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

Using Dual-Antenna Nanosecond Pulse Near-field Sensing Technology for Non-contact and Continuous Blood Pressure Measurement

Hong-Dun Lin, Yen-Shien Lee and Bor-Nian Chuang

Abstract—**Long-term and continuous non-invasive blood pressure monitoring has shown that it is the most important to clinical diagnosis of cardiovascular diseases and personal home health care. Currently, there are many preferable non-invasive methods, including optical sensor, pressure-sensitive transducers, and applanation tonometry, to get insight of blood pressure and flow signal detection. However, the operation of traditional monitors is cuff accessories needed, and also the sensing probes needed to exert pressure to the user directly. The measurement procedure is limited by long-term, continuous measurement and also easy to cause discomfort. To improve these issues, the non-pressurized and non-invasive measuring method will become an important innovation improvement. In this paper, the novel nanosecond pulse near-field sensing (NPNS) based screening technology with dual-antenna, which includes radio frequency (RF) pulse transmission and two combined flat antenna connected to transceiver of miniature radar, is proposed to derive relative blood pressure parameters from measured blood flow activity (Pulse Wave Velocity, PWV). A dedicated analysis software is also provided to calculate cardiovascular parameters, including PWV, average systolic time, diastolic and systolic pressure, for clinical and homecare applications. To evaluate the performance, the proposed method was applied on blood pressure measurement at the body site of limbs (brachial and leg). As a result, it shows error of DBP and SBP is 5.18±1.61 and 4.09 ± 1.69 mmHg in average compared with the measurement result from commercial product, and performs the capability of continuous long-term monitoring in real-time.**

I. INTRODUCTION

THE heart, cardiovascular and hypertension diseases are the Top 10 Causes of Death. It had been placed at the first position for 11 consecutive years since 1971 and has been gradually decreased since the 1980s. In clinical, cardiovascular morbidity and mortality with hypertension has shown that it is the most important cause of and also an independent risk factor to several cardiovascular diseases such as atherosclerosis, heart stroke and myocardial infarction [1]. And also, the blood pressure can be an early evaluation index of cardiovascular disorders for subacute population. Among the current non-invasive blood pressure monitoring methods, the obtained blood flow information and blood pressure parameters present promised information; it is a measurement of the pulse wave velocity (PWV) of blood in the vascular and directly relative to pressure and vascular stiffness condition. Moreover, high blood pressure results in an earlier return of the reflected wave from peripheral sites and affects circulation system. Many researches have shown that blood pressure can be assessed through the PWV measurement by combining optical and pressure sensing technology. The PWV information can widely be recognized as a significant marker of cardiovascular status monitoring, and it is correlated with many cardiovascular risk factors, including age, blood pressure, pulse pressure, hypertrophy and heart diseases. It has also been proved that PWV is a significant factor to estimate blood pressure for prediction of mortality in the elderly and in patients with hypertension disease and in the general population.

Many non-invasive methods have been maturely developed and applied on both the research and clinical applications to evaluate blood pressure continuously, and these methods have significantly improved the understanding of the physiological significance of blood flow. Those methods are to derive blood pressure based on blood flow status investigation, including local pulse signal at a particular site in the artery, regional vascular elasticity along the length of an arterial segment, and circulation information. Measuring the blood pressure over the segment of interest assesses PWV from a regional artery. Cardiovascular PWV is the speed at which the flow wave is traveling from the aorta through the arterial tree. According to the Bernoulli's theorem and equation, pressure reveals that is related to fluidic flow velocity in tubing; that is, the higher blood pressure at the artery, the faster the PWV. By investigating an average blood pressure of the preferred local artery, PWV can provide as a reference calculation weighting factor. There are many developed methods can applied to assessment of blood pressure continuous and non-invasively. When the pulse pressure and blood flow pulse propagate at the same velocity, the arterial pulse may be collected by using pressure-sensitive transducers [2], an oscillometric equipment [3], applanation tonometry sensor [4,5], Doppler ultrasound (US) probe [6] and optical sensor [7,8]. To obtain two pulse signals at the two body sites simultaneously, the optical sensor, tonometry and cuff pressure are used to measure the pulse transit time (PTT). The distance along which the pulse wave travels is usually estimated by direct superficial measurement between the located sensors position. The PWV is the ratio between the distance and PTT.

Manuscript received March 15, 2012. This work was supported in part by the ITRI B301AR5F00 grant.

