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The Ultrasound Signal Processing Based on High-Performance CORDIC Algorithm and Radial Artery Imaging Implementation

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Abstract: The radial artery reflects the largest amount of physiological and pathological information about the human body. However, ultrasound signal processing involves a large number of complex functions, and traditional digital signal processing can hardly meet the requirements of real-time processing of ultrasound data. The research aims to improve computational accuracy and reduce the hardware complexity of ultrasound signal processing systems. Firstly, this paper proposes to apply the coordinate rotation digital computer (CORDIC) algorithm to the whole radial artery ultrasound signal processing, combines the signal processing characteristics of each sub-module, and designs the dynamic filtering module based on the radix-4 CORDIC algorithm, the quadrature demodulation module based on the partitioned-hybrid CORDIC algorithm, and the dynamic range transformation module based on the improved scale-free CORDIC algorithm. A digital radial artery ultrasound imaging system was then built to verify the accuracy of the three sub-modules. The simulation results show that the use of the high-performance CORDIC algorithm can improve the accuracy of data processing. This provides a new idea for the real-time processing of ultrasound signals. Finally, radial artery ultrasound data were collected from 20 volunteers using different probe scanning modes at three reference positions. The vessel diameter measurements were averaged to verify the reliability of the CORDIC algorithm for radial artery ultrasound imaging, which has practical application value for computer-aided clinical diagnosis.

Keywords: radial artery; ultrasound signal processing; CORDIC algorithm; dynamic filtering; quadrature demodulation; dynamic range transformation



Citation: Zhang, C.; Geng, X.; Yao, F.; Liu, L.; Guo, Z.; Zhang, Y.; Wang, Y. The Ultrasound Signal Processing Based on High-Performance CORDIC Algorithm and Radial Artery Imaging Implementation. *Appl. Sci.* **2023**, *13*, 5664. <https://doi.org/10.3390/app13095664>

Academic Editors: Jürgen W. Czarske, Lars Buettner and Richard Nauber

Received: 24 March 2023

Revised: 26 April 2023

Accepted: 3 May 2023

Published: 4 May 2023



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1. Introduction

In recent years, cardiovascular disease has remained one of the leading causes of high morbidity and mortality in humans [1]. According to the pulse diagnosis theory of Traditional Chinese Medicine, the pulse converges at the radial artery [2]. It reflects the largest amount of human health information, such as heart rate, blood flow rate, etc. [3], which can assist in diagnosing physical conditions [4]. Common devices for pulse signal acquisition include piezoelectric, and photo-electronic pulse sensors [5]. However, they all have disadvantages such as high cost, low accuracy of pulse signal acquisition, and single parameter acquisition [6–8]. In addition, signal acquisition is also difficult in the radial artery due to its narrow blood vessels, abundant peripheral blood vessels, and complex tissues [9]. With the development of image-guided surgery technology and the microelectronics technique [10], ultrasound diagnosis has come into being. Medical ultrasound produces ultrasound images by emitting and receiving acoustic signals reflected from human tissues [11]. It has been widely used in clinical diagnosis due to its advantages of low cost, high sensitivity, safety, non-destructiveness, and intuitiveness [12]. Therefore, it has unique advantages in detecting radial artery ultrasound signals for disease diagnosis.

Additionally, more accurate algorithms can be further developed to help doctors obtain accurate human information from ultrasound images [13].

With the development of ultra-large array sensor technology, multi-channel signal acquisition and processing are the characteristics of ultrasound technology. The real-time and accuracy of big data processing will directly affect the ultrasound imaging effect. Currently, most ultrasound signal processing methods are derived from signal processing techniques used in wireless communications or elsewhere. Given the collection and processing modes of ultrasound signals, this article can be analyzed from filtering, envelope detection, and compression techniques [14]. For example, Lu et al. used the concept of adaptive filters to improve the signal-to-noise ratio of the system [15]. In [16,17], Xu et al. adopted an adaptive robust Kalman filtering algorithm to address the impact of non-Gaussian noise on navigation systems. For envelope detection, Liu et al. performed inverse modulation and re-modulation processing to assimilate the Doppler distortion pattern of the acoustic signal [18]. Assef A A et al. proposed the modeling and FPGA implementation of an efficient envelope detector based on the Hilbert transform approximation for medical ultrasound imaging applications [19]. In [20], Zhang et al. implemented data compression of image pixels based on FPGA lookup tables. A large number of sine and cosine, square root, and logarithmic operations are involved in the process of ultrasound signals. The main solving methods are the polynomial expansion method and the lookup table method [21]. The polynomial expansion saves ROM resources but has a high calculation delay. The FPGA lookup table can meet the real-time requirements of the output results, but it wastes a lot of hardware resources and does not solve some key functions or algorithms efficiently [22]. Therefore, for the radial artery ultrasound system, selecting appropriate data processing and calculation methods is the key to improving the data processing speed and accuracy of the FPGA module, thus reducing the system development cost and improving the imaging resolution and stability of the radial artery ultrasound system.

The coordinate rotation digital computer (CORDIC) can be a good solution to the above problem. The basic idea is to use a series of angles related to the base of the operation to continuously rotate and approximate the desired rotation angle [23,24]. It allows complex functions to be decomposed into shift and add subtract operations, providing higher accuracy and lower hardware complexity [25,26]. Currently, the CORDIC algorithm is mainly applied to beam-forming technology and coordinate scanning transformation technology in ultrasound. For example, Tang et al. proposed an efficient and non-iterative radix-8 CORDIC algorithm to solve the problem of low-delay and high-efficiency calculation of sine-cosine or phase-shift function in digital beam-forming [27]. Li et al. adopted a high-precision modified coordinate correction pipeline CORDIC algorithm to realize coordinate transformation and difference at the same time, improving the accuracy and image quality of coordinate transformation of the ultrasonic endoscope [28]. Few studies have used the CORDIC algorithm in the overall medical ultrasound signal processing. This paper proposes a method for processing radial artery ultrasound signals based entirely on the CORDIC algorithm. However, due to the large number of iterations and resource consumption of the traditional CORDIC algorithm [29,30], it is not applicable when the hardware and software resources of the ultrasound system are limited. Therefore, this paper introduces various high-performance CORDIC algorithms and designs a dynamic filtering module based on the radix-4 CORDIC algorithm, a quadrature demodulation module based on the partitioned-hybrid CORDIC algorithm, and a dynamic range transformation module based on the improved scale-free CORDIC algorithm, according to the characteristics of the three stages of radial artery ultrasound signal processing. Finally, the paper demonstrates the accuracy and effectiveness of the high-performance CORDIC ultrasound signal processing algorithm based on FPGA. The radial artery diameters of 20 subjects were measured to verify the practical application of the algorithm. To sum up, this paper not only introduces the CORDIC algorithm through the whole radial artery signal processing process but also uses various high-performance CORDIC algorithms to optimize the data processing algorithm, thus ensuring the accuracy of the calculation. This

method provides a new idea for ultrasonic signal processing of radial artery, which can further measure the diameter of blood vessels, analyze the physiological and pathological information such as blood flow and blood pressure of radial artery, and has practical application value for clinical diagnosis.

