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Using Nanosecond Pulse Near-field Sensing Technology for Non-contact Cardiovascular Parameters Measurement

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***Abstract*—**Clinically arterial stiffness has shown that it is the most important cause of cardiovascular complications and also an independent risk factor to several cardiovascular diseases. In routine, there are many preferable non-invasive methods, including pressure-sensitive transducers, applanation tonometry, Doppler ultrasound and MRI, to get insight of cardiovascular condition. However, the operation of traditional monitors is relied on professionals' experience, and also the sensing probes needed to exert pressure to the user directly. The measurement procedure is short-term and easy to cause discomfort. To improve the issues of these measuring techniques, the non-contact and non-invasive measuring method will become an important innovation. In this paper, the novel nanosecond pulse near-field sensing (NPNS) based screening technology, which includes radio frequency (RF) pulse transmission and a flat antenna connected to transceiver of miniature radar, is proposed to monitor cardiovascular activity. A dedicated analysis software is also provided to calculate cardiovascular parameters, including PWV, average systolic time, reflection index (RI), heart and heart rate variability (HRV), for clinical applications. To evaluate the performance, the proposed method was applied on aortic pulse measurement at the body site of chest. As a result, it shows 0.92 correlations with the measurement result from commercial product, and performs the capability of continuously 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 trials, artery stiffness has shown that it is the most important cause of cardiovascular complications and also an independent risk factor to several cardiovascular diseases such as atherosclerosis, heart stroke, myocardial infarction and renal failure [1]. Among the current non-invasive cardiovascular monitoring methods, the obtained vascular stiffness parameters present promised information; it is a measurement of the elasticity and distensibility of the vascular, and is artery wall increases the pulse velocity, and directly relative to atherosclerosis [2]. Moreover, stiffer results in an earlier return of the reflected wave from peripheral sites. Many research have shown that arterial stiffness can be assessed through the pulse wave velocity (PWV) measurement [3]-[5]. The PWV information can widely be recognized as a significant marker of arterial stiffness, 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 cardiovascular risk factor for prediction of mortality in the elderly and in patients with end-stage renal disease, diabetes mellitus, 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 arterial stiffness, and these methods have significantly improved the understanding of the physiological significance of homodynamic. Those non-invasive methods are available for artery status investigation, including local stiffness at a particular site in the artery, regional stiffness along the length of an arterial segment, and circulation artery stiffness. Measuring the PWV over the segment of interest assesses stiffness 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 Bramwell and Hill equation, PWV reveals that is related inversely to arterial distensibility; that is, the stiffer the artery, the faster the PWV. By investigating an average stiffness of the preferred local artery, PWV can provide a better reflection of the cardiovascular health status [6]. There are many developed methods can applied to assessment of artery elasticity non-invasively. When the pulse pressure and flow pulse propagate at the same velocity, the arterial pulse may be collected by using pressure-sensitive transducers [7], an oscillometric equipment [8], applanation tonometry sensor [9]-[10], Doppler ultrasound (US) probe [11] optical sensor [12]-[13], and dedicated magnetic resonance imaging (MRI) system [14]. The pulse signals which detected and collected at the two sites are obtained at the same time, or gating to the separate recordings to the R-wave from the electrocardiogram (ECG). The R-wave of ECG is used as timing reference to calculate PWV, and the tonometry and cuff pressure are used to measure the transit time of pulse from heart to limbs. The distance along which the pulse wave travels is usually estimated by direct superficial measurement between the two pressure transducers or other sensors used to detect the artery pulse signal. The transit time of the time delay between the feet of the proximal and distal pulse waves is measured, and the pulse contour analysis is used to evaluate circulation of whole-body arterial stiffness non-invasively [15]-[17]. The methods suggest the pressure characteristics of the radial pulse contour obtained by tonometry or pressure sensor, and the proposed method is

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used for analyzing the pulse waveform. Based on these characteristics, the compliance of the major and peripheral arteries can be estimated; however, the physiological relevance of the derived lumped compliance 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 is proposed for non-contact and non-invasive measurement of cardiovascular stiffness. By this method, aortic pulse signal is obtained and the contour and amplitude of the pulse waveform is 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 stiffness of the arteries. The artery pulse signal is measured directly and relative cardiovascular parameters can be calculated by the proposed method for the evaluation of cardiovascular healthy condition in clinical use.

II. Method and System

To achieve the purpose of artery pulse detection in a non-contact way, a signal processing with correlation processing system is utilized. The functioning of such systems 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 antenna. The probing signal is presented in the form of short RF pulses having comparable with a period of oscillations filling the probing pulse. 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 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 digital signal processor (DSP) and displayed on a computer terminal.

