Acquisition and analysis of radial artery waveforms from a wrist cuff

J. Jilek, M. Stork

***Abstract*—**Noninvasive assessment of arterial waveform contours and waveform reflections have received increased attention in recent years. The prevalent method at the present time is acquisition of radial waveforms by applanation tonometry. The disadvantage of tonometry is that a skilled application of the tonometer probe is required. The authors developed an experimental system that automatically acquires radial artery waveforms from a wrist cuff. Application of the wrist cuff does not require a special skill. The system and the method of waveform acquisition from the wrist cuff are described, representative waveforms are introduced, and several applications of the waveforms are described.

***Keywords*—**Blood pressure, artery waveforms, wrist cuff, applanation tonometry.

I. Introduction

THE last decade has seen increased interest in arterial mechanical properties [1] with increased appreciation of the importance of wave reflections in ageing and in hypertension [2]. Systolic augmentation of pressure in the ascending aorta caused by early wave reflections is described by aortic augmentation index (AI) [3]. AI is one of a number of inter-related parameters reflecting vascular stiffness that have been associated with increased cardiovascular risk. Since direct measurement of aortic pressure is invasive, non-invasive derivation methods of similar data by applanation tonometry have been developed and resulting waveforms have been described [4]. Carotid artery waveforms are the closest in distance and in shape to the aortic waveforms. Obtaining correct carotid waveforms does, however, require skilled application of the tonometer. Radial artery is often the preferred site for tonometry. Radial artery waveforms are, however, different from the waveforms of the ascending aorta. Manipulation of the radial waveforms is required for adequate approximation of the central aortic waveforms. Arterial transfer function has been used for these purposes and at least one commercial system using applanation tonometry has been developed. Skilled application of the pencil-shaped tonometer is necessary in order to acquire correct waveforms. Errors resulting from incorrect application of the tonometer have been reported [5]. Several studies compared transfer function methods with direct measurements and one study [6] concluded that transfer function may not be necessary and that a simple, linear relationship between the radial and the aortic waveforms may be sufficient to define augmentation index.

The authors developed an experimental system that uses a commercial blood pressure wrist cuff to obtain radial artery waveforms. Waveforms acquired with the system were compared with published waveforms in order to determine if wrist cuff waveforms could be used in a manner similar to the waveforms acquired by tonometry.

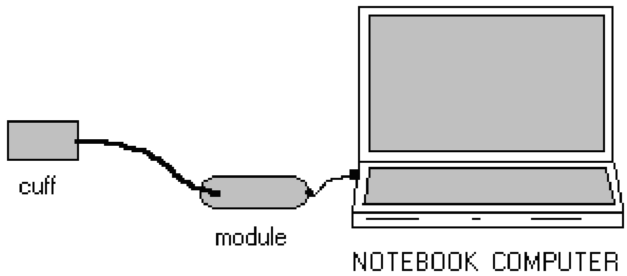

Fig. 1. The system for acquisition of wrist cuff radial artery waveforms.

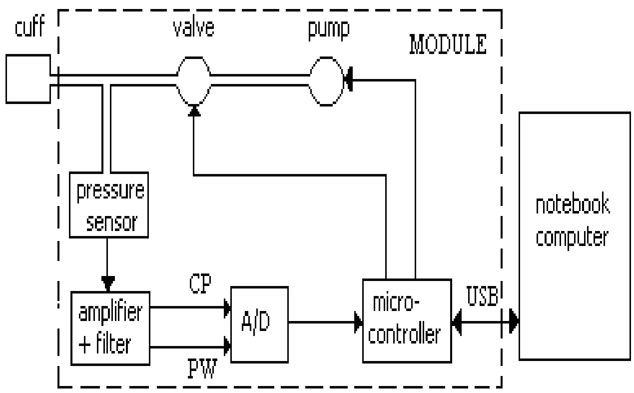

Fig. 2. Block diagram of the system's module.

II. Methods

The experimental system (Fig. 1) for acquisition of wrist cuff waveforms consists of a notebook computer, a module with pneumatic and electronic circuits and a notebook

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computer with special software. The notebook controls all pneumatic and electronic functions of the system via USB interface.

