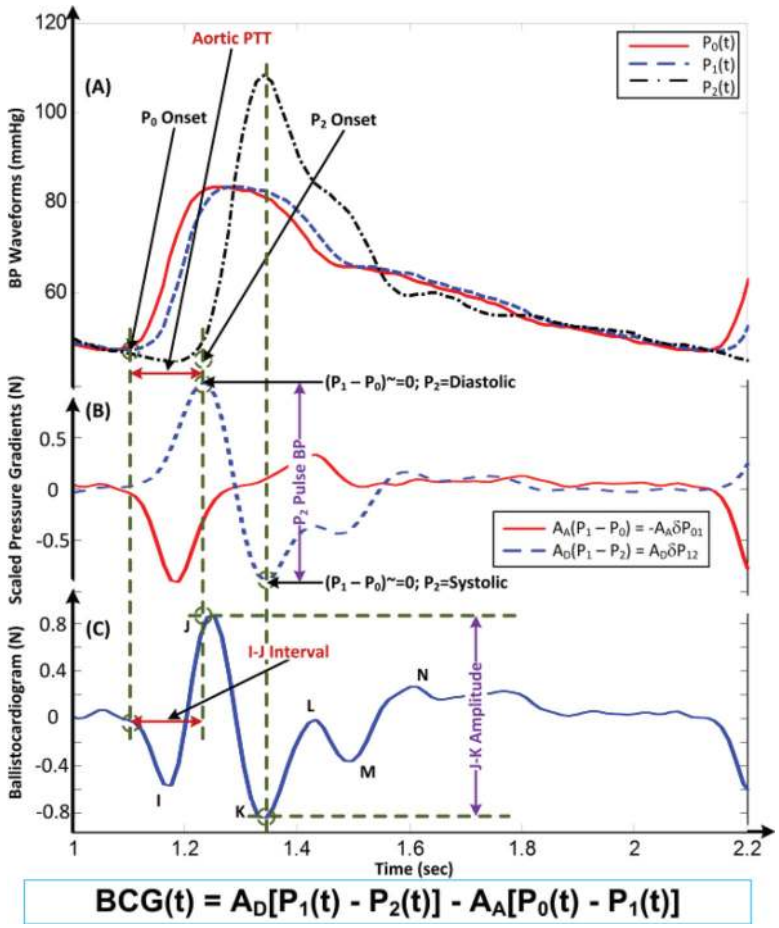

Fig. 1:

The relationship between ballistocardiogram (BCG) waves and aortic blood pressure (BP) waves. The BCG waves are generated by the ascending aortic (formed by the aortic inlet (P_0) and arch (P_1) BP waves) and descending aortic (formed by the aortic arch (P_1) and outlet (P_2) BP waves) BP gradients, each scaled by the respective aortic cross-sectional areas. (A) BP waves at the aortic inlet ($P_0(t)$), aortic arch ($P_1(t)$), and aortic outlet (near the femoral artery; $P_2(t)$) locations measured invasively from a human subject. (B) Ascending aortic ($A_A\delta P_{01}(t)$) and descending aortic ($A_D\delta P_{12}(t)$) BP gradients scaled by the respective nominal aortic cross-sectional areas, calculated from the measured BP waves shown in Fig. 1(A). (C) The BCG waveform (BCG(t)) calculated as the difference of the BP gradients shown in Fig. 1(B): $BCG(t) = A_D\delta P_{12}(t) - A_A GP_{01}(t)$. This physical insight yields two features in the BCG waveform that can potentially enable ultra-convenient cuff-less BP monitoring. First, the onsets of aortic inlet and outlet BP waves approximately correspond to the initiation of the I wave and the peak of the J wave, respectively. Hence, the time interval between the initiation of the I wave and the peak of the J wave (called the “I-J interval”) represents aortic PTT, a wellknown surrogate of DP. Second, during the J-K down-stroke the aortic inlet and arch BP waves remain at the systolic level while the aortic outlet BP wave increase from its diastolic to systolic level (i.e., by pulse pressure (PP)). Hence, the amplitude between the peaks of these waves (called the “J-K amplitude”) represents descending aortic PP.