2. Materials and Methods

2.1. Radial Artery Ultrasound Imaging System

The radial artery ultrasound imaging system comprises six parts: probe, transmit-receive circuit, beamforming, signal processing, image processing, and host computer. The block diagram of the radial artery ultrasound imaging system is shown in Figure 1. FPGA is the core of the entire ultrasound system. When the system is turned on, FPGA receives the control parameters transmitted from the host computer and sets up the beamforming, signal processing, image processing, and other modules via the bus. Each module initializes and starts the ultrasonic scanning procedure. First, the FPGA system control module sends a start signal to the transmitting beam control module, which controls the opening and closing of the high-voltage switch. The high-voltage pulse signal excites the probe to generate ultrasonic pulse waves, and the transmitting beam control module enables it to receive the permissive signal. The system control module outputs the digital signal when the received allowed signal is valid and starts the beamforming module simultaneously. After beamforming, dynamic filtering, envelope detection, and dynamic range transformation are performed by the signal processing module. The processed ultrasound data is transmitted to the image processing module and finally uploaded to the host computer via USB to display the radial artery ultrasound image.

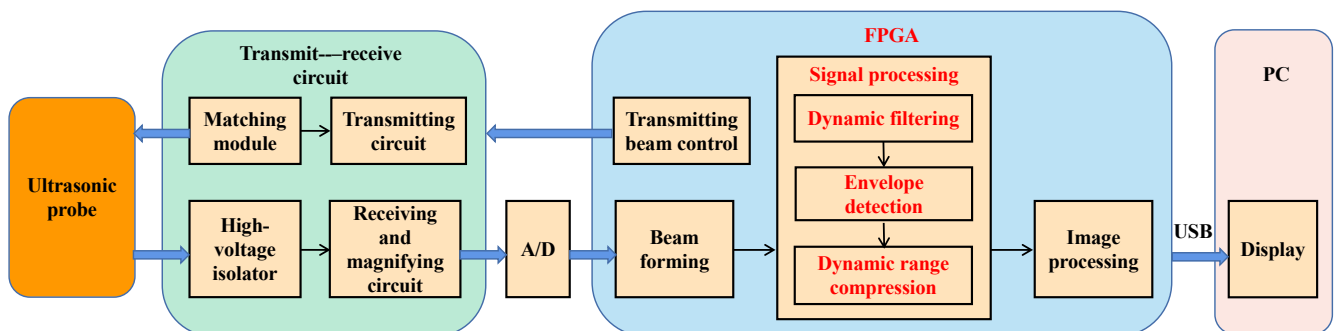


Figure 1. Block diagram of radial artery ultrasound imaging system.

2.2. Ultrasound Signal Processing

Ultrasonic signal processing mainly includes dynamic filtering, envelope detection, and dynamic range transformation [31]. The ultrasonic signal will have different degrees of attenuation as the detection depth of the human body increases, and dynamic filtering can extract the signal with diagnostic value so that the image has the best resolution over the entire depth range [32]. To further use the amplitude information of the signal for imaging, envelope detection is required [33]. As the general gray-scale display image has only 256 levels, it is impossible to display all ultrasound signals after envelope detection. The data can be compressed to 8 bits by logarithmic compression [34]. In this paper, FPGA parallel pipeline calculation and complex function hardware solution based on the CORDIC algorithm are used to accelerate the radial artery ultrasound signal processing and improve the data processing accuracy, thus giving play to the important application value of the CORDIC algorithm in radial artery ultrasound signal processing. Figure 2 shows the flow diagram of radial artery ultrasound signal processing.

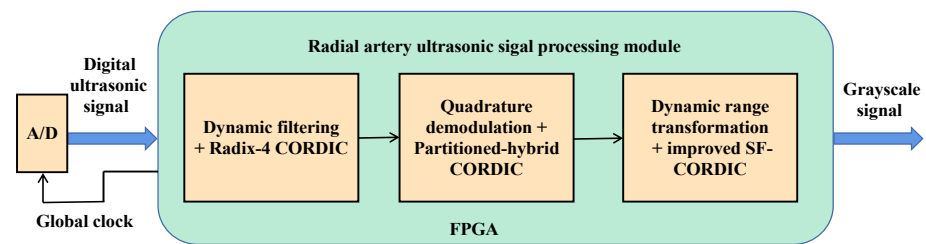


Figure 2. Flow diagram of radial artery ultrasonic signal processing.

2.2.1. Dynamic Filtering Module Based on the Radix-4 CORDIC Algorithm

This paper adopts a set of 33rd-order dynamic finite impulse response (FIR) filters with a sampling frequency of 100 MHz, a probe with a bandwidth of 1 MHz, and an initial ultrasonic echo signal with a center frequency of 3.5 MHz. Assuming that the cut-off frequency is ω_c , the filter order is N , and the filter coefficients are designed with the Hamming window. According to [35,36], the calculation formula of the filter coefficient can be determined as shown in Equation (1).

$$h(n) = \begin{cases} \frac{\sin[\omega_c(n-\tau)]}{\pi(n-\tau)} \cdot (0.54 - 0.46 \cdot \cos(\frac{2n\pi}{N-1})) \cdot R_N(n) & n \neq \tau \\ \frac{\omega_c}{\pi} \cdot (0.54 - 0.46 \cdot \cos(\frac{2n\pi}{N-1})) \cdot R_N(n) & n = \tau \end{cases} \quad (1)$$

where $\tau = \frac{N-1}{2}$. From Equation (1), the process involves a large number of sine and cosine functions and multiplication operations. The radix-4 CORDIC algorithm is used to compute high-precision sine and cosine functions. Compared with the traditional radix-2 CORDIC algorithm, the number of iterations is reduced by half, the computation delay is low [37,38], and it is suitable for pipeline structure implementation, providing a new way to solve the filter coefficients dynamically and in real-time, thus saving ROM storage resources and improving the computation accuracy of the filter coefficients. This paper uses the idea of modularization to design dynamic FIR filters. The block diagram of the dynamic FIR filter design is shown in Figure 3. The phase-locked-loop (PLL) module is used to multiply the 50 MHz clock input to a sampling frequency of 100 MHz. The relevant parameters are input into the radix-4 CORDIC operating module. The pipeline structure is adopted to increase speed. The reading of the 17 filter coefficients is controlled by a FIFO controller and a multiplexer. The FIR filter module adopts a parallel distributed architecture. It can reduce the resource consumption of the lookup table by dividing the unified lookup table into smaller lookup tables [39]. For a 33rd-order filter, four ROM tables are required, and the ROM addresses vary with the receiving depth, resulting in different filter coefficients.