H. D. Lin. is with the Center for Measurement Standards, Industrial Technology Research Institute, No. 321, Sec. 2, Kaung Fu Rd., Hsinchu, 30011, Taiwan, R.O.C. (phone: 886-3-5743848; fax: 886-3-5735747; e-mail: hongdunlin@itri.org.tw)

Y. S. Lee was with the Center for Measurement Standards, Industrial Technology Research Institute, No. 321, Sec. 2, Kaung Fu Rd., Hsinchu, 30011, Taiwan, R.O.C. (e-mail: leo.lee@itri.org.tw)

B. N. Chuang was with the Center for Measurement Standards, Industrial Technology Research Institute, No. 321, Sec. 2, Kaung Fu Rd., Hsinchu, 30011, Taiwan, R.O.C. (e-mail: B.N.Chuang @itri.org.tw)

Furthermore, estimated blood pressure could be calculated by weighting the PWV and a statistic basis value non-invasively [10,11]. The methods suggest the pressure characteristics of the pulse contour obtained by tonometry or pressure sensor, and the proposed method is used for analyzing the pulse waveform. Based on these characteristics, the blood pressure of the peripheral arteries can be estimated; however, the physiological relevance of the derived blood pressure is still unclear. Even these methods provide broadly clinical applications for cardiovascular disease investigation; additional accessories are necessary and the equipments are needed to be operated by medical professionals for pulse signal measurement and data analysis.

In this paper, a novel method based on the nanosecond pulse near-field sensing (NPNS) technology with dual-antenna design is proposed for non-contact and non-invasive measurement of PWV and blood pressure. By this method, dynamic arterial pulse signals can be obtained and the characteristics of blood flow, included PWV and pressure, are analyzed in real-time. Since the heart contracts it generates a pulse or energy wave that travels through the circulation, the speed of travel of this pulse wave is related to the pressure of the measured arteries. The artery pulse signal is measured directly, and relative diastolic blood pressure and systolic blood pressure, DBP and SBP, can be estimated by the proposed method for the evaluation of long-term cardiovascular healthcare.

II. METHOD AND SYSTEM

For the purpose of non-contact artery pulses detection, a signal processing with correlation processing system is utilized. The proposed technology is based on multiplication of the reference radio-frequency (RF) pulse and the echo RF pulse delayed by the time interval during which the signal is spread to the investigated subject and back to the receiver through antenna. The probing signal is presented in the form of short RF pulses having comparable with a period of oscillations filling the probing pulse. After the de-modulation process of emitted and received signal, the output signal of a correlation system is proportional to the phase difference between the probing RF pulse and the echo RF pulse.

In Figure 1, the essential architecture of proposed radar sensing method was present. The system is comprised of measuring probe, including transmitter, antenna and receiver; the signal processing and displaying part. The transmitter emits RF signal, and the receiver collects echo RF via designed antenna. The obtained signal is processed by a microcontroller and displayed on a computer terminal.

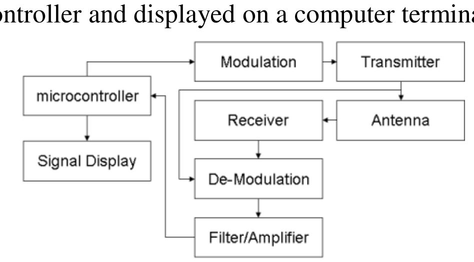

Fig. 1 Architecture of proposed NPNS based radar system for artery pulse signal detection

For measurement setup, the proposed NPNS based pulse sensing technique includes a NPNS transceiver and receiver connected to a dedicated flat dual-antenna. The function block of dual-antenna NPNS sensor is for two pulse signals collection from the artery site simultaneously, as shown in Figure 2. The NPNS transceiver is operated by a microcontroller based board with digital signal processing software. The microcontroller based board provides the wireless communication function (Bluetooth) to transfer data from NPNS transceiver to a computer terminal in real-time for data analysis.