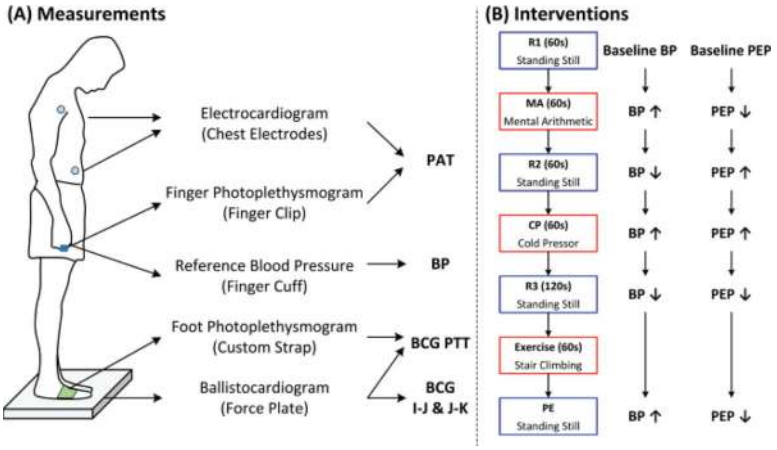

Fig. 2:

Data collection for comparison of force plate-based pulse transit time (PTT), conventional pulse arrival time (PAT), and ballistocardiogram (BCG)-based blood pressure (BP) surrogates.

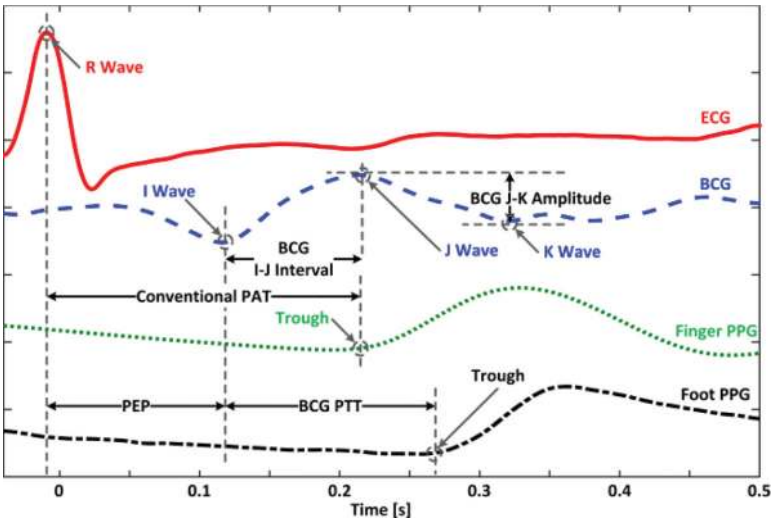

Fig. 3:

Feature extraction: BCG PTT, conventional PAT, pre-ejection period (PEP), BCG I-J interval, and BCG J-K amplitude.

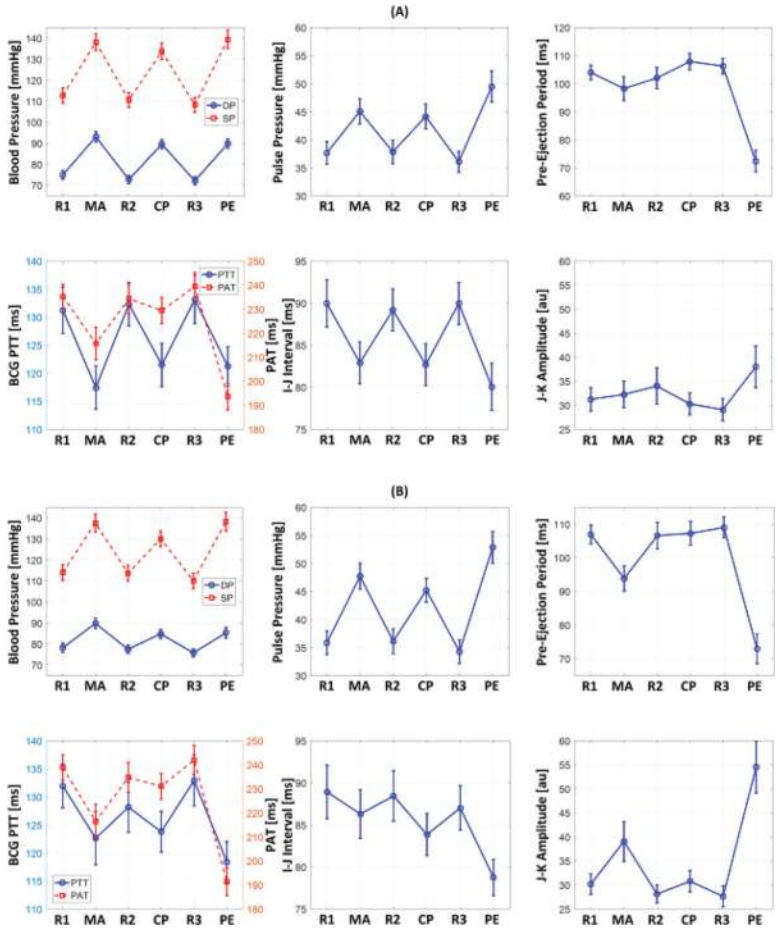

Fig. 4:

