Wearable Estimation of Central Aortic Blood Pressure: Feasibility Study

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Abstract— **Introduction: Central aortic blood pressure (CABP) estimation from electrocardiogram (ECG) and ballistocardiogram (BCG) acquisitions might be feasible, according to previous research. The result is based on acquisitions with off-the-shelf equipment and some custom electronics. This work aims to evaluate whether a proposed wearable device is capable of achieving similar feasibility results on CABP estimation, but also the study aims to situate the scope of this method to predict CABP readings. Methods: The study used data from one healthy subject involving three days of intermittent CABP observations, and waveforms from ECG and BCG signals. The methodology was evaluated in two levels, from a simple perspective to evaluate feasibility of the method for the CABP estimation (Evaluation level-1: CABP human-model (HM) is constructed and tested using the same data-sets); to moderate-hard by evaluating the capability of the calibrated CABP-HM to predict unseen CABP data accurately (Evaluation level-2). CABP variables were assessed non-invasively by the use of the SphygmoCor XCEL system (AtCor Medical, Sydney, Australia) during hemodynamic maneuvers. Results: Level-1 evaluation presented strong correlations of $r \approx 0.9$, and strong agreement (linear regression parameters) $m \approx 0.8$ and $y \approx 20mmHg$ between CABP measurements and estimations. Root mean square error of $RMSE \approx 2.3mmHg$. The level-2 evaluation showed significantly degraded performances when the same figures of merit were assessed. A three-day calibration interval was considered for the level-2 evaluation. Conclusions: Findings in this paper showed that results achieved with off-the-shelf equipment could be replicated by using a proposed wearable device. CABP estimation from the proposed wearable device could be feasible by using three feature times studied in this work (RI, RJ, and IJ intervals) as CABP surrogates. CABP could be accurately predicted by the proposed methodology when (in the order of) daily calibrations are performed.**
Keywords— **Wearable, Central aortic blood pressure (CABP), cuff-less, pulse transit time (PTT), calibration.**

Resumen— **Introducción: Recientemente se ha mostrado que la estimación de la presión aórtica central (PAc) a partir de electrocardiograma (ECG) y el balistocardiograma (BCG) podría ser factible, el resultado es basado en adquisición con equipos convencionales y elecrónica custom. Este trabajo tiene como objetivo evaluar si el dispositivo vestíble que se propone es capaz de lograr resultados de factibilidad similares para la estimación Pac, adicionalmente se busca situar el alcance de este método para predecir con precisión PAc. Métodos: El estudio utilizó 67 datos de un sujeto saludable que incluyó tres días de observaciones intermitentes de PAc y formas de onda de señales de ECG y BCG. La metodología se evaluó en dos niveles. Evaluación nivel-1 (para estudiar la factibilidad del método): el modelo humano (HM) de PAc se construyó y testeó utilizando el mismo conjuntos de datos. La evaluación nivel-2 evaluó la capacidad del PAc-MH calibrado para predecir datos nuevos de PAc. Las variables PAc se midieron de forma no-invasiva utilizando el equipo SphygmoCor XCEL durante maniobras hemodinámicas. Resultados: la evaluación de nivel-1 presentó fuertes correlaciones de $r \approx 0.9$, y una fuerte concordancia (parámetros de regresión lineal) $m \approx 0.8$ e $y \approx 20mmHg$ entre las mediciones y estimaciones de PAc. La evaluación de nivel-2 mostró rendimientos significativamente degradados cuando se evaluaron las mismas cifras de mérito. Se consideró un intervalo de calibración de tres días para la evaluación de nivel-2. Conclusiones: los resultados logrados en el trabajo anterior podrían replicarse mediante el uso del dispositivo vestíble propuesto; y, la estimación CABP podría ser factible utilizando tres tiempos de características estudiados en este trabajo (intervalos RI, RJ e IJ). Además, si se considera un intervalo de calibración dentro del día, la metodología propuesta podría lograr estimaciones precisas de la PAc.**
Palabras clave— **Vestible, presión aótica central (PAc), cuff-less, tiempo de tránsito de pulso (TTP), calibración.**