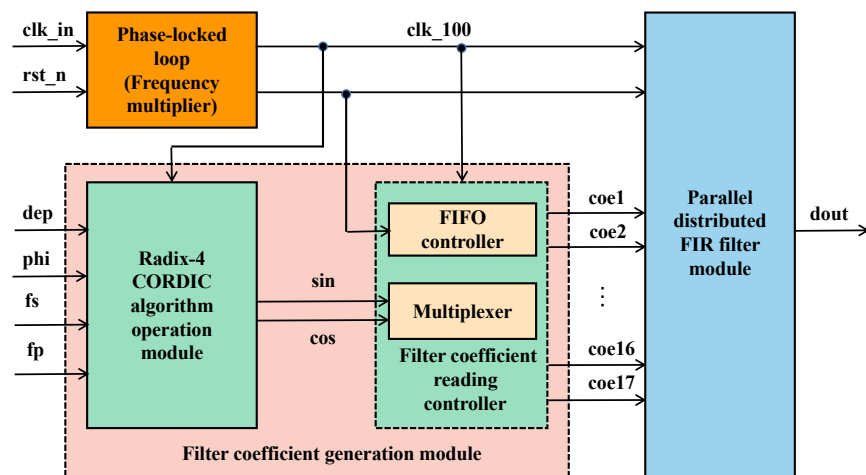


Figure 3. Block diagram of the dynamic finite impulse response (FIR) filter design.

2.2.2. Quadrature Demodulation Module Based on the Partitioned-Hybrid CORDIC Algorithm

The dynamically filtered signal not only reflects the tissue impedance characteristics. It also carries the delay of the different echo phases. This paper uses quadrature demodulation for envelope detection, splitting the signal into I and Q, then mixing and re-superimposing I and Q with the local oscillator signal at 90° phase difference, thus eliminating the echo phase effect [40,41]. Therefore, the module focuses on the square root operation. The most common implementation methods include successive approximation algorithms, non-redundant square algorithms, etc., but they consume lots of resources and have a long computation cycle [42]. This paper uses the partitioned-hybrid CORDIC algorithm for the square root operation. It can calculate the amplitude and angle of the signal I and Q with a simple addition and subtraction iteration. The block diagram of the quadrature demodulation is shown in Figure 4. The requested angle consists of two parts: the coarse angle and the fine angle. The coarse rotation and fine rotation are performed by the CORDIC processor I and CORDIC processor II, respectively [43,44]. By using a hierarchical pipeline, the first level of coarse operations and the second level of fine operations can be performed simultaneously. The CORDIC operations on the first third of the iterations and the remaining deviations are performed by processor I, while the intermediate rotation vector is passed to processor II. The first-level module derives the coarse values, which are then used as input values for the second-level modules. This method can reduce the delay in ROM-based coarse operations and improve the efficiency and accuracy of results. The block diagram of the partitioned-hybrid CORDIC algorithm is shown in Figure 5.

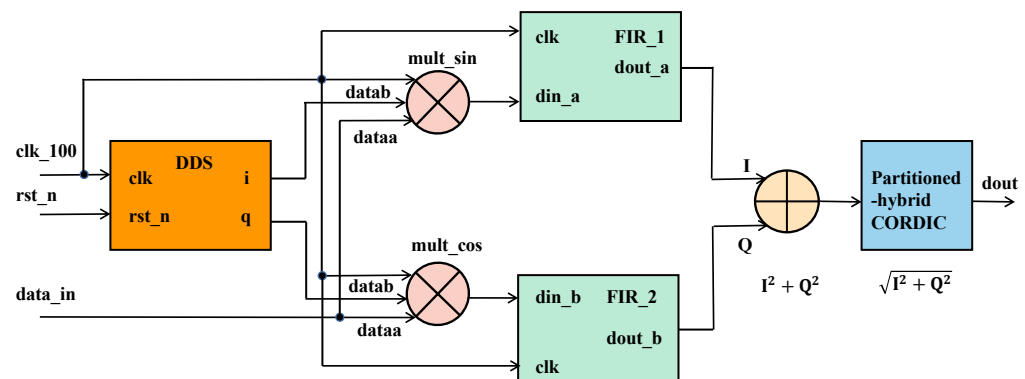


Figure 4. Block diagram of the quadrature demodulation implementation.

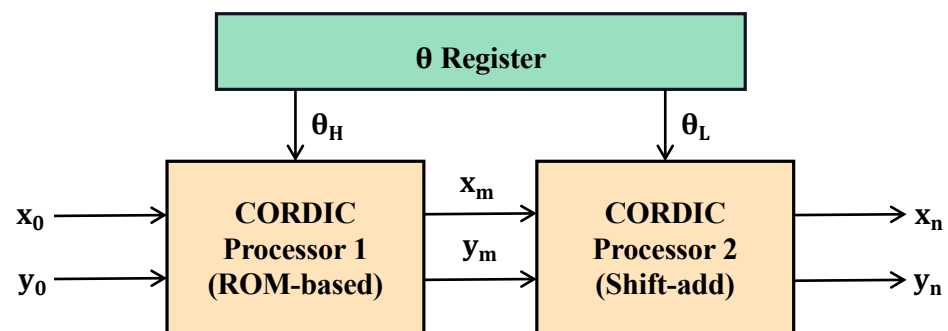


Figure 5. Block diagram of the partitioned-hybrid coordinate rotation digital computer (CORDIC) algorithm.