Group average trends (mean ± SE) of BP, BCG PTT, conventional PAT, BCG I-J interval, and BCG J-K amplitude. (A) Diastolic pressure (DP) extremum intervals. (B) Pulse pressure (PP) extremum intervals.

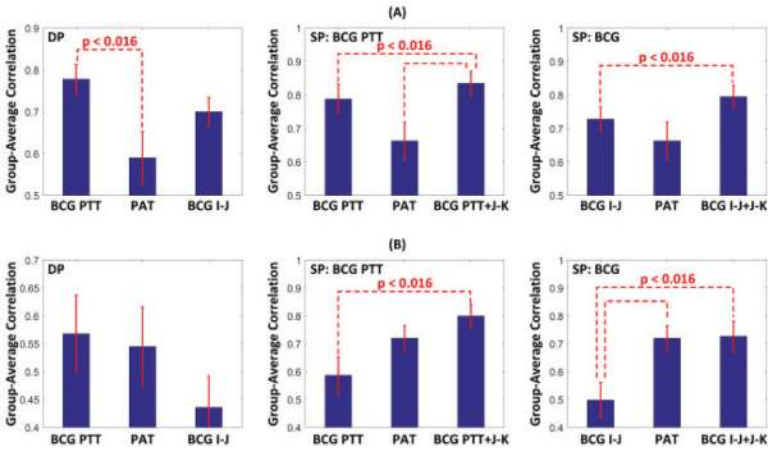

Fig. 5:

Group average correlation (mean ± SE) between BCG PTT, conventional PAT, and BCG-based surrogates versus DP and SP. (A) Diastolic pressure (DP) extremum intervals. (B) Pulse pressure (PP) extremum intervals.

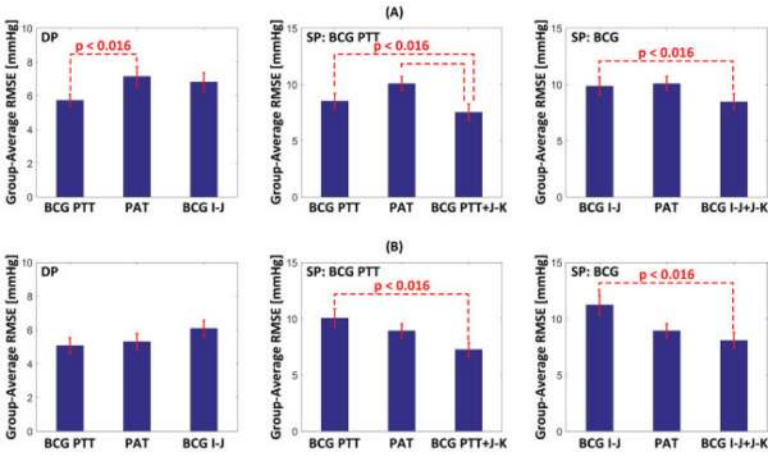

Fig. 6:

Group average root-mean-squared error (mean ± SE) between BCG PTT, conventional PAT, and BCG-based surrogates versus DP and SP. (A) Diastolic pressure (DP) extremum intervals. (B) Pulse pressure (PP) extremum intervals.