Block diagram of the module (Fig. 2) shows a pneumatic circuit and an electronic circuit. The pneumatic circuit uses a miniature air pump to inflate the cuff, and a solenoid valve to deflate the cuff. Commercial wrist cuff (Omron, model 602) was used. The cuff has a small bladder and a stiff exterior fabric. This feature diminishes damping of higher frequencies and improves signal-to-noise ratio. Cuff pressure is converted into voltage by a piezoresistive pressure sensor. The sensor output is amplified by an instrumentation amplifier (Burr-Brown INA118), filtered and separated into 2 analog channels. Channel 1 represents cuff pressure (CP) and channel 2 represents radial artery pressure waveforms (PW). The 2 analog signals are digitized by a 12-bit AD converter and transmitted to the notebook via USB interface. Sampling rate is 85 samples/sec. The controller provides 2 digital lines that control the air pump and the solenoid valve. Notebook software, developed by the authors, controls cuff inflation and deflation, acquisition and display of wrist cuff waveforms, and waveform storage and retrieval. Acquired waveforms can be analysed manually with a cursor that can move in increments as small as 11.8 milliseconds (the sampling rate). Cuff pressure and waveform pressure are displayed after each cursor step.

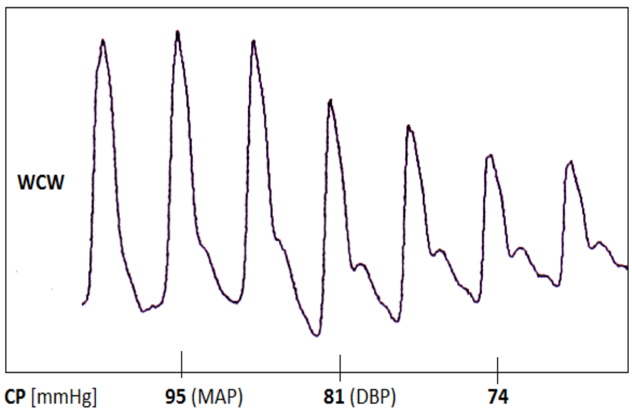

Figure 3. Wrist cuff waveforms (WCW). CP is cuff pressure in mmHg.

Cuff inflation pressure is entered manually after a blood pressure measurement is performed. Best waveforms are obtained with the cuff inflated to the pressure just below the expected diastolic pressure (DBP). At lower cuff pressure (CP), the waveform amplitudes are smaller and signal-to-noise ratio is decreased. At low CP, the waveforms can be altered by pressure in smaller arteries. At CP higher than DBP, the waveforms are distorted by partial occlusion of the radial artery [7]. Figure 3 illustrates the above explanation. The wrist cuff waveform (WCW) shapes can be best observed by concentrating on dicrotic notch (small indentation on the descending slope of a WCW). The dicrotic notches can be easily identified at CPs at and below DBP. At CPs higher than DBP the dicrotic notches are increasingly obliterated. Undistorted WCWs are compared with waveforms obtained simultaneously from a finger photoplethysmograph (PPG) in Fig 4. The contours of the PPG and WCW waves are almost identical.

Wrist cuff radial waveforms were acquired from 4 volunteers younger than 35 years, 4 volunteers between 35 and 60 years, and 4 volunteers older than 60 years. All data were acquired with the subjects in sitting position. Data acquisition procedure started with an automatic cuff inflation to the pressure approximately 5 mmHg below the manually entered diastolic blood pressure. When cuff pressure reached the desired level, the pump was automatically turned off and a 10 second data acquisition started. At the end of 10 sec interval the cuff was deflated and the waveforms were displayed. Waveforms free of artifacts and arrhythmias were accepted and stored.

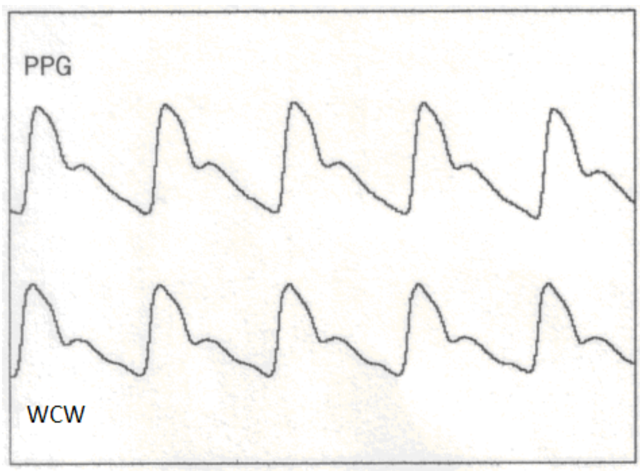

Fig. 4. Waveforms obtained from a finger photoplethysmograph (PPG) and waveforms from a wrist cuff (WCW).

After completion of data acquisition, the waveforms were analyzed and several variables were computed: heart rate (HR) was computed from time intervals between successive waveforms, upstroke time (UT) was computed as time in milliseconds from the foot to the peak of a waveform, and amplitude (AMPL) was computed from the the waveform foot to the peak and expressed in pascals. Means of 3 variables were computed.