I. INTRODUCTION

ARTERIAL hypertension affects a third of the world's population and is a significant risk factor for cardiovas-

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cular disease. Blood pressure (BP) is one of the most relevant parameters used for monitoring of possible hypertension states in patients at high cardiovascular risk. Conventional techniques for non-invasive BP monitoring are based on occluding the blood flow on a limb artery by using an inflatable cuff. Such a cumbersome procedure provides only intermittent periph-

eral blood pressure (PBP) assessments. Published evidence suggests that central aortic blood pressure (CABP) is a more accurate predictor of future cardiovascular events than peripheral pressure, thus potentially providing a better hemodynamic determinant for clinical outcomes. There exists a need for novel technologies that, dispense with using inflatable cuffs, and, provide the best prognostic capability for cardiovascular events.

Another issue to be addressed is the problem of monitoring cardiovascular health at home with inexpensive and connected technologies, this would provide better control in the management of hypertension, which in turn would reduce the burden on the healthcare system. In order to make this possible, it is necessary to contribute to the generation of technology to make ambulatory health monitoring using wearable devices. Such technologies will allow BP monitoring to go unnoticed, generating minimal discomfort for the patient; in other words, allowing genuinely ambulatory monitoring.

Moens-Korteweg model [1] is among the main principles to estimate blood pressure by measuring the time it takes the pressure pulse to propagate between two pre-established vascular points, accordingly PTT-method. Therefore, beat-to-beat surrogate values of BP can be constructed by continuously measuring PTT. Sometimes PTT acquisition is approximated by the acquisition of another feature time (FT), which is related-to-PTT and also simplifies the acquisition set-up [2]. For instance, when the electrocardiogram (ECG) is used as a proximal reference, the time elapsed in the isometric contraction is considered in the FT computation. Some works have reported that such FT computation might degrade [3] the PTT-based BP estimation; others have reported the opposite [4], there exist some controversy in this point. Moreover, physics involved in the conception of the PTT principle establishes the method is only exploitable at elastic arteries, not in muscular peripheral ones [5]. Recently in [6], an aortic FT was proposed for aortic BP estimation. The technique evaluated with off-the-shelf equipment showed a strong correlation between the RJ-interval and CABP during strength maneuver interventions.

One of the critical aspects of the PTT-based approaches is the calibration interval of the BP estimation by using calibrated human models (HM) and acquired FTs. Although theory indicates that BP may be estimated for periods of months by properly tracking PTT at central elastic arteries [2]; it has been reported that the method requires re-calibrations (with a cuff) on the order of minutes for accurate BP readings [7] [8]. Only a few works are focusing on the time-stability of the calibration of the PTT-based BP estimations [2] . Still, even fewer works focus on the estimation of CABP through this cuff-less method [5] [6].

This paper studies the feasibility of the CABP estimation from a wearable PTT-based method. The study also aims to situate the scope of this method to predict CABP readings by evaluating the calibration stability of the method along days. The study uses data from one healthy subject involving three-days trials for CABP estimation from a wearable ECG and ballistocardiogram (BCG) acquisition. The methodology was evaluated in two levels, which are defined in the way CABP estimations are constructed. The level-1 procedure aims to estimate the feasibility of the proposed method, but also was evaluated to determine whether the wearable version of

the method achieves similar results as the obtained previously [6], mainly based on acquisitions with research equipment. Meanwhile, the level-2 evaluation aims to mimic a device capable of predict unseen CABP data. The two types of method evaluations presented in this work provided relevant information about HM-parameter scattering, calibration interval, accuracy, and, the strength of agreement and association in the CABP estimation. The paper is organized as follows: section II presents the methods used to acquire and process the data, and the procedure to construct the estimation of CABP. In sections III and IV the results of the proposed method are presented and discussed. Finally, conclusions and future work are drawn in sections V and VI.

