Wearable Smartwatch based on Optical Fiber for Continuous Blood Pressure Monitoring.

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Abstract: We present a wearable smartwatch based on optical fiber for continuous blood pressure monitoring. Clinical results show errors of systolic pressure and diastolic pressure are 0.93 ± 3.97 mmHg and -3.07 ± 2.69 mmHg.

1. Introduction

Hypertension is a major cause of death globally, and it can significantly increase the risk of heart, brain and kidney disease. Real-time and continuous blood pressure monitoring is becoming more and more indispensable for early prevention of hypertension and cardiovascular diseases. However, current sphygmomanometer such as Photoplethysmogram (PPG) sensors [1], and ultrasonic types [2] face challenges with low sensitivity and electromagnetic interference to distinguish physiological information carried by pulse waveforms, which leads to a large error in blood pressure monitoring. Thus, accurate and no-scenes-limit blood pressure monitoring devices are highly desirable. Optical fiber sensors based on Fiber Bragg Gratings (FBGs) [3], Fabry-Perot interferometer (FPI) [4] present excellent performance in reusability, biocompatibility, and the electromagnetic insulation, but they usually suffer from position alignment and poor portability. Therefore, it is critical to develop a highly sensitive, alignment-free and wearable blood pressure monitoring device.

In this paper, we demonstrate a wearable smartwatch based on optical fiber for continuous blood pressure monitoring. The blood pressure can be monitored from the pulse transit time (PTT) which is extracted from the continuous high-fidelity pulse wave signal. The clinical experiment is carried out on 15 subjects and the results show that the errors of systolic pressure (SBP) and diastolic pressure (DBP) are 0.93 ± 3.97 mmHg and -3.07 ± 2.69 mmHg, demonstrating the high precision of the proposed blood pressure smartwatch meets the requirements of the Advancement of Medical Instrumentation.

2. Working Principle and Fabrication

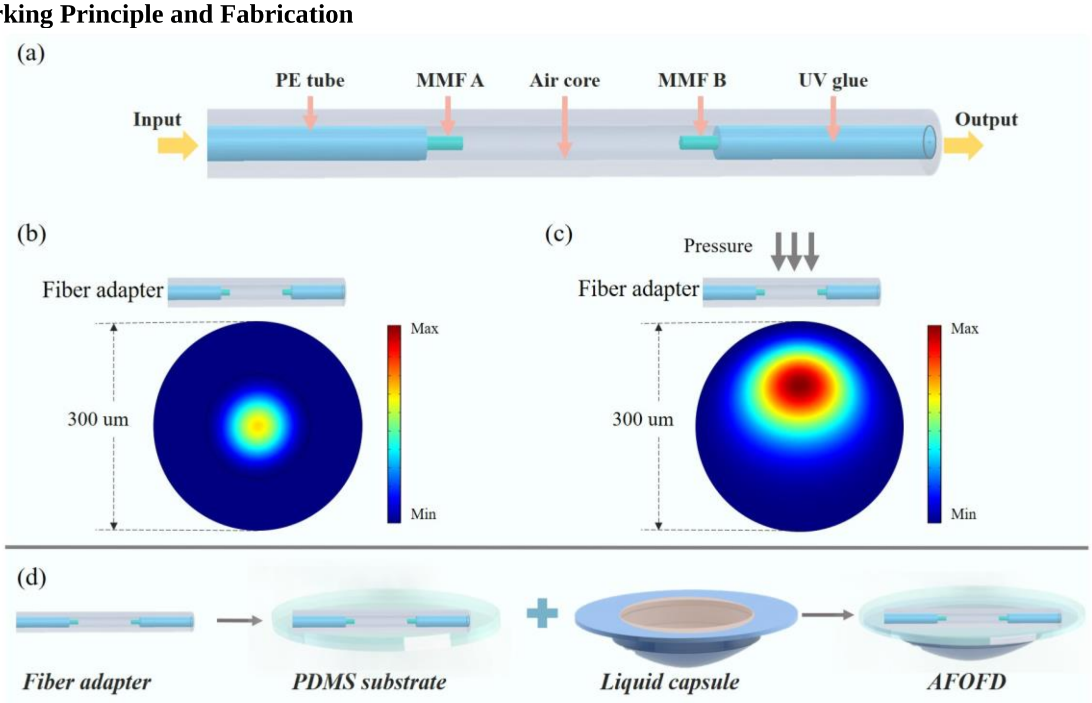

Fig. 1. (a) The structure of the fiber adapter. (b) Optical field energy density distribution of the straight optical fiber adapter. (c) Optical field energy density distribution of the pressed optical fiber adapter. (d) The fabrication of alignment-free optical fiber-based device.