III. Results

The computed wrist cuff waveform variables are in the Table I. HRs could not be matched exactly. The reason for matching HR is that UT has a tendency to shorten with HR acceleration.

Waveform amplitudes (AMPL) increased by 15% from age <30 to age 35 -60 and 49% from age <30 to age >60. Upstroke time (UT) increased 30% from age <30 to age 35-60 and 59% from age <30 to age >60.

TABLE I.
MEAN VALUES OF VARIABLES HR, AMPL, UT COMPUTED FOR 3 AGE GROUPS

Age	HR [bpm]	AMPL [pasc]	UT [mSec]
< 30	69	594	102
35 – 60	72	735	134
> 60	66	1197	162

IV. DISSCUSSION

The values of computed variables from the Table I. show similar chronological changes to those observed in studies using radial tonometry [8].

Increases in amplitudes are attributed to decreased arterial compliance and increases in upstroke time are caused by the combined effects of decreased arterial compliance [9] and arterial wave reflections [8].

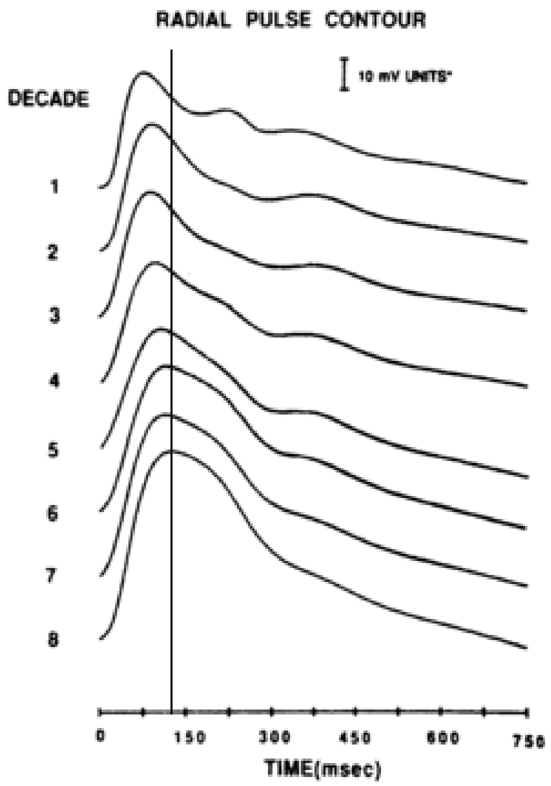

Fig. 4. Averaged tonometric radial waveforms from ages 10 to 80 (decade 1 – 8). The solid vertical line uses the peak of decade 8 waveform as timing reference.

The waveforms in Fig. 4 were obtained by applanationn tonometry and waveforms in Fig. 5 were acquired from wrist cuff. The waveforms from Fig 4 and the waveforms from Fig. 5 show similar changes with age. Waveforms obtained from radial arteries of young subjects have shorter UT because the heart ejects its stroke volume faster into compliant arteries [8]. Young subject's arteries have much more pronounced dicrotic notch. In middle age the dicrotic notch is diminished and in old age it is almost completely obliterated. Such age-dependent waveform alterations are considered to be of structural origin and they do not change substantially with blood pressure or with heart rate.

An important application of radial pressure waveforms is the determination of aortic AI. AI is usually calculated as the ratio of aortic augmentation pressure and overall aortic pressure. Aortic AI is highly predictive of cardiovascular mortality [9]. Increased aortic AI increases the load presented to the left ventricle. The brachial or radial arterial pressures do not represent the load accurately. Application of a transfer function allows the determination of aortic AI and facilitates synthesis of the aortic pressure waveform. Accuracy of the transfer function depends on high frequency information. The transfer function shows inter-subject variability of aortic AI and its accuracy has been questioned. A recent report [6] showed that aortic AI can be derived from the radial waveform without use of a mathematical transfer function. Such approach is suitable for waveforms acquired by the wrist cuff method because the air in the wrist cuff is likely to dampen high frequencies. Computation of aortic AI from the wrist cuff waveforms is currently under investigation. Another potential application of wrist cuff method is computation of "oscillatory" arterial compliance [10]. Oscillatory compliance reflects changes affecting central aortic pressure.

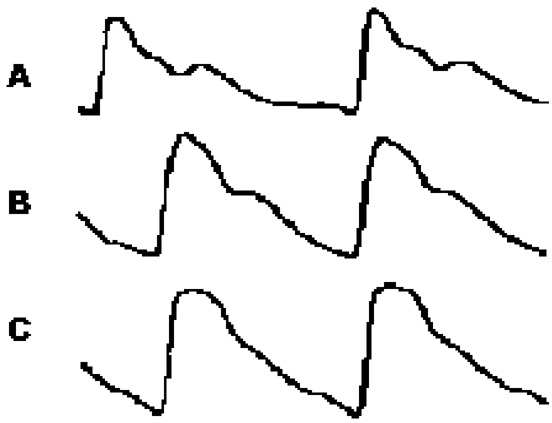

Figure 5. Age related waveforms obtained from wrist cuff. (a) 22 years old female, (b) 51 years-old male, (c) 70 years old female.

