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Abstract. We report a blood pressure evaluation methodology by recording the radial arterial pulse waveform in real time using a fiber Bragg grating pulse device (FBGPD). Here, the pressure responses of the arterial pulse in the form of beat-to-beat pulse amplitude and arterial diametrical variations are monitored. Particularly, the unique signatures of pulse pressure variations have been recorded in the arterial pulse waveform, which indicate the systolic and diastolic blood pressure while the patient is subjected to the sphygmomanometric blood pressure examination. The proposed method of blood pressure evaluation using FBGPD has been validated with the auscultatory method of detecting the acoustic pulses (Korotkoff sounds) by an electronic stethoscope. © 2013 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JBO.18.6.067010]

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1 Introduction

Hypertension is known to adversely affect the cardiovascular and renal systems.¹ Hence, it is important to precisely measure the blood pressure to aid the diagnosis and management of hypertension. Direct intra-arterial measurement of blood pressure, though being the gold standard method,² has limited clinical usage due to its invasive nature.³ Physicians commonly palpate the peripheral arterial pulse to study the cardiovascular status of subjects, and have relied on it to measure the blood pressure in conjunction with the Riva-Rocci cuff.⁴ The detection of Korotkoff sounds during deflation of the Riva-Rocci cuff by auscultatory method has been the mainstay for clinical measurement of blood pressure.²

Further, oscillometric devices have been developed for the automated blood pressure measurement, which are limited by accuracy of the algorithms used, stiffness of the arteries, differences between various makes of devices, and assumption of a regular pulse rate between bladder deflation bleed steps.⁵ Also, other methods such as tonometry, finger-cuff method of Penaz,⁶ and ultrasound techniques have been developed, which have their own drawbacks.⁵

In sphygmomanometry,³ when the cuff wound on the upper arm is inflated above the systolic blood pressure (SBP), the brachial artery is occluded resulting in complete cessation of blood flow. On gradual deflation, there is an initial turbulent blood flow which transforms into a normal laminar flow as the pressure of blood in the brachial artery overcomes the decreasing cuff pressure. The pressure at which the laminar flow is reestablished represents the diastolic blood pressure (DBP).

Using the same principle, a fiber Bragg grating pulse device (FBGPD) has been designed and developed in the present work, for detecting the arterial pulse; the aim of this work, is to study the corresponding changes in the arterial pulse waveform from the radial artery and to provide a noninvasive assessment of blood pressure. The devices which measure blood pressure non-invasively at the wrist, such as the Colin radial tonometer,⁷ the Vasotrac monitor,⁷ the arterial pulsimeter equipped with Hall device,⁸ etc., apply the principle of tonometry⁹ to measure blood pressure with a single pulse, providing beat-to-beat estimation of blood pressure. The FBGPD developed differs from these devices by focusing on the volumetric flow response and radial arterial diametrical variation for the evaluation of SBP and DBP during sphygmomanometry. The use of fiber Bragg grating (FBG) sensors brings potential advantages, such as insensitivity to electromagnetic interference, low fatigue, and ultra-fast response, making the proposed FBGPD an effective means for the evaluation of the blood pressure.

2 Fiber Bragg Grating Sensors

FBG is a periodic modulation of the refractive index of the core of a single-mode photosensitive optical fiber, along its axis,¹⁰ established by exposing the core to an intensity-modulated UV light. When a broadband light is launched into an FBG, a single wavelength which satisfies the Bragg's condition will be reflected back, and the remaining part of the spectrum is transmitted.¹¹ This reflected Bragg wavelength (λ_B) of the FBG is given by

$$\lambda_B = 2n_{\text{eff}}\Lambda. \quad (1)$$

Here, Λ is the pitch of the grating and n_{eff} is the effective refractive index of the fiber core.