II. Methods

A. Acquisition

The Atcor Medical SphygmoCor XCEL device was used as a CABP reference in the experiment. The device employs a cuff-based methodology that provides a non-invasive CABP estimation [9]. The device does not require an experienced operator and has been validated for non-invasive central hemodynamic assessment [9] [10]. Each CABP assessment through the pulse wave analysis (PWA) lasted in the order of two minutes to be accomplished, in-which the cuff-based device constructs a CABP waveform from a brachial-level volume displacement and proprietary processing [9]. PWA sub-diastolic recording was configured to last 20 seconds at CABP assessments [9]. On the other hand, ECG and BCG waveforms were recorded from a wearable platform simultaneously acquired with CABP measurements.
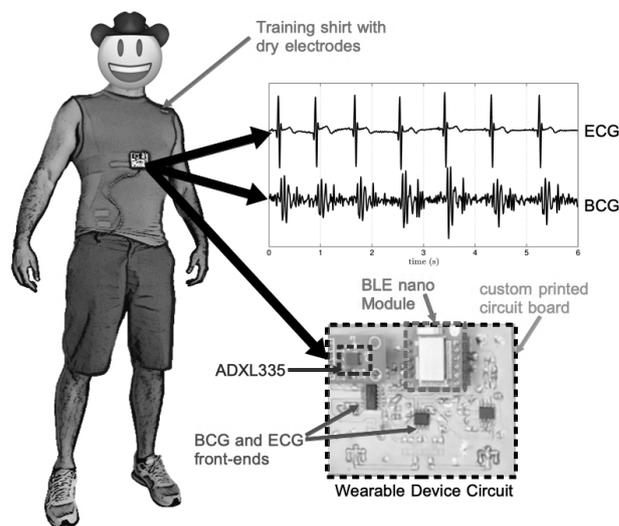
Fig. 1.   Details of wearable device prototype [11] in a volunteer.

Wearable platform (Fig. 1) features a custom printed circuit board (PCB), including a longitudinal (head-to-foot) accelerometer (ADXL335) and the analog front-ends for conditioning the biomedical signals (BCG and ECG). The proposed wearable device also includes a Bluetooth Low Energy module for signal acquisition (sampling per channel = 250 samples per second [sps]) and to provide data transmission to an external computer for signal processing. The PCB is attached to a training shirt that features dry electrodes for the unconstrained ECG acquisition. The proposed wearable platform takes care
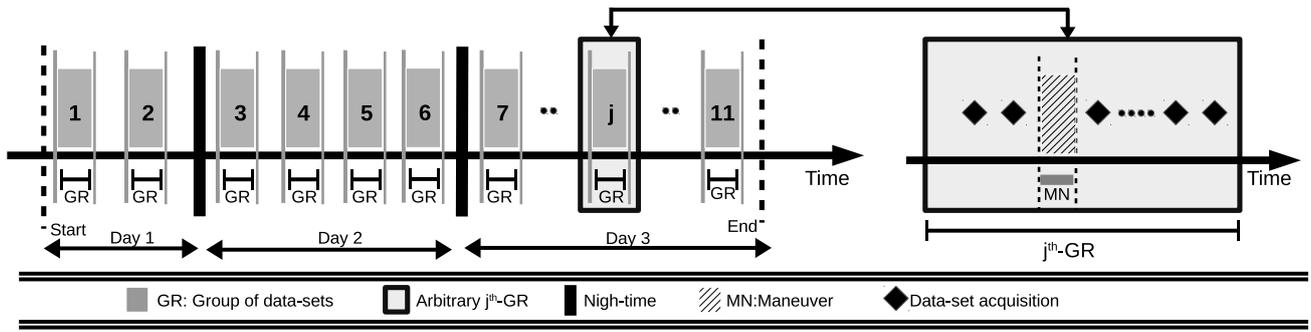
Fig. 2.   Acquisition procedure. Eleven Groups of data-sets were acquired for three days of intermittent observations. Each group consists of five to seven data-sets, where, data-sets included simultaneous CABP assessments and ECG and BCG recordings. Rhombus markers indicate a data-set collection event. Hatched boxes indicate a hemodynamic maneuver (MN = [HB: Hold breathing, SB: Slow breathing, HG: Handgrip, VA: Valsalva])

of minimizing the impact of spurious delays in the PTT acquisition due to the presence of bandwidth limiting stages. Experimental results of its application are reported [11], showing a spurious timing error, which is negligible (less than 2ms) in the context of the physiological signals considered.