2.2.3. Dynamic Range Transformation Module Based on the Improved Scale-Free CORDIC Algorithm

There are certain shortcomings in the commonly used hardware implementations for dynamic range transformation. For example, the memory cell of the table lookup method increases exponentially with increasing precision, and the Taylor series expansion

method requires a large hardware area [45]. In contrast, the scale-free CORDIC algorithm in hyperbolic coordinates can implement logarithmic operations and has no scale factor, low algorithm complexity, and a simple structure that is easy to implement [46,47]. However, due to the high number of iterations and the high computational delay, it is only suitable for applications with low requirements for real-time performance [48]. In hyperbolic coordinates, assuming that after the i -th rotation, the vector (x_i, y_i) rotated by an angle α_i yields the vector (x_{i+1}, y_{i+1}) , the corresponding relationship between the two coordinates is as follows [49,50]:

$$\begin{bmatrix} x_{i+1} \\ y_{i+1} \end{bmatrix} = K_i \begin{bmatrix} 1 & \delta_i \tanh \alpha_i \\ \delta_i \tanh \alpha_i & 1 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \quad (2)$$

where $K_i = \cosh \alpha_i$, the direction of micro rotation of the vector is $\delta_i \in \{1, -1\}$. Let the micro rotation angle $\alpha_i = \tanh^{-1}(2^{-i})$ simplify the calculation.

Aggarwal S. et al., validated that when the angle $\alpha \in [0, 7\pi/88]$, the sine and cosine functions in the scale-free CORDIC algorithm can take a 3rd-order approximation of the McLaughlin series expansion, thus meeting the accuracy requirements for a given word length [51]. Therefore, this paper uses an improved scale-free CORDIC algorithm to solve the logarithm function and selects the 3rd-order approximation of the Maclaurin series expansion of the sine and cosine functions to ensure real-time logarithmic operation of ultrasound signals. The block diagram of the improved scale-free CORDIC algorithm is shown in Figure 6, including the iterative processing module and the angle accumulation module. Assuming that b represents the word length, the target angle $\theta = \sum_i \delta_i \alpha_i$, $i = 2, 3, \dots, b$, the micro-rotation angle $\alpha_i = 2^{-i}$, the third-order coefficients of the function expansion $M_i = (3!)^{-1}$, the iteration equation in hyperbolic coordinates is:

$$\begin{bmatrix} x_{i+1} \\ y_{i+1} \end{bmatrix} = \begin{bmatrix} 1 + \delta_i \cdot 2^{-i} \alpha_i & \delta_i (\alpha_i + M_i \cdot \alpha_i^3) \\ \delta_i (\alpha_i + M_i \cdot \alpha_i^3) & 1 + \delta_i \cdot 2^{-i} \alpha_i \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \quad (3)$$

To reduce the number of adders, when $i > 2$, $M_i = 2^{-3}$. When $i \geq (b-1)/2$, $2^{-i} \alpha_i^2 = 0$ and $\alpha_i^3 = 0$, the iterative operations are simplified. Making the initial rotation angle $z_0 = |\theta|$, $z_{i+1} = z_i - \delta_i \cdot 2^{-i}$, the corresponding value of δ_i is determined by the binary code of z_0 . Therefore, by appropriately selecting the approximate order of the McLaughlin expansion of the sine and cosine functions, the iterative calculation of the path in the CORDIC algorithm can be omitted, thus improving the accuracy and speed of data processing.

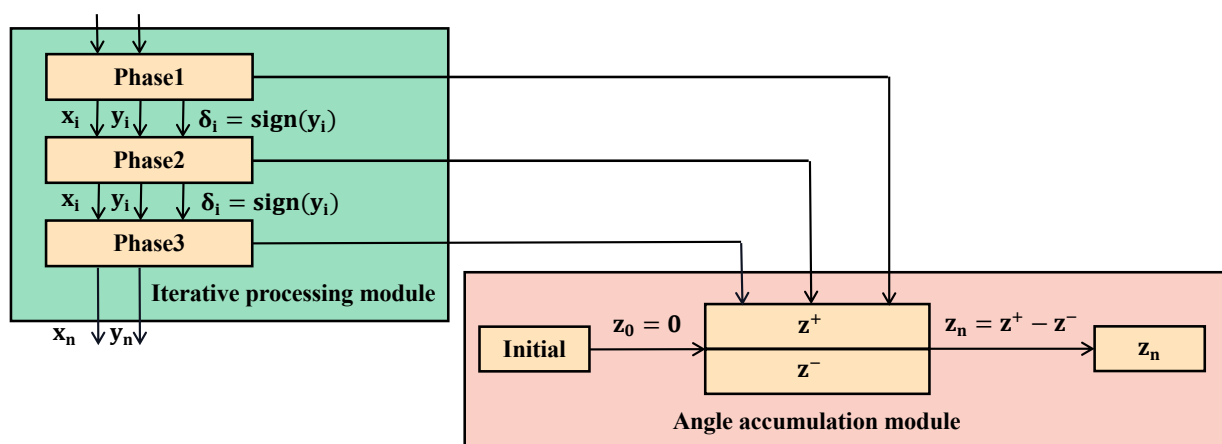


Figure 6. Block diagram of the improved scale-free CORDIC algorithm.

3. Results and Discussions

3.1. Experimental Setup

In this paper, an experimental platform for radial artery ultrasound imaging based on FPGA was built, as shown in Figure 7. The experiment used a 128-channel ultrasound probe with a center frequency of 3.5 MHz, with a MAX4940 chip as the transmitter module and an AFE5805 chip as the receiver module. The FPGA was used as a controller and signal processor for the transmission, acquisition, storage, processing, and display of the radial artery ultrasound signal. The processed ultrasound data were finally read out from the hardware via the USB driver, and the radial artery ultrasound images were displayed on the host computer for analysis. A list of the main parameter settings for the ultrasound system is given in Table 1.

