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Noninvasive Detection of Vessel Stiffness from Continuous Blood Pressure Recordings in Hypertensive Subjects

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Abstract—**This paper presents results of blood pressure dynamicity analysis aimed at vessel stiffness detection and subsequent cardiac risk stratification. We analyzed ECG and BP parameters from 12 normotensive young healthy volunteers, 10 old healthy volunteers, and two groups of hypertensive patients – 12 young non-medicated hypertensive subjects with no other known complications and 16 hypertensive non-medicated subjects with confirmed obesity (according to waist circumference), hyperlipidemia or diabetes mellitus. The dynamic parameters obtained from a derivative continuous blood pressure signal provide additional information about vessel compliance. They can differentiate hypertensive subjects according to the level of cardiovascular risk.**

I. Introduction

Hypertension is one of the most important factors contributing to cardiac and cerebrovascular disease. There is a number of negative markers of hypertension, including advancing age, male gender, cigarette smoking, diabetes mellitus, obesity, other forms of hyperlipidemia and hyperuricemia. The levels of systolic and diastolic blood pressure are usually the first parameters to be identified as factors of upcoming risk. Moreover, there are other predictive simply measurable risk factors, such as increased heart rate, decreased heart rate variability, increased arterial pulse pressure and increased pulse wave velocity [1,5]. The last two of these factors are closely related to the ability of a blood vessel wall to expand and contract passively with changes in blood pressure. This ability of a vessel to distend with increasing pressure is quantified as vessel compliance.

Nowadays, the study of structural and mechanical alternations of small arteries, as well as their possible role in the pathogenesis of essential hypertension, still remains a matter of clinical and scientific interest. Essential hypertension is associated with normal cardiac output but increased peripheral resistance and decrease of vessel compliance. Hypertensive damage of arterioles and small arteries contributes to the complications of hypertension. Therefore, the study of structural and mechanical properties of vessels and their contribution to the prognosis of patients are considered to be of great importance [2,3].

One currently available technique for continual noninvasive measurement of arterial blood pressure (BP) is Penas's finger-cuff photoplethysmographic method [4,6]. A continuous BP recording obtained from the finger provides measurements not only of heart beat intervals (RR), systolic (SBP) and diastolic (DBP) blood pressure and pulse wave, but also of structural properties such as vascular compliance and other parameters describing cardiovascular functions [7]. This study presents parameters computed from a derivative continuous BP signal in the diastolic-systolic time region [8]. These parameters reflect dynamic properties of BP changes closely connected with vessel stiffness. We present these parameters along with SBP, DBP and RR, and tested its contribution to the differentiation of two hypertensive groups. We also discuss the possibility of the given parameters differentiating the influence of hypertension, age and other diagnostic factors.

II. Methods

The measurement protocol includes one 5-minute measurement with paced breathing at 0.1 Hz (10-second period) in the supine position [9]. The breathing waveform

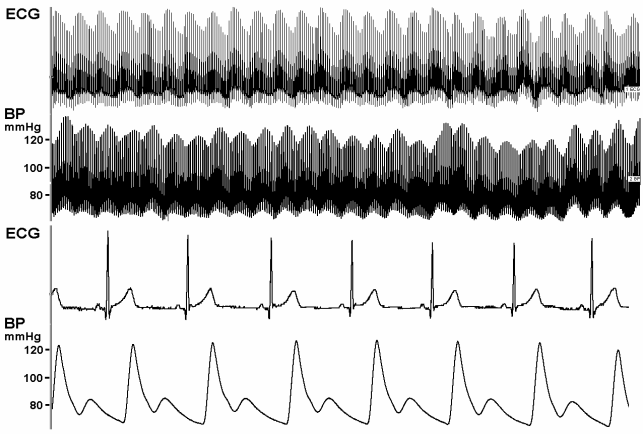

Fig. 1 . Example samples of 5-minute measurement of ECG and BP (top panel) and 5-second time window (bottom panel). Paced breathing 0.1 Hz.

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was measured by a calibrated turbine spirometer (ANNAlab Spirometer SM2) along with ECG and blood pressure (Finapres-2300, Ohmeda). The signals were digitized via an Analogue-to-Digital 16-bit converter with a sampling frequency of 500 Hz, Fig. 1. Data processing was performed by the custom developed software ANNAlab ScopeWin ANS.