B. Protocol

The study used eleven groups of data-sets (GR_1 to GR_{11}) from a healthy subject recorded intermittently along three days. Each GR_j corresponded with a trial in which five to seven data-sets were acquired during a hemodynamic maneuver (as shown in fig. 2). Each data-set included simultaneous CABP assessments and ECG and BCG recordings. A healthy male of 33 years, 184 cms tall with a weight of 86 kg volunteered the trials after an informed consent was signed. The principles of the declaration of Helsinki were followed. The CABP was assessed non-invasively from the ShpigmoCor brachial cuff device using PWA. BCG and ECG signals were recorded (with the proposed wearable device) simultaneously with the CABP assessments, and particularly, during the sub-diastolic recording period of each PWA assessment [9]. Every measurement was performed during the subject was relaxed at sitting up straight position.

Two groups of data-sets (GR_1, GR_2) were acquired along day one, four on day two (GR_3-GR_6), and five groups of data-sets (GR_7-GR_{11}) were acquired on day three, as shown in fig. 2. Hold and slow breathing, Hand-grip and Valsalva maneuvers were also carried out to produce BP fluctuations along with the recordings (See fig. 2).

C. Data processing

1) Ensemble averaging: Although the data acquisition system provided a clean ECG waveform for all trials, the intrinsic nature of the BCG signal (small head-to-foot body accelerations were taken from a sensor) made the ensemble averaging a required technique to help with the BCG processing. Nonetheless, both signals, ECG and BCG, were treated with the same processing (averaging technique) to prevent inducing any phase lag between signals. Additionally, and most important, by averaging the signal pulses along the considered period (sub-diastolic Sphygmocor XCEL recording), a systematic procedure to find a representative beat-long waveform (from the 20-seconds-long ECG and BCG signals at each data-set) was created.

2) Feature Times Extraction: Averaged signals were used to extract the feature times (FTs) that were used for the CABP estimation (see section II-C3). FT considered in this work were the intervals defined the R-wave (ECG), J-wave (BCG) [12] and I-wave (BCG) [12] taken in pairs, i.e., R-I, R-J, and I-J intervals (RI, RJ, IJ hereinafter). Further information about averaging procedure along with FT extraction procedure over the ECG and BCG waveforms included in a data-set could be found in [13]. Once finished, the procedure generated pairs of FTs and CABP variables for each data-set.

3) CABP-Human Model : In [6] RJ-interval was proposed to estimate CABP. Strong correlations between CABP estimations and measurements were achieved by using the human model (HM) in 1 and 2 [2] [6].

$$BP_{S_{FT}} = \frac{A_{S_{FT}}}{FT} + B_{S_{FT}} \qquad (1)$$

$$BP_{D_{FT}} = \frac{A_{D_{FT}}}{FT} + B_{D_{FT}} \qquad (2)$$

The model was extended here to be evaluated for CABP estimation by using not only with RJ (as input FT) but also with RI and IJ. Equations 1 and 2 were the HM used to estimate systolic ($BP_{sys_{FT}}$) and diastolic CABP ($BP_{dias_{FT}}$) from a particular FT (RI, RJ and IJ). $A_{S_{FT}}$, $B_{S_{FT}}$, $A_{D_{FT}}$ and $B_{D_{FT}}$ are constants tailored by curve fitting procedures over a group of data-set (GR_J).