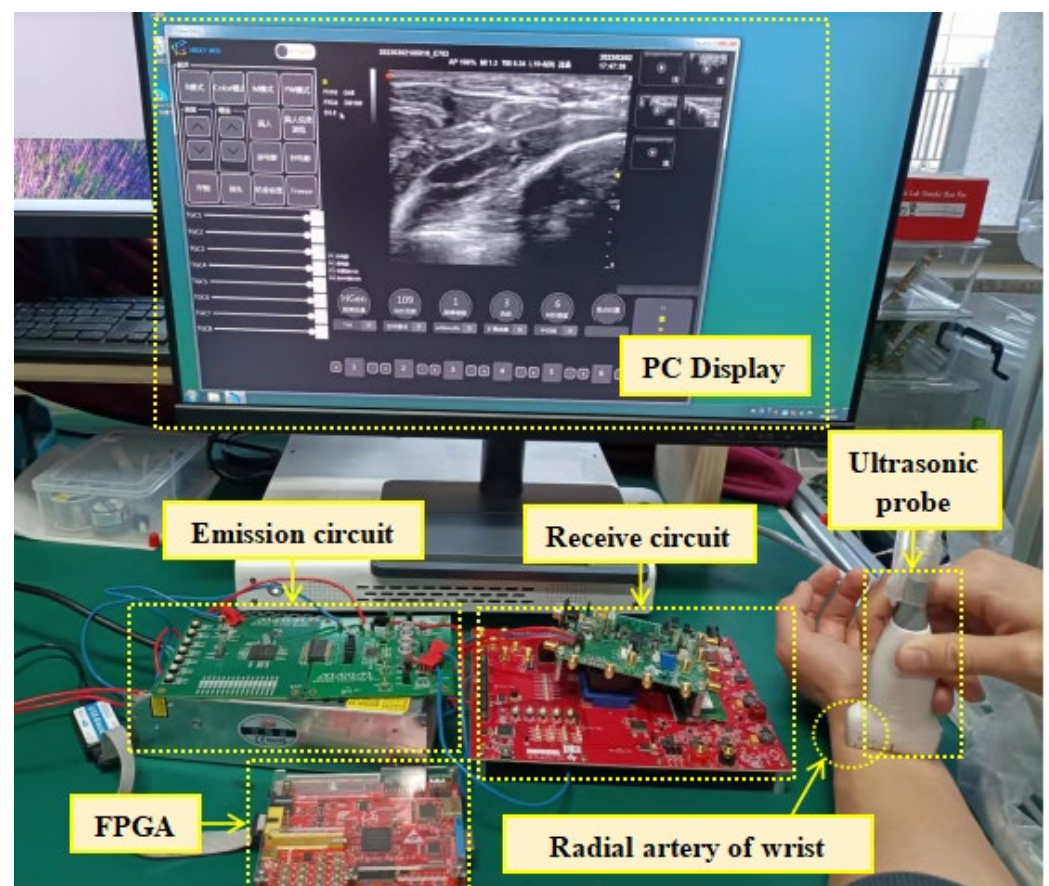


Figure 7. Experimental platform of digital radial artery ultrasound imaging system based on FPGA.

Table 1. The main parameter settings for the ultrasound system.

Name	Parameter
Digital frequency	100 MHz
Array elements center spacing	0.8 mm
Array elements length	10 mm
Transmitting focus delay accuracy	2.5 ns
Maximum detection depth	10 mm
Detection width	8 cm
Scanning method	Receive/transmit interval scanning
Transmitting pulse width	190 mm

3.2. Accuracy Verification of CORDIC Algorithm

3.2.1. Dynamic Filtering

First, verify the output accuracy of the dynamic filter coefficient generation module based on the radix-4 CORDIC algorithm on FPGA. A set of 33rd-order low-pass FIR filter coefficients is generated by Equation (1) based on the radix-4 CORDIC algorithm. Additionally, the filter coefficients with the same parameters as theoretical values are produced by the filter-Designer toolbox in MATLAB software (version number R2021b). Figure 8a shows the comparison of the 33rd-order FIR filter coefficients generated by radix-4 CORDIC and filter-Designer, the coefficients of both are close to each other; Figure 8b shows the error of the output filter coefficients of the radix-4 CORDIC algorithm, it can be seen from the figure that the error of the output filter coefficients of the radix-4 CORDIC algorithm does not exceed 4×10^{-3} , which meets the requirement of FIR filtering accuracy in radial artery ultrasound signal processing.

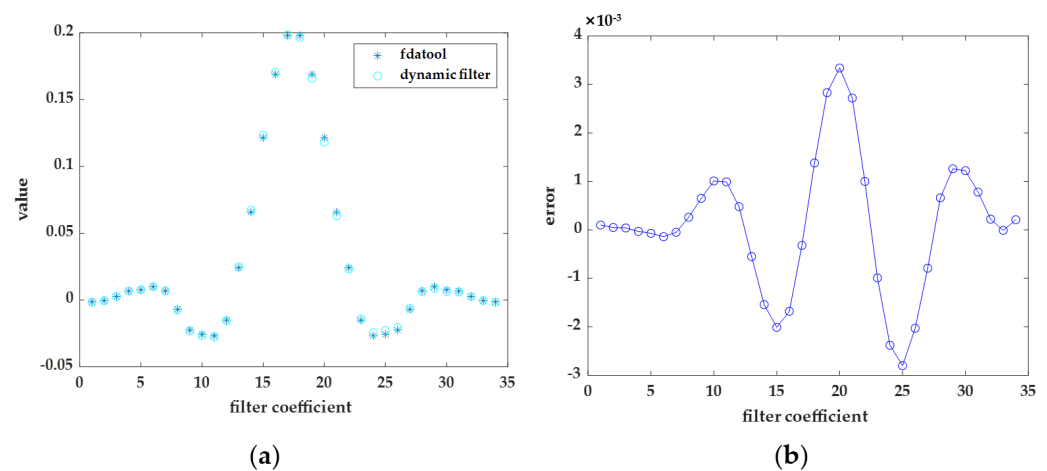


Figure 8. Accuracy of dynamic FIR filter coefficients based on the radix-4 CORDIC algorithm. (a) The comparison of the 33rd-order low-pass FIR filter coefficients generated by the radix-4 CORDIC and filter-Designer; (b) The error of the output filter coefficients of the radix-4 CORDIC algorithm.