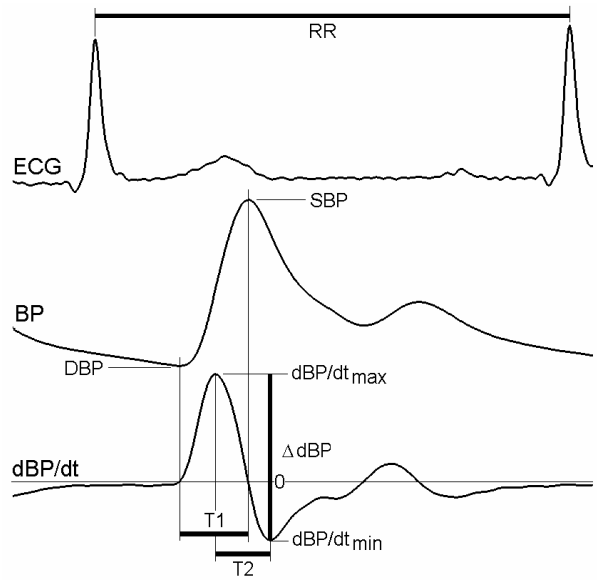

Fig. 2. Graphical interpretation of computed parameters. ECG, BP in pass band 0-20 Hz, derivative BP (dBP)

A. Recording

Short training of each subject preceded testing. To ensure subject environmental accommodation, the first measurement is commenced after the subject has spent at least 15 minutes at rest in the supine position on the bed. Vital capacity was measured 5 minutes prior to the beginning of the measurement.

Breathing frequency was managed optically using a bar LED indicator, which generates sinus waves. The depth of 0.1 Hz breathing has to be controlled at between 50-70 % of vital capacity.

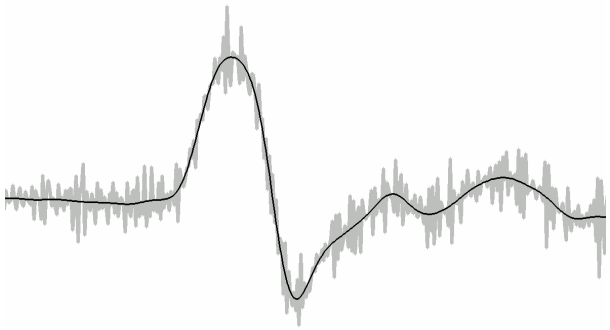

Fig 3. Derivative BP; gray: raw signal, black: 20 Hz BP filter.

The 0.1 Hz breathing modulation of HR and BP represents fusion of the respiratory sinus arrhythmia (RSA) mechanism with baroreflex oscillation at the baroreflex control frequency. It results in the resonance effect: the maximal transfer of respiration oscillation to BP and HR. In this way we can obtain two components of BP and HR parameters – steady-state parameters and short-term variability parameters [10].

B. Study groups

We measured four groups of subjects: 12 young healthy individuals (YH, age 26±4, 4 female), 10 old healthy individuals (OH, age 54±10, 2 female), 12 patients with non-medicated newly diagnosed untreated essential arterial hypertension (H1, age 31±9, 3 female), and 16 non-medicated hypertensive patients with additional risk factors – metabolic syndrome, hyperlipidemia, diabetes mellitus and obesity (H2, age 40±11, 6 female). All measurements were taken in the Laboratory for Research of Circulation Control at St. Anne's University Hospital, Brno. Informed consent from all subjects was obtained prior to participation in this study.

TABLE I
COMPUTED PARAMETERS

	YH	OH	H1	H2
RR	932±95	935±97	877±112	866±143
SBP	117±22	115±15	145±20	147±16
DBP	63±16	64±12	79±11	74±14
SBP-DBP	54±10	50±7	66±12	74±15
RR_{STD}	133±31	59±35	81±27	54±26
SBP_{STD}	7.29±1.45	6.62±1.52	7.01±2.8	7.32±2.08
DBP_{STD}	4.01±1.24	2.99±0.61	3.68±1.06	3.56±1.01
dBP/dt_{max}	824±230	732±136	999±205	1195±310
dBP/dt_{min}	-436±140	-270±123	-616±294	-878±507
ΔdBP	1260±339	1002±239	1615±494	2073±768
$T1_{SBP-DBP}$	117±12	128±15	120±16	113±13
$T2_{dtmax-dtmin}$	90±11	84±18	85±8	75±11