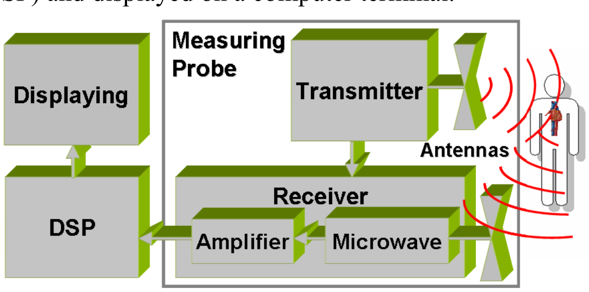

Fig. 1 Architecture of proposed NPNS based radar system for cardiovascular pulse signal detection

For measurement setup, the proposed NPNS based cardiovascular sensing technique includes a NPNS transceiver and receiver connected to a flat antenna. The NPNS sensor is put on the chest, and collect pulse signal from the aorta site, 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.

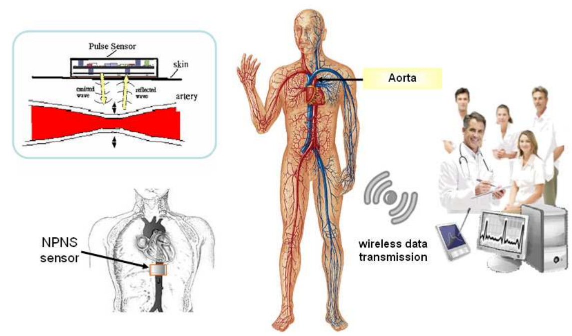

Fig. 2 Illustration of cardiovascular pulse measurement scenario

A. *Nanosecond Pulse Near-field Sensing Method*

In this paper, the nanosecond pulse near-field sensing (NPNS) technology, which comprises low power miniature radar with 1GHz Electromagnetic (EM) wave of the transmitted by the antenna RF pulse, is proposed. The measurement of signal carrying useful information performs through evaluation of a 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.

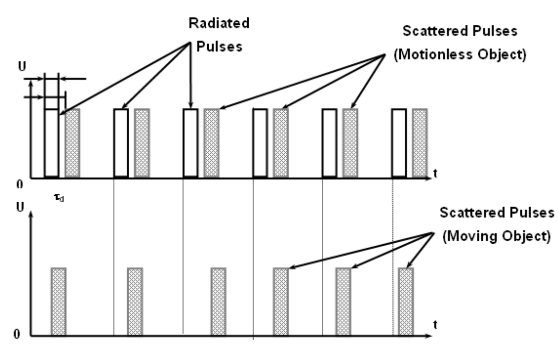

Fig. 3 Architecture of proposed UWB based intestine motility measurement

For the radar design, the radar works in interference and re-reflections conditions of signals reflected from stationary and moving objects around the body and body tissues. Time slots, opening the receiver at the moment of the input of the signal reflected from the abdominal cavity 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 1 GHz was chosen, and the functional 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:

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

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:

$$\varphi = 4\pi \frac{R_1}{\lambda}, \qquad (2)$$

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

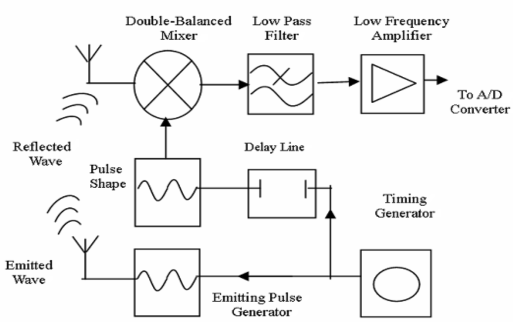

Fig. 4 The functional diagram of NPNS sensing circuit

B. Signal Processing

To obtain desired cardiovascular 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 is filtered out by a design *Chebyshev* filter with the filtering range from 0.8 to 2 Hz. To analyse artery pulse, the main characteristics of waveform have to be extracted. Here the pulse contour is assumed that it performs a *Gaussian* distribution [18]. In the waveform analysis, the major peak, P1, is obtained by searching the value in a moving window is maxima. The valley position, V_L, is estimated and symmetric contour is defined to form a main pulse waveform. The second peak, P2, can be extracted by subtracting main pulse formed by P1 from original pulse signal. The flowchart of the waveform analysis is shown in Figure 5. Once the first and second peak is obtained, the body height is divided by the time difference of these two peaks, which reveals the systolic time, to calculate the PWV at the screening aorta site. The ratio of the amplitude of P2 and P1 is defined as the Reflection Index (RI). The heart rate and heart rate variability (HRV) can also be calculated by the frequency domain analysis and the time variance of peak to peak in spatial domain, respectively.