The wearable smartwatch based on optical fiber comprises of a fiber adapter and a liquid capsule, while fiber adapter is utilized to sense the weak pulse signals and the liquid capsule is used to eliminate position drift and misalignment. As presented in Fig.1 (a), fiber adapter is made up of a polyethylene (PE) tube (inner/outer diameter: 150/300um), multimode fiber A (MMF A, core/cladding: 62.5/125 um), multimode fiber B (MMF B, core/cladding: 105/125 um) and air core. The multimode fibers and PE tube are sealed together by the ultraviolet (UV) glue. To employ fiber adapter for sensitive and robust wearable device, the fiber adapter is embedded and assembled in the Polydimethylsiloxane (PDMS) substrate.

When incident light travels through the MMF A and enters the straight PE tube, most of the optical field energy is distributed in the air core, as illustrated in Fig.1 (b). When the pulse wave signal is applied on the fiber adapter, the deformation of PE tube would change, causing the distribution of the optical field energy to tend to the cladding and then radiate outside the air core, which is presented in Fig.1 (c). It can be seen that the pressing of the soft PE tube will cause transmission loss in the fiber adapter, leading to the intensity variation of transmitted light. The measurement of the micro-scale pressure signal is achieved by measuring the light intensity output of the MMF B at the receiving end.

As for the flexible liquid capsule made of PDMS, the external diameter and the thickness are 20 mm and 500 μm, respectively. The capsule is fabricated, filled with glycerol and sealed by fiber adapter which is embedded in the PDMS substrate to form an alignment-free optical fiber-based device (AFOFD), as illustrated in Fig.1 (d). According to Pascal's principle [5], pressure change at any point in a confined fluid at rest is transmitted undiminished to all points in the fluid. Therefore, pulse wave signal sensed by any point of the liquid capsule will be transmitted undiminished to the fiber adapter sealed in the capsule. The distortion of physiological signals caused by position drift and misalignment can be eliminated by the proposed wearable smartwatch.

3. Experimental setup and Results

To achieve the continuous blood pressure monitoring, a wearable smartwatch based on optical fiber system was employed and displayed in Fig.2. The probe light was guided to the alignment-free optical fiber-based device. The artery pulse signal traveled to the surface of the skin and then perceived by sensing unit. The transmitted signal from the device can be detected by the photodetector. The time delay from the percussion wave peak to dicrotic wave peak is defined as Pulse Transit Time (PTT), while the relationship between PTT and systolic blood pressure (SBP), PTT and diastolic blood pressure (DBP) have been illustrated in our previous work [6].

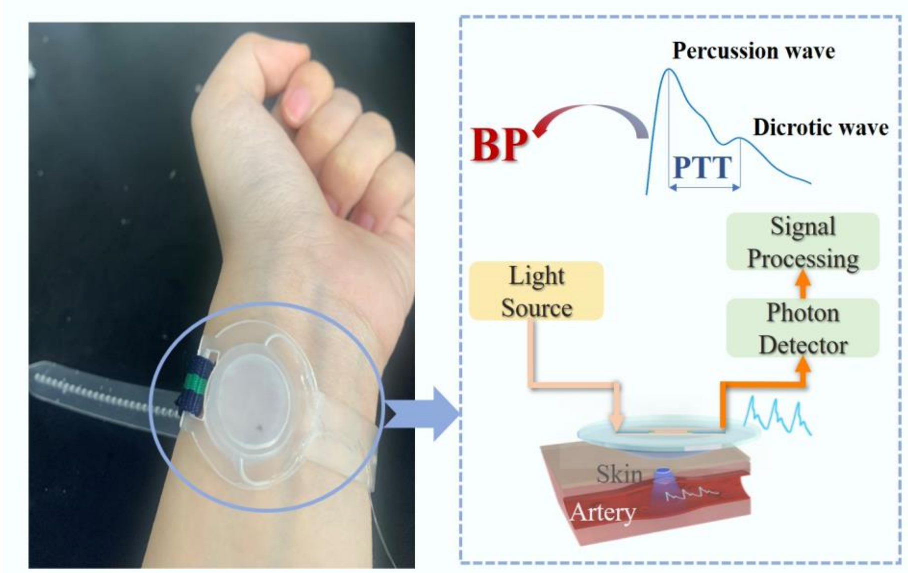

Fig. 2. The schematic of the continuous blood pressure monitoring smartwatch based on optical fiber.