D. CABP Estimation: Evaluation levels

The methodology was evaluated in two levels, which are defined in the way CABP estimations (BP_e) are constructed, which in turn defined two levels of rigorousness [2]. Distinguished levels were based on how HM parameters (in 1 and 2) were found and then used to estimate CABP over different groups of data-sets. The two levels are summarized in Figs. 3a and 3b. Evaluation level-1, when the model-parameters in the HMs were resolved using a particular group of data-sets (GR_j), then were used to find BP_e by testing the same data-set group (GR_j) (Fig. 3a). Such a simple approach might evaluate the feasibility of the method for the CABP prediction (i.e., BP-human-models constructed and tested using the same data-sets).

A moderate-hard evaluation for the propsed method was carried out by evaluating the capability of the calibrated HM model to predict accurately unseen CABP data. Thus,

11 Groups of data-sets

Arrow References:
$\longrightarrow$ Testing HM with FT to estimate BP
$\longrightarrow$ Calibrate HM from a set $\longrightarrow$ Trained HM to be tested with FT

(a) Level-1 procedure

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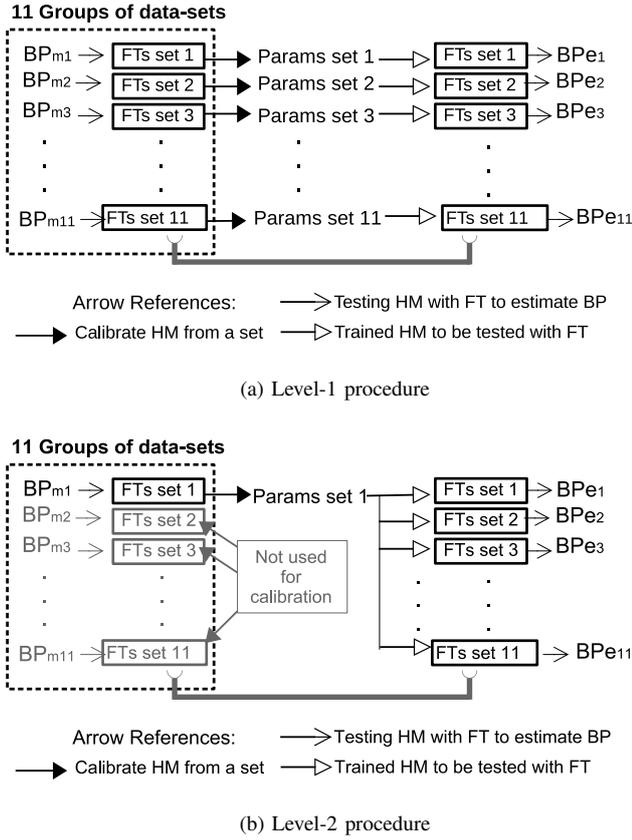
(b) Level-2 procedure

Fig. 3. Evaluation levels used to find the CABP estimations (BP_e). Measured CABPs (BP_m) from cuff-based device and FTs from wearable device, are part of each group of data-sets.

in this level-2 procedure, evaluation of the CABP prognosis capability was based on CABP estimations by testing a group of data-set (GR_i) with HM being calibrated with data included in a different group of data-set (GR_j $j \neq i$). In this study, parameters were resolved from the first group of data-sets GR_1 (Fig. 3b); which constituted a group of baseline-state data-sets.

E. Data Analysis

The strength of association between cuff-based device and wearable device were assessed by Pearson correlation. Linear regression was also used to gauge the agreement of estimated CABP (BP_e) and measured CABP (BP_m). The two-sample Kolmogorov-Smirnov test was used to evaluate if data in vectors BP_e and BP_m are from the same statistical distribution functions. P-value (p) was taken two-tailed and p<0.05 was considered statistically significant. Agreement between devices was considered with a mean difference of BP_m and BP_e to be less than 5mmHg ($\mu_e < 5$ mmHg), accordingly, compliant with Association for the Advancement of Medical Instrumentation (AAMI) requirements.