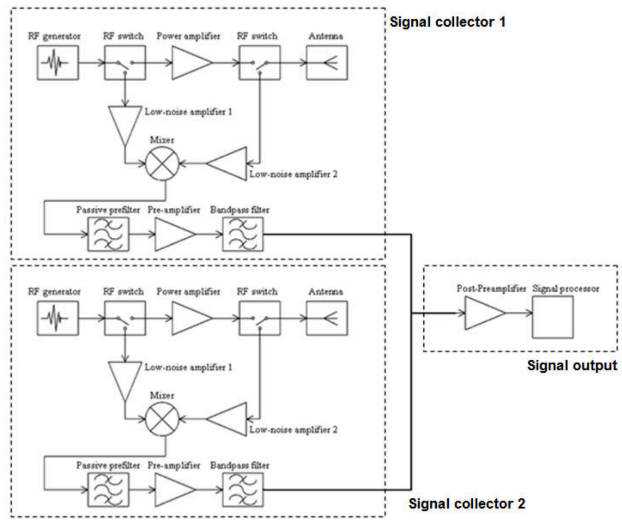

Fig. 2 Illustration of dual-antenna NPNS sensor design

A. *Nanosecond Pulse Near-field Sensing Method*

The nanosecond pulse near-field sensing (NPNS) technology, which comprises low power miniature radar with 300MHz electromagnetic (EM) wave of the transmitted by the antenna RF pulse, is proposed in this study. The de-modulated signal carrying useful information performs through analyzing the phase difference between the reflected and the reference RF pulse signals. The radar uses correlation system; it is based on multiplication of reflected and reference RF pulse signals. The output signal of the correlation system is proportional to amplitude and phase difference between those signals. The emitted RF signal and the signals reflected from moving and motionless objects are shown in Figure 3.

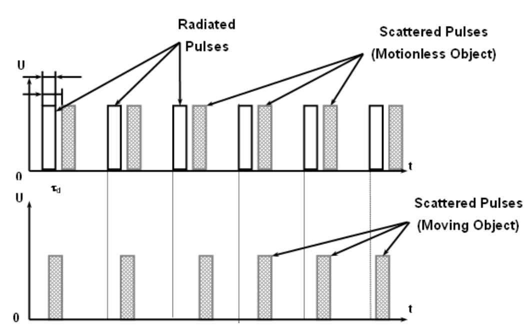

Fig. 3 Illustration comparison of the signals with/without motion in proposed NPNS

For the radar design, the EM signal works in interference and reflections conditions of signals reflected from stationary and moving objects around the artery. Time slots, opening the receiver at the moment of the input of the signal reflected from the artery through skin, muscle and bone at distance defined, are formed in the receiving path to eliminate signal distortion due to interfering pulses. The reference RF pulse signal is conducted to input of the mixer. During reference RF pulse time interval radar detects received signal, all rest time the receiver is shut. This defines time slots of the received RF pulse detection and distance range which has high sensitivity. Reflected pulses which arrive after the end of the reference RF pulse will not be detected. The oscillator generates two RF pulses, one pulse is transmitted, and another one is used as reference RF pulse. Oscillator could be switched on and off during 1 – 2 ns, this allows to have pulse length as low as 5 ns. Switches are changing their state when oscillator is off. So their transition time does not affect pulse length value. Central frequency 300MHz was chosen, and function diagram of NPNS radar is shown in Figure 4.

The Mixer has one channel signal output connected to the low-frequency signals processing sub-circuit. In the output channel, a signal is formed which is in-phase with respect to a reference signal. This eliminates the probability that phase of reflected RF pulse will fall at low sensitivity area of the Mixer. The band pass filter process signal which correspond to the cardio-activity from the patient's body movement. In case the investigated subject is in a fixed position, the amplitude of the output signal after processing is characterized by the following ratio:

$$A = \frac{E_0 E_1}{2} n T_0 \cos(\varphi) \tag{1}$$

where E_0 is a maximum amplitude of the probing RF pulse; E_1 is a maximum amplitude of the received echo RF pulse; T_0 is a period of oscillations of the probing RF pulse; n is a whole number of periods of oscillations filling the probing RF pulse. The phase difference value φ in the expression (1) is defined by the time of spreading the electromagnetic waves to the investigated subject and back:

$$\varphi = 4\pi \frac{R_1}{\lambda}, \tag{2}$$

where λ is a wavelength of oscillations filling the probing RF pulse; R_1 is a distance between the investigated subject and the sensor.

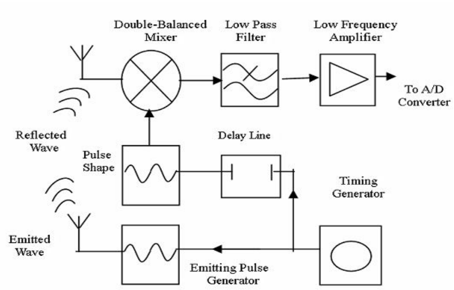

Fig. 4 The function diagram of NPNS sensing circuit

B. Signal Processing

To obtain desired artery pulse information from received signal, it is necessary to design a signal processing method based on physiological understanding. For artery pulse, the heart pumping cycle takes from 0.5-1.2 seconds of myocardial contraction and following relaxation in general adult population. Thus, the breath and motion signal can be roughly filtered out by a design *Chebyshev* filter with the frequency range from 0.8 to 2 Hz. To measure desired PWV, the two peaks, Peak1 and Peak2, measured from the proposed dual-antenna NPNS sensor, sensor1 and sensor2, are obtained by searching the value in a moving window is maxima separately and simultaneously, shown in Figure 5.