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FBG can be fabricated using a variety of ways; in the present work, FBGs of 3-mm lengths have been fabricated in photo-sensitive germania-doped silica fiber using the phase mask method.¹²

The sensing action of the FBG is based on the principle that any external perturbation, such as strain, temperature, etc., will alter the pitch of the grating and in turn the reflected Bragg wavelength. By interrogating the shift in Bragg wavelength, the external perturbation at the grating site can be quantified.¹³⁻¹⁵ For example, the strain effect on an FBG sensor is expressed as

$$\Delta\lambda_B = \lambda_B \left\{ 1 - \frac{n_{\text{eff}}^2}{2} [P_{12} - \nu(P_{11} - P_{12})] \right\} \epsilon, \quad (2)$$

where P_{11} and P_{12} are components of the strain-optic tensor, ν is the Poisson's ratio, and ϵ is the axial strain change.¹⁶ The strain sensitivity of a FBG inscribed in a germania-doped silica fiber is approximately 1.20 pm/ $\mu\epsilon$.¹⁷ As the temperature variations can also cause a shift in the Bragg wavelength, it is important to compensate for temperature variations (if any) while using the FBG sensor for strain measurements.¹⁸ However, in the present work, temperature effect on the FBG sensor has been ignored, as the temperature change during the experimental course was negligibly small.

3 Arterial Pulse Waveform Detection

The FBGPD consists of a hollow, open-bottomed rectangular box with a dimension of 25 mm \times 15 mm \times 15 mm, made of a plastic material attached to a strap. An elastic silicone diaphragm of dimension 60 mm \times 20 mm \times 0.75 mm is adhered to the open side of the box. The FBG sensor of gauge length 3 mm is bonded to the outer surface of the silicone diaphragm, ensuring that the FBG sensor is positioned at the center of the bottom surface of the rectangular box as shown in Fig. 1. The silicone diaphragm facade of the FBGPD is placed on the flexor aspect of the wrist, corresponding to the site of maximal impulse

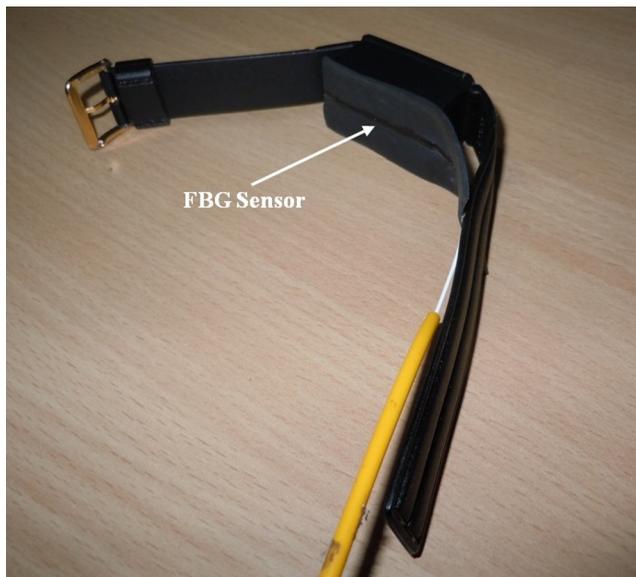


Fig. 1 Pictorial representation of fiber Bragg grating pulse device (FBGPD).

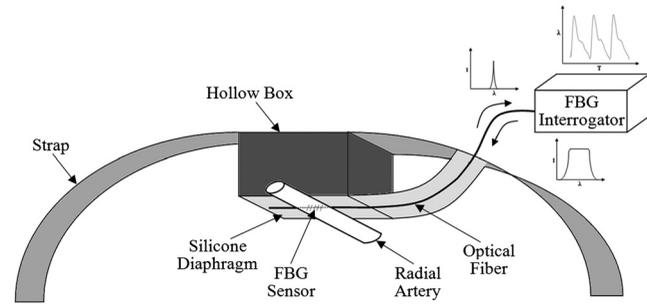


Fig. 2 Schematic representation of FBGPD.

of the radial arterial pulse as illustrated schematically in Fig. 2. The broadband light being launched into the fiber and the reflected wavelength interrogated for the arterial pulse pressure acquisition are depicted. The FBGPD fixed on the wrist recording the arterial pulse waveform is shown in Fig. 3(a).

The FBGPD can be fixed on the wrist using a strap, which also exerts minimal inward pressure on the rectangular box. During the measurement, the FBG sensor site on the FBGPD is positioned on the skin surface exactly above the radial artery which is approximately 2 mm in diameter. The pulsatile flow of blood in the radial artery applies pressure on the silicone diaphragm, creating strain variations on it, which is sensed by the FBG sensor to provide the fundamental quantitative information of arterial pulse waveform of the subjects, as shown in the Fig. 3(b). The pulsatile nature of blood flow in the artery generates the beat-to-beat amplitude variation. A sustained push on the diaphragm due to the arterial diametric distension is also recorded in the response curve of the FBGPD.