III. RESULTS

Sixty-seven data-sets (N=67) were acquired during the three days of study to evaluate the performance of the proposed method by the two degrees of rigorousness (sec. II-D). The first evaluation (Level-1) provides an insight into the feasibility of the method for estimating CABP. Level-2 evaluation procedure features a more rigorous metric by evaluating the capability for predicting CABP from an initial calibration. Tables

I and II summarize the performance of the presented method considering this two-level evaluation. The common figure of metrics (FOMs) on the tables are: Correlation (r), slope (m) and intercept (y) from linear regression plots (Measurements vs. Estimation), and root-mean-square error (RMSE).

A. Method results: Level-1 Evaluation

Level-1 procedure (HM is calibrated and then CABP is estimated with the same group of data-sets) was used to construct CABP estimations (BP_e). Each calibration generates a pair of $A_{X_{FT}}$ and $B_{X_{FT}}$ parameters (see Fig. 3a). Besides including common FOMs (r, m, y, RMSE), table I summarizes the HM parameter scattering resulting from calibrations performed at each group of data-sets. $\frac{\sigma}{\mu}(A_{X_{FT}})$ and $\frac{\sigma}{\mu}(B_{X_{FT}})$ represent standard deviation of the parameter over the mean value of the parameter along the eleven trials. If the method had absolute time stability over the three days, $\frac{\sigma}{\mu}(A_{X_{FT}})$ and $\frac{\sigma}{\mu}(B_{X_{FT}})$ would be zero. Fig. 4 shows the evolution of HM parameters along different groups of data-sets. Scatter on parameters is written as a relative scatter (error) from the parameters resolved from the first group of data-sets; thus, defined scatter at GR_1 is zero.

(a) CABP estimation from RJ   (b) CABP estimation from RI

(c) CABP estimation from IJ   (d) Parameter Reference
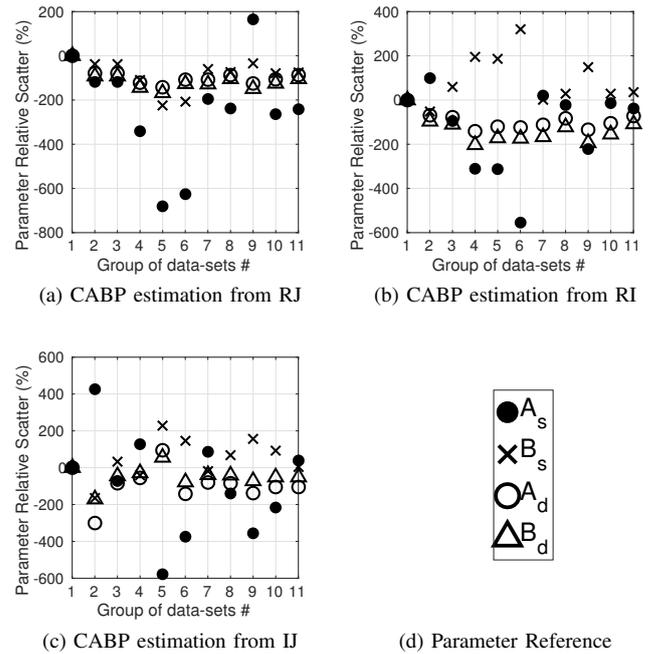
Fig. 4. Scattering of parameters of the used in CABP-HM: evolution along the eleven groups of data-sets acquired during three days of intermittent assessment. Parameter variability is written as a relative scatter (error) from the parameters resolved from the first group of data-sets

B. Method results: Level-2 Evaluation

Central aortic blood pressure estimations (BPe) were constructed by testing the groups of data-set with the HM being calibrated with the first-acquired group (see fig. 3b). Table II includes the calibration parameters. Fig. 5 shows the mean of the estimation error segmented in days from its calibration.