YH – young healthy volunteers, OH – old healthy volunteers, H1, H2 – hypertensive groups. RR intervals (ms), SBP (mmHg), DBP (mmHg), pulse pressure SBP-DBP (mmHg), RR variability RR_{STD} (mmHg), SBP variability SBP_{STD} (mmHg), DBP variability DBP_{STD} (mmHg), maximum of derivative BP dBP/dt_{max} (mmHg/s), minimum of derivative BP dBP/dt_{min} (mmHg/s), difference ΔdBP = dBP/dt_{max} -dBP/dt_{min} (mmHg/s), SBP peak – DBP depression time T1 (ms) and dBP/dt_{max} -dBP/dt_{min} time T2 (ms)

C. Computed parameters

The mean and standard deviation values from 5-minute paced breathing measurement were computed. The differences among groups were given by P values computed by ANOVA. The following key parameters were obtained and compared between groups, see Fig. 2. : RR intervals (ms), SBP (mmHg), DBP (mmHg), pulse pressure SBP-DBP (mmHg), RR variability RR_{STD} (mmHg), SBP variability SBP_{STD} (mmHg), DBP variability DBP_{STD} (mmHg), maximum of derivative BP dBP/dt_{max} (mmHg/s), minimum of derivative BP dBP/dt_{min} (mmHg/s), difference ΔdBP =

dBP/dt_{max} -dBP/dt_{min} (mmHg/s), SBP peak – DBP depression time T1 (ms) and dBP/dt_{max} -dBP/dt_{min} time T2 (ms).

We used an optimal 20 Hz low pass band on BP signal to eliminate noise and measurement artifacts. Fig. 3. shows the derivative raw BP signal (gray) and derivative BP after filter application (black).

TABLE 2
DIFFERENCES BETWEEN GROUPS

	YH-OH	YH-H1	YH-H2	OH-H1	OH-H2	H1-H2
RR	NS	NS	NS	NS	NS	NS
SBP	NS	**	***	**	****	NS
DBP	NS	*	*	**	NS	NS
SBP-DBP	NS	*	***	**	****	NS
RR_{STD}	****	***	****	NS	NS	**
SBP_{STD}	NS	NS	NS	NS	NS	NS
DBP_{STD}	*	NS	NS	NS	NS	NS
dBP/dt_{max}	NS	*	**	**	***	*
dBP/dt_{min}	**	*	**	**	**	NS
ΔdBP	NS	*	**	**	***	*
$T1_{SBP-DBP}$	NS	NS	NS	NS	**	NS
$T2_{dtmax-dtmin}$	NS	NS	**	NS	NS	**

ANOVA computed differences among groups YH-OH, YH-H1, YH-H2, OH-H1, OH-H2, H1-H2.
NS – not significant p>0.05, * p<0.05, ** p<0.01, *** p<0.001, **** p<0.0001

III. RESULTS

A. Numerical results

Complete numerical results are presented in Table 1 and differences between groups in Table 2.

B. Limitations

It is important to note that it is necessary to conscientiously supervise blood pressure measurement. The positioning and size of the finger cuff and incorrect Finapres calibration may cause distortion of the blood pressure curve and erroneous results [Wesseling]. We performed BP calibration before and after each 5-minute measurement and compared the differences between the measured BP after calibration. If we obtained a different SBP or DBP or BP shape we repeated the measurement. We always compared finger blood pressure with brachial blood pressure measurement.

In order to ideally compare groups we need more measured subjects and a different age structure within groups. The ideal state would be for the OH, H1 and H2 groups to have the same mean age and gender. Different ages in the measured groups introduces a new factor which significantly affects heart rate and heart rate variability in particular. We can assume that the age effect will also be variously reflected in other parameters.

Regardless of all these limitations the results presented are significant and credible.