To verify the performance of the proposed smartwatch, 15 subjects aged from 22 to 62 years old were randomly selected for the clinical experiment. For each subject, we used the smartwatch to monitor the blood pressure and a reference sphygmomanometer to verify the accuracy simultaneously. Fig. 3(a) displays the correlation plot of the measured blood pressure against the reference values. The correlation coefficients of SBP and DBP are calculated as 0.67 and 0.71 respectively. The Bland-Altman plots of SBP and DBP are depicted in Fig. 3(b) and Fig. 3(c). The 95% confidence interval and mean are drawn in red solid-lines and gray dot-line, respectively. The mean of the deviation value of SBP is 0.93 mmHg, and the 95% confidence interval ranges from -6.85 mmHg to 8.72 mmHg, while the mean of the deviation value of DBP is -3.07 mmHg, and the 95% confidence interval ranges from -8.33 mmHg to 2.20 mmHg. It is observed that the results are within the 95% confidence limits, indicating that the measured blood pressure values from wristband are in close agreement with those of a standard device. The error analysis results are listed in Table 1. It can be concluded that the maximum absolute error (Ea) of SBP and DBP are 7 mmHg. The mean error (Em) and error standard deviation (SD) of SBP are 0.93 mmHg and 3.97 mmHg, respectively. For DBP, the Em and SD are -3.07 mmHg and 2.69 mmHg, respectively. According to the Association for the Advancement of Medical Instrumentation (AAMI) to the blood pressure measurement device, the required standard of Dm ± SD is 5 ± 8 mmHg [7]. The accuracy of the wearable wristband based optical device meets the requirements of the Association for the Advancement of Medical Instrumentation.

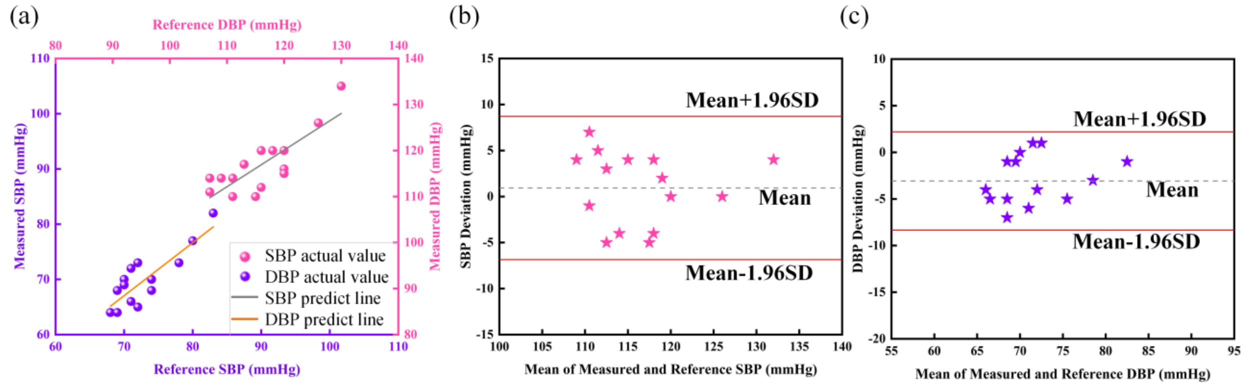

Fig. 3. (a) Correlation plot of blood pressure, (b) Bland-Altman plot for SBP, and (c) Bland-Altman plot for DBP

Table 1. Blood Pressure Measurements Results

Blood pressure	Ea (mmHg)	Em (mmHg)	SD (mmHg)
SBP	$Ea \leq 7.00$	0.93	3.97
DBP	$Ea \leq 7.00$	-3.07	2.69

4. Conclusion

A wearable smartwatch based on optical fiber which comprises a fiber adapter and liquid capsule for non-invasive, accurate and continuous blood pressure monitoring is proposed and experimentally demonstrated. The results show that the errors (Em ± SD) of SBP and DBP are 0.93 ± 3.97 mmHg and -3.07 ± 2.69 mmHg, respectively, which meets the requirement of the Advancement of Medical Instrumentation. This work paves a portable, convenient and user-friendly approach for continuous blood pressure monitoring, which has the potential to open up the individual-centered disease diagnosis.

5. Acknowledgement

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6. References

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