Next, the distributed FIR filtering module is analyzed. The design idea is first to simulate a single-point frequency superimposed input signal and a white noise input signal. The simulated input is then used as a test input, and the filter output is simulated. Finally, the output signal of the filter is analyzed, and the time domain and spectrum diagram of the input/output signal are compared. The test results of the dynamic FIR filtering performance based on the radix-4 CORDIC algorithm are shown in Figure 9. The time domain waveform and spectrum before and after filtering of a single-frequency signal synthesized by the FPGA simulation are shown in Figure 9a,c, respectively. The original signal is a mixed signal of 100 Hz, 300 Hz, 600 Hz, 800 Hz, 1200 Hz, and 1400 Hz. The sampling frequency is 3000 Hz, and the cut-off frequency is 400 Hz. It can be seen that the filtered synthesized single-frequency signal has been transformed into a regular single-frequency signal with a frequency of 100 Hz. Figure 9b,d show the time domain waveform and spectrum of the FPGA simulation of the white noise signal before and after filtering, respectively. The trend of the white noise in the time domain after filtering is significantly moderated, i.e., the high-frequency signal component is filtered out. Therefore, the dynamic low-pass FIR filtering based on the radix-4 CORDIC algorithm can effectively filter out high-frequency signals while retaining low-frequency signals, achieving a stop-band attenuation of more than -50 dB. It demonstrates the superiority and practical application of the CORDIC algorithm to the dynamic FIR filtering technology of ultrasound systems, with good filtering and clinical diagnostic effects.

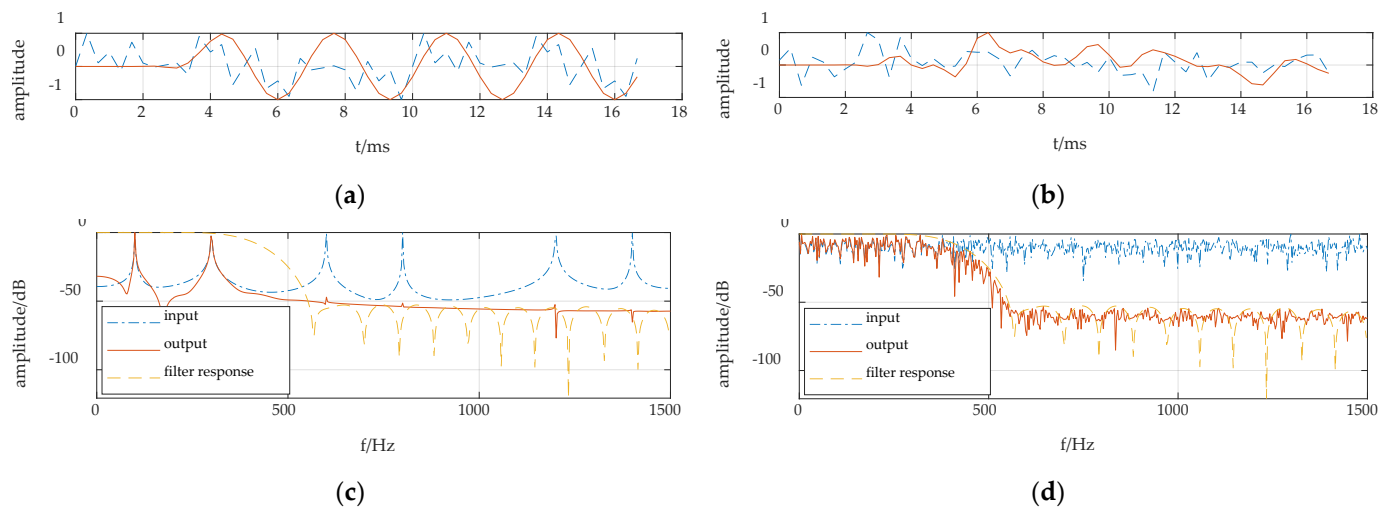


Figure 9. Test results of the dynamic FIR filtering performance based on the radix-4 CORDIC algorithm. (a) FPGA simulation of time-domain waveform before and after filtering of synthetic single-frequency signals; (b) FPGA simulation of time-domain waveform before and after filtering of white noise signal; (c) FPGA simulation of the spectrum before and after filtering synthetic single-frequency signals; (d) FPGA simulation of the spectrum before and after filtering white noise signal.

3.2.2. Quadrature Demodulation

To specifically test the performance of the simulation results, some sampling points can be taken on the simulation curve and then compared with the theoretical values to calculate the absolute error values. The absolute error distribution of the MATLAB square root simulation based on the partitioned-hybrid algorithm is shown in Figure 10a. The square root operation based on the partitioned hybrid CORDIC algorithm can achieve absolute error values below 2.5×10^{-4} . To further verify the reliability of the algorithm's accuracy, the same sampling points on the Model Sim simulation plot are selected for data reading and then analyzed for absolute error value magnitude. The ModelSim square root simulation data based on the partitioned hybrid CORDIC algorithm is shown in Table 2. The absolute error value of the Model Sim square root simulation results is in the order of 10^{-3} , which is significantly larger than the MATLAB simulation results. The two main reasons for this phenomenon can be explained as follows:

1. During the FPGA simulation, 16-bit wide data is used that can be accurately represented in MATLAB. This process introduces quantization errors, especially in the quantization of the calibration factor, which can have a large impact on the final results.
2. The number of pipeline stages is limited. Considering the complexity of programming and the consumption of internal resources of the FPGA, the number of pipeline stages is 7, which affects the accuracy to some extent.

For the 8-bit gray-scale image of the radial artery ultrasound system, the error is extended to the 8-bit range, i.e., $10^{-3} \times 2^8 = 0.256 < 1$. Since it is less than 1 bit, the error is undetectable in this digital resolution system, so the output accuracy of the orthogonal demodulation module can meet the requirements of the ultrasound imaging system.

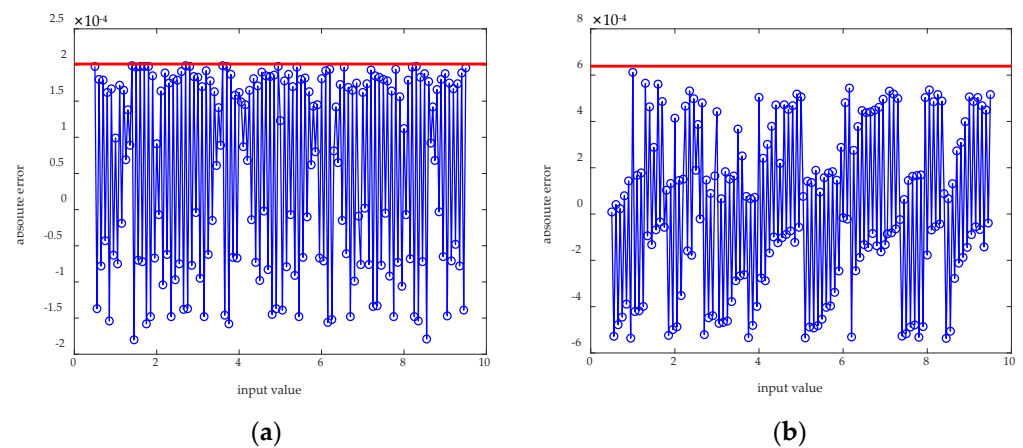


Figure 10. (a) Absolute error distribution of the MATLAB square root simulation based on the partitioned–hybrid algorithm. (b) Absolute error distribution of the MATLAB logarithmic simulation based on the improved scale–free CORDIC algorithm.