IV. DISCUSSION

The results have demonstrated that there are differences among groups and parameters. The fundamental parameters are SBP and pulse pressure SBP-DBP, which as expected differentiate between normotensive groups YH,OH and hypertension groups H1,H2. The heartbeats interval RR was shorter in the groups H1 and H2 [11], but the differences between groups was non-significant. SBP_{STD} and DBP_{STD} variability was also a non-significant parameter. It shows that blood pressure variability is not connected with age and mean SBP and DBP. However, the RR_{STD} variability significantly decreases with increased age. This parameter is not dependent on blood pressure.

The dynamic parameters dBP/dt_{max}, dBP/dt_{min} and ΔdBP provide significant group differentiation among almost all groups without a strong age effect. The mean T2 parameter in the H2 group is only 75 ms, even though in the H1 group it is comparable with healthy controls. The T2 value in the H2 group shows a rapid blood pressure increase. This fact is also documented by the highest dBP/dt_{max} and ΔdBP parameter in the H2 group.

From the point of view of higher risk of cardiac death the most important differences are those between the H1 and H2 groups. These groups of hypertensive subjects have similar

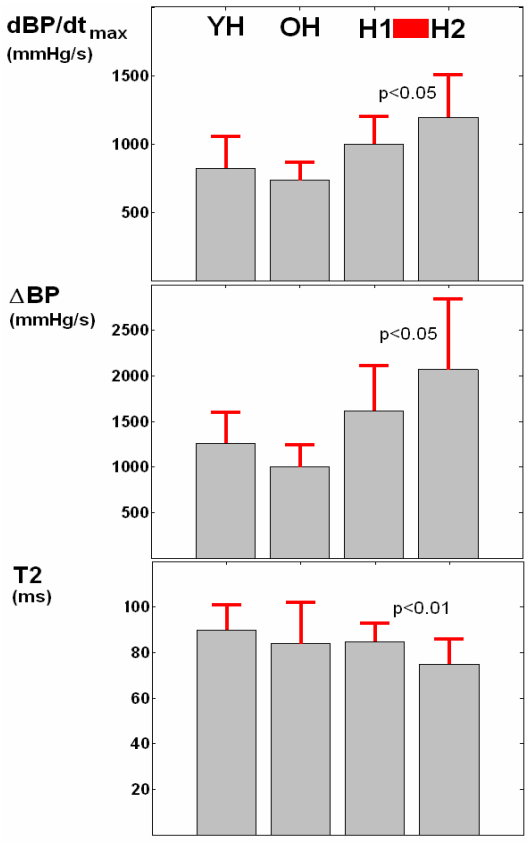

Fig. 3. Dynamic BP parameters dBP/dt_{max}, ΔdBP and T2 for groups YH, OH, H1 and H2. The remaining computed parameters from Table 1,2 don't significantly reflect differences between the H1 and H2 groups.

traditional parameters such as blood pressure and heart rate. The degree of vessel stiffness and compliance connected with cardiac risk is reflected in vessel reaction to dynamic blood pressure change. So it is clear and expected that the dBP/dt_{max}, ΔdBP and T2 parameters can differentiate between the H1 and H2 groups, Fig. 3. Measured dBP/dt_{max}, ΔdBP are significantly higher and T2 is significantly shorter in the H2 group. This fact determines higher stiffness and lower compliance of vessels in the H2 group. The T2 parameter reflects the heartbeat RR interval. If we normalize the T2 parameter to 1000 ms RR (60 beats per minute) we will obtain values YH-OH-H1-H2: 97-90-97-86 ms. It is evident that the age factor (26-54-31-40 years) plays an additional role in T2 interpretation and different H1-H2 mean age must be taken into consideration.

An interesting finding is the significant difference of the RR_{STD} parameter between the H1 and H2 groups, Table 2. However, if we compare the RR_{STD} value of all groups YH-OH-H1-H2: 133-59-81-54 (ms) with the mean age 26-54-31-40 years, we can postulate that the H1-H2 difference in the RR_{STD} parameter primarily reflects the different age of the H1 and H2 groups.

V. Conclusion

It has been proposed that information relating to the compliancy of a subject's vasculature can be simply extracted from dynamicity in blood pressure recorded by Penaz's plethysmographic method. Dynamic parameters separated from the derivative continuous BP curve provide additional information that can determine the higher cardiovascular risk of hypertensive subjects. The most contributing parameter from this point of view are dBP/dt_{max} and ΔdBP. The remaining parameters are not able to differentiate risk groups or are affected by the age of measured subjects.

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