TABLE I
PERFORMANCE TABLE OF THE BP MODELS (EQS. 2 AND 1) ON THE ESTIMATION OF CENTRAL AORTIC BLOOD PRESSURE THROUGH THE DIFFERENT FEATURED TIMES (FT). MODEL CONSTANTS ARE ESTIMATED THROUGH CURVE FITTING ROUTINES USING THE DISCUSSED *Level-1* EVALUATION METHOD

Mode	*Evaluation Level-1*						
FT	RJ-interval		RI-interval		IJ-interval		
CABP	S	D	S	D	S	D	Units
r	0.89	0.88	0.88	0.87	0.90	0.88	-
m	0.79	0.77	0.78	0.75	0.80	0.77	-
y	23.2	18	25	19	22	18.0	mmHg
RMSE	2.25	2.35	2.2	2.4	2.1	2.38	mmHg
$\frac{\sigma}{\mu}(A_{X_{FT}})$	758	450	887	430	944	735	%
$\frac{\sigma}{\mu}(B_{X_{FT}})$	119	524	64	187	80	104	%
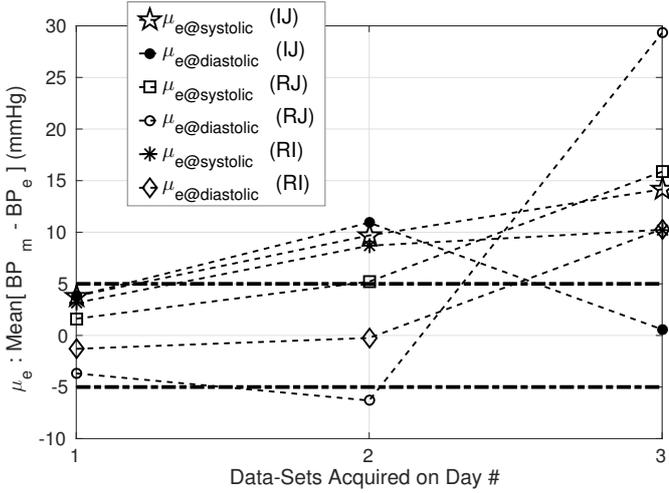
Fig. 5.   Estimation error evolution along days

IV. DISCUSSION

Evaluation level-1 procedure shows that the central CABP estimation is feasible by the proposed methodology. Findings showed that always it is possible to find a pair of parameters to be used with HM and the FT, to estimate a group of CABP accurately. Additionally, evaluation level-1 showed that similar feasibility on CABP estimation could be achieved by considering all three FT alternatives (RJ, RI and IJ). CABP-HM level-1 evaluation presents performances of $r \approx 0.9$ ($p < 0.05$), $m \approx 0.8$ and $y \approx 20mmHg$ and $RMSE \approx 2.3mmHg$. Similar results were reported in [6] when RJ interval was used as input FT. Thus, the proposed wearable device was capable

TABLE II
PERFORMANCE TABLE OF THE BP MODELS (EQS. 2 AND 1) AS ESTIMATORS OF CENTRAL AORTIC BLOOD PRESSURE THROUGH THE DIFFERENT FEATURED TIMES (FT). MODEL CONSTANTS ARE ESTIMATED THROUGH CURVE FITTING ROUTINES USING THE DISCUSSED *Level-2* EVALUATION METHOD.

Mode	*Evaluation Level-2*						
FT	RJ-interval		RI-interval		IJ-interval		
CABP	S	D	S	D	S	D	Units
r	0.14	0.04	0.3	-0.14	0.16	-0.27	-
m	0.04	0.01	0.09	-0.02	0.06	-0.02	-
y	113	80	106	83	103	84.6	mmHg
RMSE	9.6	6.2	7.1	5.9	5.0	8.2	mmHg
$A_{X_{FT}}$	6.15	-0.51	4.27	-0.18	-1.75	0.02	mmHg sp
$B_{X_{FT}}$	8.4	10.8	8.4	9.6	14.2	7.9	mmHg