The present study involved 30 volunteers (19 males and 11 females) aged between 20 and 35 years, who are nonsmokers, nonalcoholics, and nonhypertensives. Two trials have been carried out on each subject. Prior to the onset of the test, the subjects are made to sit comfortably on a chair with a back rest, and are allowed to acclimatize to the surroundings for 15 min. While seated, the subject's legs are not crossed, and the feet are placed on the ground. A Riva-Rocci cuff is wound on the right arm, two finger breadths above the ante-cubital fossa at the elbow, with the cuff applied directly on the skin. The forearm of the subject is rested on a table on which a mercury sphygmomanometer is placed such that their height corresponded to the level of the heart,¹⁹ as shown in Fig. 4.

4 Experimental Method

The estimate of the SBP is made by the palpatory method of blood pressure measurement to avoid an auscultatory gap.²⁰ The FBGPD is subsequently placed on the flexor aspect of the wrist as described earlier, which records the changes in reflected Bragg wavelength of the FBG sensor using an FBG interrogator (Micron Optics, SM130, Atlanta, GA). The diaphragm of the electronic stethoscope (3M Littmann brand model 3200), which transmits the acoustic signals to a computer, has been placed at the ante-cubital fossa over the brachial artery.

Both the FBG sensor and electronic stethoscope are triggered simultaneously to ensure comparability of the acquired data. The pressure in the cuff, indicated by the sphygmomanometer, is then raised to 30 mm of mercury higher than the value of SBP as estimated by the palpatory method. The cuff pressure is then decreased at an approximate rate of 1 mm of mercury per

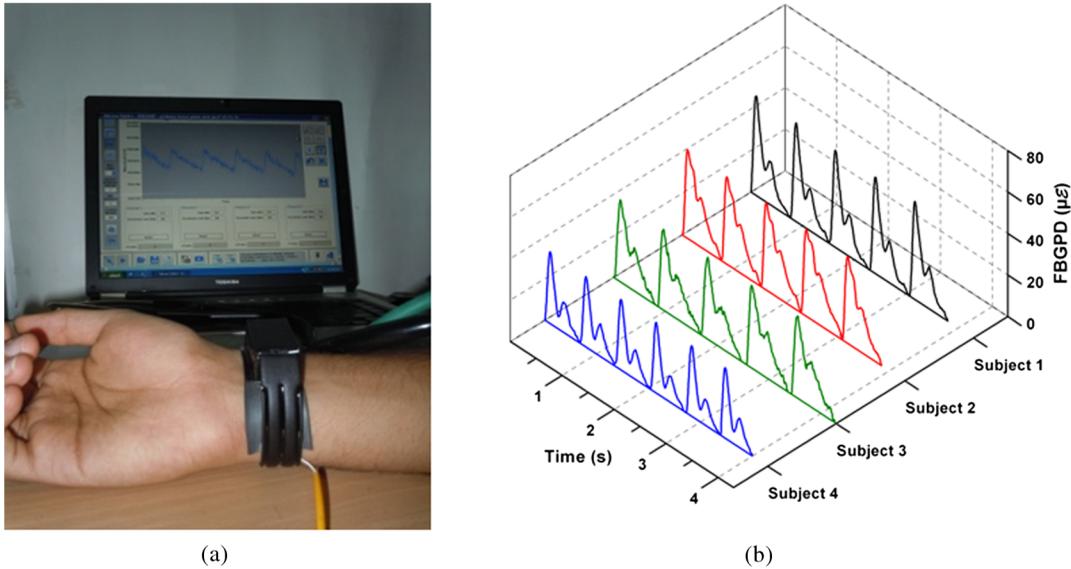


Fig. 3 FBGPD applied on the wrist, and the arterial pulse waveform response is recorded.

second. Following the conventional auscultatory technique, the level of pressure in the cuff when the first Korotkoff sound is heard through the stethoscope is taken to represent SBP. The level of pressure when Korotkoff sounds disappeared completely marks the DBP.²¹ The data obtained from both techniques have been compared.

5 Results and Discussion

Data obtained from a typical male subject of age 24 years is used to validate the blood pressure measurement using the present FBGPD. Analysis of the response of the FBGPD shows the pressure exerted by the radial artery over the silicone diaphragm.