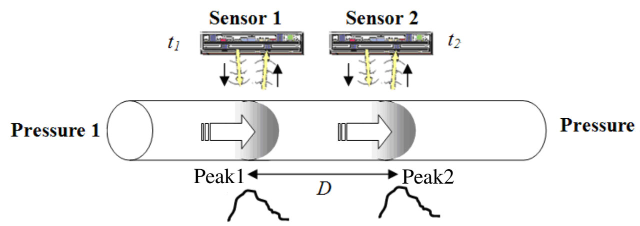

Fig. 5 Illustration of pulses measurement by proposed method

Therefore, the pulse transition time, *PTT*, is obtained from the time difference (t_2-t_1) of Peak1 and Peak2. The distance, D , of blood travelling is defined from the antenna design (5 cm), thus the blood PWV, V, can be calculated by

$$V = \frac{D}{t_2 - t_1} \tag{3}$$

According the Bernoulli's theorem, the relation between flow velocity, V, and pressure, P, is the difference of Pressure 2 and Pressure 1, can express as

$$\frac{P}{\gamma} + Z + \frac{V^2}{2g} = H_{const} \tag{4}$$

In this paper, the DBP and SBP, BP_{Dia} and BP_{Sys}, is estimated according to the blood flow information by derived equation as

$$\begin{aligned} BP_{Sys} &= a_1 \times V + b_1 \\ BP_{Dia} &= a_2 \times V + b_2 \end{aligned} \tag{5}$$

where the a_1 and a_2 are weighting factors of PWV, and the linear basis variables, b_1 and b_2, are statically calculated by the population in the experiment.

Since the proposed method is used to monitoring artery pulse signal continuously, the individual waveform of artery pulse signal is analysed, and the cardiovascular parameters are calculated in real-time. To eliminate the affect from undesirable noisy signal, such as body motion and internal disturbance, a serial continuous pulse signals are averaged, and the average process is applied to obtain a smooth signal that is used to obtain the cardiovascular parameters in long-term measurement.

III. RESULTS

With respective to the preliminary test, five healthy subjects (male; mean age = 33.5 years) were voluntarily for clinical test in this study. In the experiment design, the Colin VP-1000 (Omron Corporation) is used as a gold standard for non-invasive PWV measurement. The method records pulse waves via electrographic signal, heart sound and four pressure transducers to measure cardiovascular parameters, including pulse wave velocity, blood pressure and arteriosclerosis by PWV (Pulse Wave Velocity: an index of arterial wall stiffness) and ABI (Ankle Brachial Index: an index to assess arterial occlusion). Waveforms were referenced to a concurrently recorded ECG, and the pulse transit time was calculated from the time difference between pulse peaks (arm and leg). After the waveform recorded, distance measurements between the limb sampling sites were taken with a standard tape measure.

The proposed dual-antenna NPNS sensor is located subject's wrist without contact skin for the two pulse signals acquisition. The developed detector is shown in Figure 6. The size of the NPNS device is 10×3.5cm^2, and the built-in a Bluetooth module for wireless data transmission. By the proposed method, the artery pulses are detected and recorded simultaneously, and the signal is analyzed to reveal the PWV and blood pressure information in real-time.

Fig. 6 The proposed NPNS based dual-antenna pulse signal detection device and clinical test scenario

In the Figure 7, the PWV and blood pressure (DBP and SBP) were measured from limbs by proposed method and commercial product, respectively. As a result, the data collected from 5 subjects shows the correlation about 0.76 in the experiment.

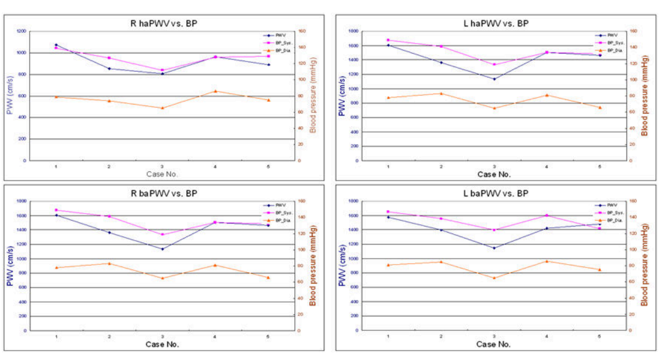

Fig. 7 The trend and correlation analysis between PWV and blood pressure

Based on the proposed equation for blood pressure estimation, the results compares to the gold standard of 5 cases was shown in Figure 8. The weighting factor a_1 = 0.84 and a_2 =0.66, and the basis variables, b_1 =6.39 and b_2 =5.29, were applied in this study. The result shows the error of DBP and SBP is 5.18±1.61 and 4.09±1.69 mmHg in average, and the correlation of DBP and SBP between estimated and gold standard is 0.66 and 0.84, respectively.