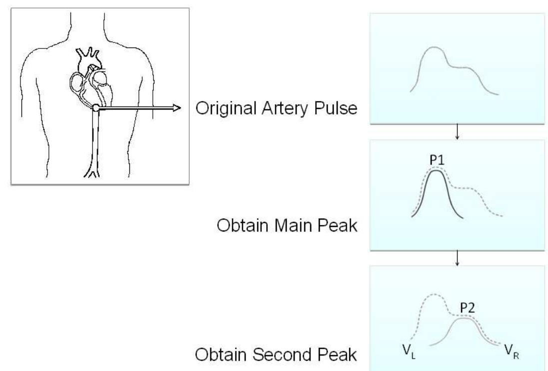

Fig. 5 The main flowchart for characteristic extraction of pulse waveform for cardiovascular pulse signal analysis

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. The example is shown in Figure 6.

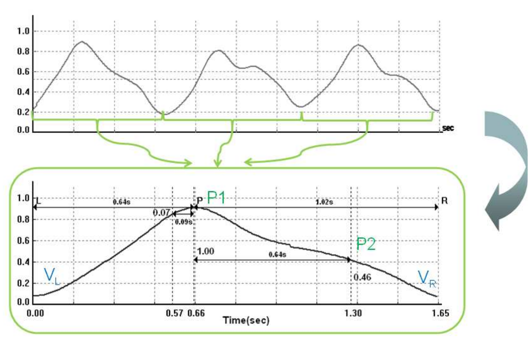

Fig. 6 The example of the cardiovascular parameter calculation from a average aortic pulse signal

III. Results

With respective to the preliminary test, three healthy subjects (male; mean age = 33 years) were voluntarily involved in this study. In the experiment design, the SphygmoCor (AtCor MEDICAL) is used as a gold standard for non-invasive PWV measurement. The method records pulse waves via piezo-electronic pressure transducers and determines the PWV. By the method, aortic PWV was determined from carotid and femoral pressure waveforms obtained non-invasively by applanation tonometry (SPT-301, Millar Instruments) using the SphygmoCorR system (SCOR; PWV Medical, Sydney, Australia). Waveforms were referenced to a concurrently recorded ECG, and the carotid-to-femoral pulse transit time was calculated from the foot-to-foot time difference between carotid and femoral waveforms. After the waveform recorded, distance measurements between the carotid and femoral sampling sites were taken with a standard tape measure. PWV was calculated by dividing the time by the estimated distance.

The proposed NPNS sensor is located subject's chest without contact skin for the signal acquisition. The developed detector and analysis software is shown in Figure7. The size of the NPNS device is 5×7cm^2, and the built-in a Bluetooth module for wireless data transmission. By the proposed method, the aortic pulse is detected and recorded simultaneously, and the signal is analyzed to reveal the cardiovascular information in real-time.

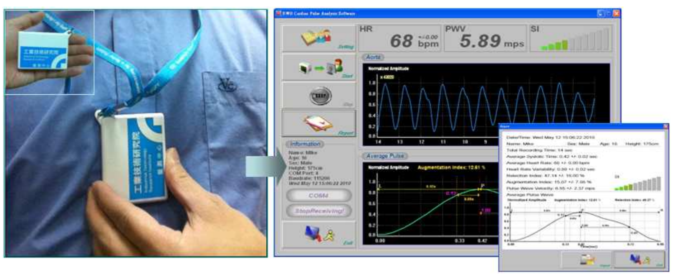

Fig. 7 The proposed NPNS based cardiovascular pulse signal detection device and data analysis software

In the Figure 8, the comparison result of PWV measurement from proposed method and AtCor MEDICAL device. As a result, the data collected from 3 subjects shows the correlation about 0.92 in the experiment.

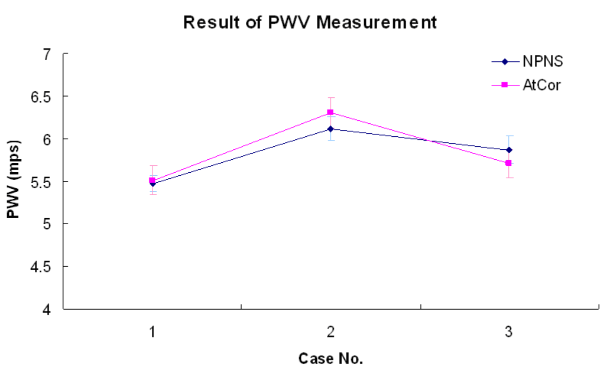

Fig. 8 Comparison Result of PWV measurement from NPNS based and AtCor devices

IV. Conclusions

In this paper, the impulse based NPNS radar and high selective digital filtering techniques were constructed for measuring artery pulse signal in a non-contact and non-invasive way. By this technique, the dynamic cardiovascular activity can be easily detected and also revealed in real-time. Regarding to performance, the method shows potential capability and the feasibility. 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 more significant diagnosis information in routine cardiovascular examination at home. In the future, the NPNS sensing technique is also potential to increase the number of transceiver for medical applications in clinical.

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