of achieving similar results that the ones obtained in the previous work [6]. This validation of the proposed wearable device represents one of the main findings in this study. Furthermore, this work showed that more FT alternatives could be used for the CABP estimation from the proposed wearable device. When BP_e was constructed with the level-1 procedure, there was no statistical difference between BP_e and BP_m distributions functions for any of the studied BP variables, systolic ($p > 0.6$) and diastolic ($p > 0.3$), when different FT were considered (RI,RJ and IJ intervals). Nevertheless, although table I presents feasibility for the CABP estimation, and also for the three presented FT, calibrated constants $A_{S_{FT}}$, $B_{S_{FT}}$, $A_{D_{FT}}$ and $B_{D_{FT}}$ varies significantly along group of data-sets. Parameter scattering of the HM, measured in terms of sigma-over-mean (rows $\frac{\sigma}{\mu}(A_{X_{FT}})$ and $\frac{\sigma}{\mu}(B_{X_{FT}})$ in table I), varies from 450 to 944 % for all over the $A_{X_{FT}}$ parameters, while from 64 to 524 % for the respective $B_{X_{FT}}$ counterpart. Scattering in parameters of the HM can also be observed in fig. 4. Since parameters are resolved from curve fitting procedures over several grouped data-sets, with no additional constraints for the convergent solution, it is reasonable to expect some scatter on such best solutions for parameters. A more physical-assisted calibration approach might reduce the scattering along with groups of data-sets.

On the other hand, when HM was calibrated with the first group of data-sets, and then HM attempted to estimate CABP along three days from calibration, CABP prediction presented poor performance. Negative and less than $r = 0.3$ Pearson correlations were obtained; almost zero slopes ($m \approx 0$) and intercepts larger than $y = 80mmHg$ resulted from linear regression analyses. Also, the two-sample Kolmogorov-Smirnov test rejected the null hypothesis of BP_e and BP_m being of the same distribution functions ($p < 0.001$) for the three considered FT cases. Last two rows on table II provides the calibration parameters ($A_{S_{FT}}$, $B_{S_{FT}}$, $A_{D_{FT}}$ and $B_{D_{FT}}$) used by the HM to perform the CABP estimation. Aim to estimate CABP by the proposed method with a three-day calibration interval can not be achieved in the light of evidence found here. Nevertheless, fig. 5 shows that CABP estimations compliant with the AAMI requirements could be achieved by the proposed method by considering within-day calibration intervals.

V. CONCLUSION

This work investigates the possibilities for estimating CABP from a proposed wearable device. CABP estimation performance was assessed by using two levels of validation; that is, feasibility (Level-1) and prognostic capability (Level-2) on CABP estimation were reported. Previous work proved that CABP estimation from ECG and BCG is feasible, findings in this paper showed that similar results could be replicated by using a proposed wearable device. The study used groups of data-sets (defined by CABP measurements and wearable acquisitions of ECG and BCG) from a healthy subject recorded along three days; favorable results were obtained when the method was calibrated and tested over the same group of data-sets (level-1 evaluation). In this context, extracted feature times from wearable acquired signals (intervals: RI, RJ, and IJ) might lead to three alternatives for estimating CABP from this proposed PTT-based methodology. The ability of the trained

HM to predict unseen CABP data was also evaluated (level-2 evaluation). CABP prediction from the proposed method showed poor performance when a three-day calibration interval was considered. Nevertheless, findings showed that CABP could be accurately predicted employing daily calibrations.

VI. FUTURE WORK

The findings presented in this article meant a first set of validations for the proposed methodology to estimate CABP from a wearable device. Further validations should be part of our future research; particularly, validations should be centered in the evaluation of prognosis capability for estimating CABP (Level-2-type evaluations). Upcoming method evaluations should include the investigation of the prognosis capability in a study involving more volunteers. Additionally, the use of data-sets distributed along one day might be helpful to determine more precisely the calibration interval supported by this methodology.

On the other side, the level-1 evaluation showed that HM calibrations based on tailoring HM through regression procedures might lead to parameters that fluctuate along with groups of data on the same subject. Reducing the degree of freedom by including physical constraints in the curve fitting procedures might reduce the scatter of parameters in the HM. Providing the HM with the most physical considerations as possible would give more robustness to the method, and might provide better insights into the assessments of cardiovascular health. Having a wearable device designed to capture CV timing events accurately will be advantageous for this purpose. Further work will be centered on incorporating more physical considerations to our proposed methodology to estimate CABP.

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