Figure 5 shows the response of both FBGPD (in $\mu\epsilon$) and acoustic signals (in arbitrary units) recorded from the electronic stethoscope compared in real time during sphygmomanometric test. The test has been carried out for about 116 s, and the FBGPD response has been classified into five phases:

Phase 1: The normal pulsation of the subject is recorded for 12 s.

Phase 2: The Riva-Rocci cuff is then inflated to a pressure above SBP that causes occlusion of the brachial artery, which results in collapse of the radial artery by decreasing its diameter, represented by the drop in the strain curve of FBGPD at around 16 s.

Phase 3: Deflation of the cuff is initiated. As the cuff pressure is still higher than the SBP, the radial artery remains collapsed. Hence, no change in the pulse waveform is detected.

Phase 4: It is known that between SBP and DBP, when arterial blood pressure is below the cuff pressure, the brachial artery is occluded; when arterial blood pressure is greater than the cuff pressure, the brachial artery is open with turbulent blood flow. As the cuff pressure reaches the SBP, blood flow through the brachial artery is resumed and the resulting pulse is sensed by the FBGPD. Simultaneously, acoustic signals (Korotkoff sounds) are detected by the electronic stethoscope at 44 s, as shown in Fig. 6. The corresponding pressure in the sphygmomanometer represents the SBP, which is measured as 118 mm of mercury for the test subject. On further deflation of the cuff, as the cuff

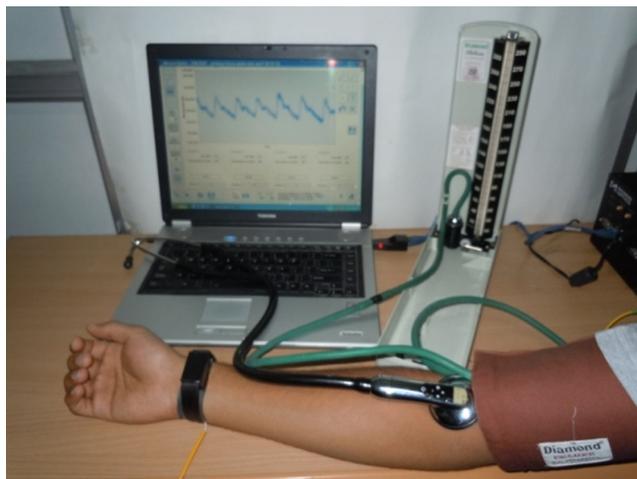


Fig. 4 Photograph of the FBGPD and the electronic stethoscope showing simultaneous data acquisition during sphygmomanometry.

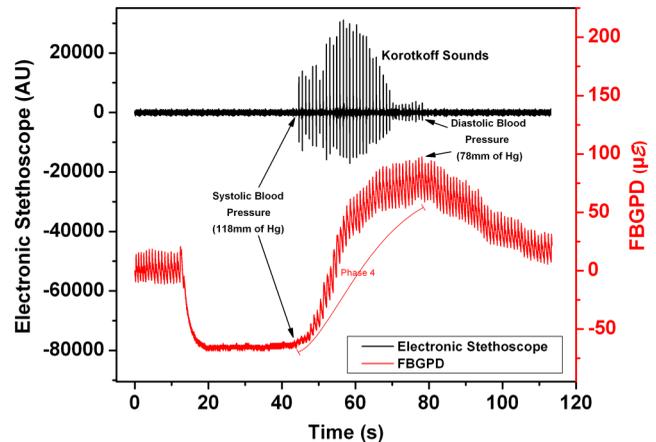


Fig. 5 Comparison of response of FBGPD and electronic stethoscope acoustic signals during sphygmomanometry.