Table 2. ModelSim square root simulation data based on the partitioned–hybrid CORDIC algorithm.

Input Value	Theoretical Value	Partitioned-Hybrid CORDIC Value	Absolute Value
1	1.0000	0.9946	5.4×10^{-3}
2	1.4142	1.4047	9.5×10^{-3}
3	1.7321	1.7402	8.1×10^{-3}
4	2.0000	1.9959	4.1×10^{-3}
5	2.2361	2.2322	3.9×10^{-3}
6	2.4495	2.4581	8.6×10^{-3}
7	2.6458	2.6426	3.2×10^{-3}
8	2.8284	2.8352	6.8×10^{-3}

3.2.3. Dynamic Range Transformation

The absolute error distribution of the MATLAB logarithmic simulation based on the improved scale-free CORDIC algorithm is shown in Figure 10b. As can be seen from the figure, the module can achieve absolute errors below 7.0×10^{-4} . To further verify the accuracy of the algorithm, similarly, select the sampling points on the ModelSim simulation diagram to read the data and then analyze the absolute error. Table 3 shows the ModelSim logarithmic simulation data based on the improved scale-free CORDIC algorithm. The absolute error of the ModelSim logarithmic simulation is in the order of 10^{-3} , which is significantly larger than the MATLAB simulation results, mainly due to the influence of the number of data bit widths or the number of pipeline stages. In summary, logarithmic compression based on the improved scale-free CORDIC algorithm can achieve better accuracy.

Table 3. ModelSim logarithmic simulation data based on the improved scale–free CORDIC algorithm.

Input Value	Theoretical Value	Improved Scale-Free CORDIC Value	Absolute Value
1	0	0.0031	3.1×10^{-3}
2	0.6932	0.6991	5.9×10^{-3}
3	1.0986	1.1043	5.7×10^{-3}
4	1.3863	1.3877	1.4×10^{-3}
5	1.6094	1.6125	3.1×10^{-3}
6	1.7918	1.7985	6.7×10^{-3}
7	1.9459	1.9517	5.8×10^{-3}
8	2.0794	2.0866	7.2×10^{-3}

3.2.4. FPGA Simulation and Testing

To verify the implementation effect of the ultrasonic signal processing technology based on the high-performance CORDIC algorithm on FPGA, the FPGA development programming software Quartus II 13.1 was used for simulation. The chip was Cyclone IV series EP4CE15F17A7, and the simulation clock frequency was 100 MHz, using a pipeline structure for hardware acceleration. The hardware resource utilization of ultrasonic signal processing technology based on the high-performance CORDIC algorithm comprehensively realized on FPGA is shown in Table 4. As can be seen from the statistics table, the key resources, such as LUT, RAM, and FF, are still relatively free, and there is plenty of space for resource expansion. Under the premise of ensuring the computational speed and accuracy to meet the application requirements, the ultrasonic signal processing technology based on the high-performance CORDIC algorithm greatly reduces the cost of storage resources, makes full use of FPGA parallel processing to improve the data processing ability, and meets the requirements of ultrasonic system resource design. In addition, at an operating temperature of 24.7 °C, the overall power consumption of the system logic was only 1.673 W after being implemented on the FPGA chip layout.

Table 4. The hardware resource utilization of ultrasonic signal processing technology is based on the high-performance CORDIC algorithm.

Resource	Utilization	Available	Utilization %
Logic elements	1232	15,408	8%
Register	924	15,408	6%
Embedded memory	15,482	516,096	3%
Embedded multipliers	2	56	3%
Pins	64	166	39%

3.3. Validation of CORDIC Algorithm

After signal processing, the ultrasonic data of the radial artery were stored in the RAM. The upper computer reads the ultrasonic data from the hardware via the USB driver, forming a frame of ultrasonic data. The image of the radial artery of the wrist of a healthy adult male displayed on the upper computer without signal processing is shown in Figure 11. As shown in the figure, the background is relatively bright, the noise is relatively high, and the contrast of the radial artery contours is not very clear. It does not achieve the effect of distinguishing different media, filtering out the noise, amplifying small signals, and suppressing large signals. Additionally, the image of the radial artery in the wrist of the same healthy adult male displayed on the host computer after ultrasound signal processing is shown in Figure 12. Compared to Figure 11, the result shows a wealth of clear blood flow information, with weak echoes from other stationary tissues, such as the vessel wall, and a relatively obvious delineation between blood and fixed tissue without artifacts. In summary, after the signal processing module based on the high-performance CORDIC algorithm, the image has high brightness and good imaging quality, which helps to observe blood flow in real-time and assist in disease diagnosis, basically meeting the requirements of ultrasound imaging work. Although the upper edge of the blood vessel wall is not very clear, it has little effect on the observation and diagnosis of blood vessel images. Image processing techniques can be studied to further improve image quality. The difference in vessel diameters obtained by scanning the probe parallel and perpendicular to the radial artery vessels is approximately 0.03 mm. In this way, it can indirectly verify the effectiveness of the high-performance CORDIC algorithm used in radial artery ultrasound signal processing in this paper.



Figure 11. Ultrasound image of the radial artery in the wrist of a healthy adult male without signal processing. (a) Probe scanning direction parallel to the vessel; (b) Probe scanning direction perpendicular to the vessel.

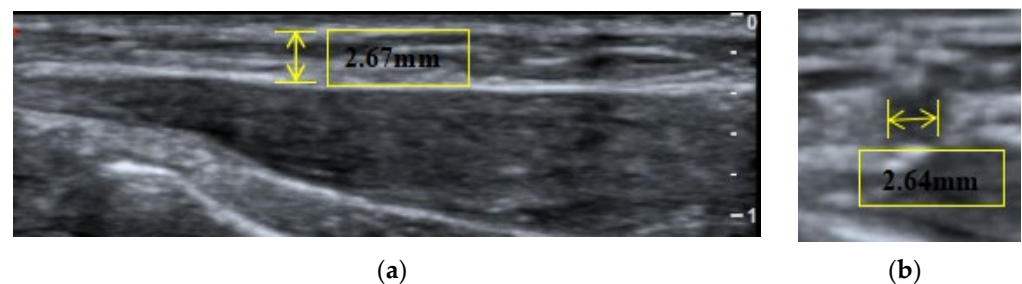


Figure 12. Ultrasound image of the radial artery in the wrist of the same healthy adult male after signal processing. (a) Probe scanning direction parallel to the vessel; (b) Probe scanning direction perpendicular to the vessel.