Wrist cuff radial waveforms contain information that reaches beyond variables determined in this study. An experimental system for the determination of blood pressures and hemodynamics from wrist cuff waveforms has been developed by the authors and described previously [11,12]. The system described in this paper is a modification of the earlier version [11,12]. The system for determination of blood pressures and hemodynamics utilizes wrist cuff waveforms obtained automatically after a determination of BPs by the system. Stroke volume (SV), heart rate (HR), cardiac output (CO), and left ventricular ejection time (LVET) are derived from acquired waveforms. Additional (computed) variables are total peripheral resistance (TPR) and systemic arterial compliance (SAC).

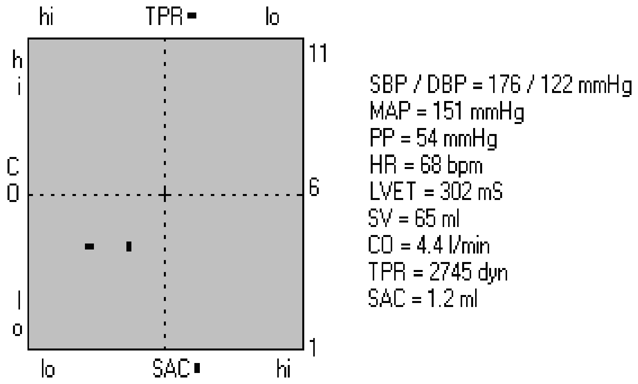

Fig. 6. Blood pressures and hemodynamic variables in numerical and graphic "quadrant" form.

Blood pressures and hemodynamic variables are displayed as numeric values and hemodynamic variables are also displayed in the form of a graphic "quadrant". Fig 6 shows a numeric and "quadrant" display of BP and hemodynamic values. The quadrant the relationships of CO, TPR and SAC. TPR and SAC are graphically represented by small rectangles and they move together on the vertical (CO) axis according to the value of CO. TPR and SAC are positioned on the horizontal axis according to their values. Normal values of TPR and SAC are displayed graphically in the right half of the quadrant. The hemodynamic values shown in Fig 6 represent hypertension. The TPR and SAC are positioned in the lower left half of the quadrant.

V. Conclusions

Radial arterial waveforms obtained with the wrist cuff method are similar to those obtained with radial tonometry and other methods. Wrist cuff method has the advantage of automatic data acquisition where trained observer is not required as is the case with radial tonometry.

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Mr. Jiri Jilek received MSEE degree from University of Southern California (USC), Los Angeles . From 1972 to 1981 worked as research engineer at USC-Medical Center, Los Angeles, in the field of instrumentation for perinatal medicine. Research projects included a method for evaluation of fetal heart rate variability and an on-line system for evaluation of fetal heart rate patterns. From 1989 to 1997 worked as research engineer at Drew University of Medicine and Science, Los Angeles. Projects included development of an experimental system for evaluation of maternal cardiovascular parameters and data acquisition from fetal monitors. From 1997 to 2007 worked at King-Drew Medical Center, Los Angeles as a senior R&D engineer. He has also worked as an independent engineering consultant. Research projects included processing of digital arterial waveforms, development of a system for noninvasive evaluation of blood pressures and hemodynamics, and a new method for bench-testing of blood pressure monitors. Mr. Jilek published numerous journal and conference papers. He is a member of the Association for Advancement of Medical Instrumentation (AAMI) sphygmomanometer and blood pressure committees.

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Further, the mathematical analysis of CNAP pulse waves enables the noninvasive estimation of stroke volume and cardiac output.[7] A meta-analysis of 29 clinical trials evidences that goal-directed therapy using these hemodynamic parameters leads to lower rates of morbidity and mortality in moderate and high-risk surgical procedures.[8]. Current noninvasive blood pressure technologies[edit].Â It is well known that good access to a â€œbigâ€ artery is at the wrist by palpating.Â Reliability of hypotension detection with noninvasive radial artery beat-to-beat versus upper arm cuff BP monitoring. Anesth Analg 2006, 102 Suppl:S10. ^ Michard, F., Chemla, D., Richard, C., Wysocki, M., Pinsky, M. R., Lecarpentier, Y., & Teboul, J. L. (1999).