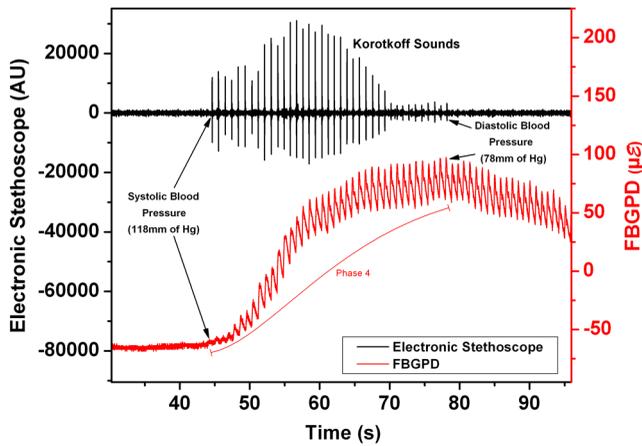


Fig. 6 Detailed data showing the enlarged region of Phase 4.

pressure reduces gradually from SBP to DBP, the turbulent blood flow in the radial artery sets up hemodynamic changes resulting in arterial distention, which can be seen as the rise in the curve of FBG pulse response. The DBP denoted by the disappearance of Korotkoff sounds is attributed to the maximum radial arterial distention identified by the peak position attained by the FBG response curve at 78 s. The corresponding pressure in the sphygmomanometer represents the DBP which is 78 mm of mercury for the current subject. The radial arterial pulse acquired between SBP and DBP is in beat-to-beat coordination with the Korotkoff sounds with a total of 38 beats recorded by both the sensors for a pressure decrease of 40 mm of mercury in sphygmomanometer for the duration of 33 s. It can also be seen that the beat-to-beat pulse amplitude is increasing in this phase owing to the increase in the blood flow with decrease in the cuff pressure.

Phase 5: As the cuff pressure falls below DBP, the laminar blood flow is re-established in the radial artery and the arterial wall initiates its return to normalcy, which makes the FBG pulse response curve dip downward. It is observed that the beat-to-beat pulse amplitude increases with the decrease in pressure denoting the increase in the volumetric blood flow in the radial artery.

The unique signatures of pulse detection and peak point of the FBG pulse response with corresponding pressure values from the sphygmomanometer represent the SBP and DBP of the subject. This method of blood pressure evaluation has been tested for accuracy with 30 test subjects, and the accuracy of the measured values has been calculated.

The time delay between the unique signatures of FBGPD-sensed waveform and occurrence and disappearance of Korotkoff sounds detected by the electronic stethoscope is used to generate the accuracy of the two techniques. The number of trials of both SBP and DBP is divided into brackets of time delay, which indicates the blood pressure difference recorded by both the techniques knowing the pressure deflation rate of 1 mm of mercury per second. Table 1 shows the statistical distribution of the acquired trials with the difference in timing for SBP and DBP obtained from FBGPD and electronic stethoscope signals, which correspond to the differences in the blood pressure values. It is observed that for SBP, for ± 4 mm of mercury pressure difference measured by both methods, an accuracy of 99.99% (93.33% + 6.66%) is achieved. Similarly for DBP,

Table 1 Statistics of the acquired trials for accuracy calculation.

# Trials	Type	Time difference between both methods (s)	Blood pressure difference between both methods (mm Hg)	Acquired trials	Accuracy (%)
60	Systolic blood pressure	0 to 2	2	56	93.33
		2 to 4	4	4	6.66
		4 to 10	10	0	0
	Diastolic blood pressure	0 to 2	2	31	51.66
		2 to 4	4	17	28.33
		5 to 10	10	8	13.33
		10 to 20	20	4	6.66

for ± 4 mm of mercury pressure difference measured by both the methods, an accuracy of 79.99% (51.66% + 28.33%) is achieved. The variation in the results obtained by both methods can be attributed to the positional offset of the FBGPD above the radial artery or to an additional pressure application on the radial artery by the FBGPD, which may limit the expansion of the radial artery. Further, the present FBGPD can also provide information regarding hemodynamic changes in the radial artery in the form of volumetric flow response and arterial diametrical change simultaneously, which makes this technique very unique and effective for blood pressure evaluation.

6 Conclusion

In the present work, a blood pressure evaluation method has been demonstrated which uses FBGPD for recording the radial arterial pulse waveform in real time during sphygmomanometry. The results obtained are compared with the data recorded from the electronic stethoscope, and have been found to be in good agreement. In addition, the FBGPD provides information about the arterial diametrical variations. The noticeable constraints of this technique are the difficulty in placement of the device and precise pressure application by the FBGPD over the radial artery. Further, this study can be extended to observe the arterial pulse waveform in hypertensive subjects with significant atherosclerosis and also in hypotensive subjects.

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