To ensure the repeatability and reliability of the experiment, twenty volunteers, including ten males and ten females, were selected to participate in this experiment. The basic physiological data of the subjects are shown in Table 5. After each subject completed one radial artery data acquisition, the left wrist was removed, and the next acquisition was performed, with each acquisition held in a consistent position. The radial artery data were collected six times for each subject, with the probe taken three times parallel and three times perpendicular to the radial artery at the positions of three reference points, respectively [52]. Finally, the average values of the measured data were calculated as the final diameter of the radial artery. The comparison of radial artery diameters in subjects with different probe scanning modalities is shown in Figure 13. Note that the radial artery diameters measured in the parallel and perpendicular vessel directions of the probe are almost identical, with the radial artery diameters ranging from 2.51 to 3.02 mm in males and 2.20 to 2.63 mm in females, which is consistent with the actual radial artery diameters in humans [53]. The result also verifies the effectiveness of applying ultrasound signal processing technology based on the high-performance CORDIC algorithm for radial artery ultrasound imaging.

Table 5. Basic physiological data of the subjects.

Characteristic (Unit)	Number or Mean $\pm$ SD
Number (n)	20
Age (year)	30 ± 5.8
BMI (kg/m^2)	21.2 ± 1.4
Bp _{systolic} (mmHg)	121.0 ± 6.3
Bp _{diastolic} (mmHg)	71.0 ± 6.2
Heart Rate (beats/min)	71.2 ± 5.6

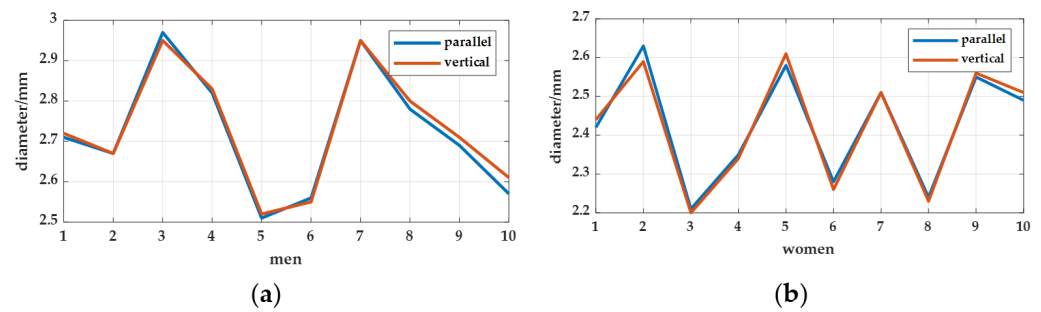


Figure 13. Comparison of radial artery diameters in subjects with different scanning modalities of the probe. (a) Men; (b) Women.

4. Conclusions

The radial artery contains the richest physiological and pathological information related to the entire circulatory system of the human body. Since traditional digital signal processing methods cannot process large amounts of ultrasound data in real time, and the CORDIC algorithm is superior in calculating complex functions, this paper applies the CORDIC algorithm to the entire ultrasound signal processing. Considering the shortcomings of the classical CORDIC algorithm and the computational requirements of the signal processing, this article focuses on the research of dynamic filtering technology based on the radix-4 CORDIC, quadrature demodulation technology based on the partitioned-hybrid CORDIC algorithm, and dynamic range transformation technology based on the improved scale-free CORDIC algorithm. The accuracy of each module's algorithm is then verified separately based on the FPGA. The filter coefficient error of the dynamic FIR filtering module does not exceed 4×10^{-3} , can effectively filter out high-frequency signals, retain low-frequency signals, remove noise, and achieve a stop-band attenuation of over -50 dB with a good filtering effect. The absolute error in the square simulation results is of order 10^{-3} , and the absolute error of the logarithmic simulation is of order 10^{-3} . So the accuracy of the data processed by each module can meet the requirements of ultrasound imaging. To ensure the repeatability and reliability of the experiment, the probe is positioned parallel and perpendicular to the radial artery to collect data from 20 volunteers several times. The experimental results show that the radial artery ultrasound imaging system based on CORDIC provides a clear picture of the radial artery vessels and that the readings match the actual vessel diameters. It also verifies the effectiveness of the ultrasound signal processing technology based on the high-performance CORDIC algorithm in radial artery ultrasound imaging, which lays the foundation for computer-aided medical diagnosis.

In this paper, the focus is only on the three key links of radial artery ultrasound signal processing in combination with three CORDIC algorithms. The application of other improved CORDIC algorithms to radial artery ultrasound signal processing is still worth exploring. In addition, the CORDIC algorithm is not limited to ultrasound signal processing modules. It can also be applied to fast and accurate delay control of ultrasound emission/reception focusing modules, as well as fast spatial coordinate conversion for 3D ultrasound image reconstruction. Further research into the performance advantages of the CORDIC algorithm in radial artery ultrasound imaging is planned for the future. It will ultimately reduce system development costs, improve overall system stability and real-time reconstruction of radial artery ultrasound images, and achieve the goal of computer-aided diagnosis of human health conditions.

Author Contributions: Conceptualization, C.Z. and X.G.; methodology, C.Z.; software, C.Z. and X.G.; validation, C.Z., X.G. and F.Y.; data collection, C.Z., L.L. and Z.G.; data analysis, C.Z.; writing—original draft preparation, C.Z.; writing—review and editing, C.Z. and X.G.; final approval, C.Z., X.G., L.L., Z.G., Y.W., F.Y. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National key Research and Development Program, grant no. 2022YFC3502300 provides necessary financial support for data acquisition and algorithm verification.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the research we conducted was only to collect pulse wave signals on the surface of the body. It did not cause any physiological harm to the volunteers and did not involve the privacy of the volunteers.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw/processed data required to reproduce these findings cannot be shared at this time, as the data also form part of an ongoing study.

Conflicts of Interest: The authors declare no conflict of interest.

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