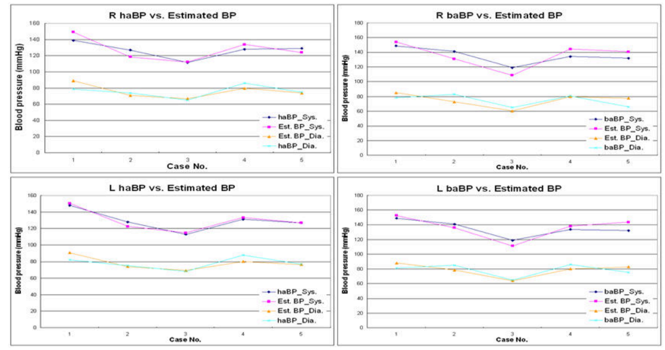

Fig. 8 Comparison results of blood pressure (DBP and SBP) measured from clinical equipment and proposed method

IV. Conclusions

In this paper, the impulse based dual-antenna NPNS radar and estimation algorithm were constructed for measuring artery pulse signal in a non-contact and non-invasive way. By this technique, the pulse wave velocity and relative blood pressure information can be easily detected and estimated in real-time. For the prospective development, integration of all functions, including sensing, signal processing and wireless data transmission, into a dedicated system can be helpful to provide long-term and continuous blood pressure monitoring for personal healthcare. In the future, the NPNS sensing technique is also potential for medical applications in clinical.

References

[1] M. E. Safar, B. I. Levy, H. Struijker-Boudier, "Current perspectives on arterial stiffness and pulse pressure in hypertension and cardiovascular diseases", *Circulation,* 2003, vol. 107, pp. 2864–2869.

[2] R. Asmar, A. Benetos, J. Topouchian, et al., "Assessment of arterial distensibility by automatic pulse wave velocity measurement: validation and clinical application studies," *Hypertension*, 1995, vol. 26, pp. 485-90.

[3] M. Y. Cortez-Cooper, J. A. Supak, H. Tanaka, "A new device for automatic measurements of arterial stiffness and ankle-brachial index," *Am J Cardiol*, 2003, vol. 91, pp. 1519-1522.

[4] I. B. Wilkinson, J. R. Cockcroft, D. J. Webb, "Pulse wave analysis and arterial stiffness," *J. Cardiovasc. Pharmacol., 1998, vol.* 32 pp. 33–37.

[5] I. B. Wilkinson, S. A. Fuchs, I. M. Jansen, et al., "Reproducibility of pulse wave velocity and augmentation index measured by pulse wave analysis," *J. Hypertens., 1998, vol.* 16, pp. 2079–2084.

[6] S. Kontis, R. G. Gosling," On-line Doppler ultrasound measurement of aortic compliance and its repeatability in normal subjects," *Clin Phys Physiol Meas.*, 1989, vol. 10, pp. 127-135.

[7] R. D. Boehmer, "Continuous, real-time, noninvasive monitor of blood pressure: Peñaz methodology applied to the finger," *J Clin Monit.,* 1987, vol. 3, pp.282–287.

[8] S. Loukougeorgakis, R. Dawson, N. Phillips, et al., "Validation of a device to measure arterial pulse wave velocity by a photoplethysmographic method," *Physiol Meas.*, 2002, vol. 23, pp. 581-596.

[9] G. E. McVeigh, C. W. Bratteli, D. J. Morgan, et al., "Age-related abnormalities in arterial compliance identified by pressure pulse contour analysis: aging and arterial compliance," *Hypertension*, 1999, vol. 33, pp. 1392-1398.

[10] J. M. Padilla, E. J. Berjano, J. Sáiz, R. Rodriguez and Fácila, " Pulse wave velocity and digital volume pulse as indirect estimators of blood pressure: pilot study on healthy volunteers.," *Cardiovasc Eng.*, 2009, vol. 9, pp. 104112.

[11] J. M. Padilla, E. J. Berjano, J. Sáiz, L. Fácila, P. Díaz, S. Mercé, "Assessment of Relationships between Blood Pressure, Pulse Wave Velocity and Digital Volume Pulse," *Computers in Cardiology*, 2006, vol. 33, pp.893−896.