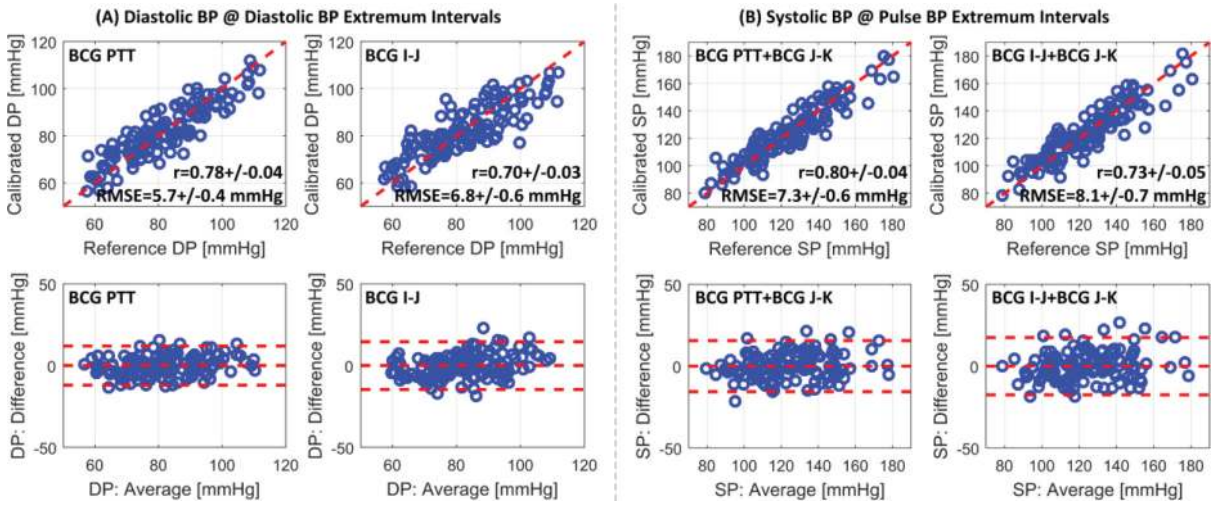

Fig. 7:

Correlation and Bland-Altman plots for (A) BCG PTT and BCG I-J interval versus DP in the DP extremum intervals and (B) BCG PTT-BCG J-K amplitude pair and BCG I-J interval-BCG J-K amplitude pair versus SP in the PP extremum intervals (mean+/−SE). BCG PTT (r=0.78+/−0.04 and RMSE=5.7+/−0.4 mmHg) and BCG I-J interval (r=0.70+/−0.03 and RMSE=6.8+/−0.6 mmHg) were comparable in DP monitoring (p=0.07 for r and p=0.04 for RMSE). BCG PTT-BCG J-K amplitude pair (r=0.80+/−0.04 and RMSE=7.3+/−0.6 mmHg) and BCG I-J interval-BCG J-K amplitude pair (r=0.73+/−0.05 and RMSE=8.1+/−0.7 mmHg) were comparable in SP monitoring (p=0.09 for r and p=0.08 for RMSE).

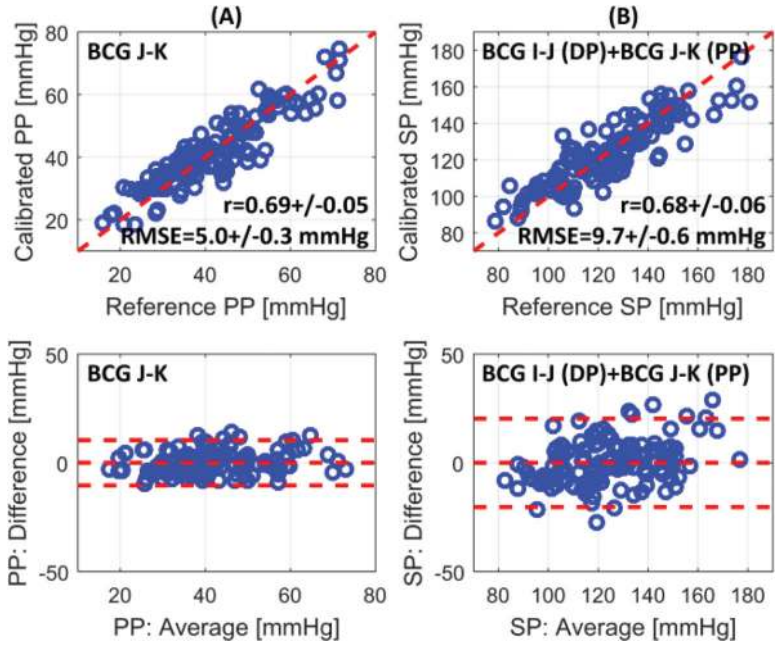

Fig. 8:

Correlation and Bland-Altman plots for (A) BCG J-K amplitude versus PP and (B) SP computed as the sum of DP calibrated from BCG IJ interval and PP calibrated from BCG J-K amplitude versus SP, both in the PP extremum intervals (mean+/−SE).