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FULL ARTICLE

Fiber bragg grating sensor based device for simultaneous measurement of respiratory and cardiac activities

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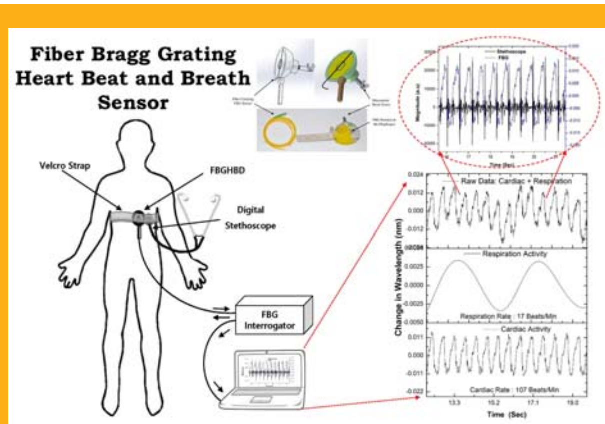
This paper reports a novel optical ballistocardiography technique, which is non-invasive, for the simultaneous measurement of cardiac and respiratory activities using a Fiber Bragg Grating Heart Beat Device (FBGHBD). The unique design of FBGHBD offers additional capabilities such as monitoring nascent morphology of cardiac and breathing activity, heart rate variability, heart beat rhythm, etc., which can assist in early clinical diagnosis of many conditions associated with heart and lung malfunctioning. The results obtained from the FBGHBD positioned around the pulmonic area on the chest have been evaluated against an electronic stethoscope which detects and records sound pulses originated from the cardiac activity.

In order to evaluate the performance of the FBGHBD, quantitative and qualitative studies have been carried out and the results are found to be reliable and accurate, validating its potential as a standalone medical diagnostic device. The developed FBGHBD is simple in design, robust, portable, EMI proof, shock proof and non-electric in its operation which are desired features for any clinical diagnostic tool used in hospital environment.



1. Introduction

In the last century, cardiovascular illnesses are found to be the main causes of fatality in most of the developed countries [1]. The monitoring of the cardiac activity is one of the major investigative procedures in healthcare, which plays a vital role in the diagnosis of many fatal cardiac and cardiovascular diseases [2–5]. The combined effects of the sympathetic and parasympathetic nervous systems modulate heart

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rate which has its unique signature on many parts of body including the chest [6]. Safe, accurate and real-time measurement of cardiac activity is warranted for clinical diagnoses of fatal diseases like cardiac stroke, multiple sclerosis, renal disease, neonatal distress, diabetes mellitus, ischemic heart disease, myocardial infarction, cardiomyopathy, vacuolar heart disease, congestive heart failure, etc. [7, 8]. Similarly, heart rate variability is another important factor, which has been used to identify high risk people, to understand the autonomic components of different disorders and to evaluate the effect of different interventions [9–11].

For the measurement and quantification of cardiac activity, researchers have employed several direct and indirect methods from different domains. These methods aim at measuring low frequency body vibrations, displacements, accelerations and movements at different parts of the body like chest, head, neck, knee, etc., caused by the heartbeat [12, 13]. Several researchers have also reported methods placing sensors directly onto the body beneath pillows, mattresses or embedded in to frequently used objects [14–17].

Similarly, simultaneous and accurate measurement of heart rate and breathing rate has been a significant investigative practice for diagnosis of many critical diseases connected to cardiac and pulmonary abnormalities [18]. Among many indirect methods, Ballistocardiography (BCG), Apexcardiography (ACG) and other methods which belong to Mechanocardiography (MCG) play a vital role in simultaneous measurement of respiratory and cardiac activity over the last few decades [17]. In recent past, the significant progress in the field of signal extraction and signal processing has renewed the interest in these techniques, which require specific and accurate signal processing techniques [19, 20]. In addition, numerous types of sensors have been tried such as strain gauge bridge [21], piezoelectric [22], accelerometer [23], load cell [24], electromechanical film [25], etc., for accurate and reliable extraction of cardiac and respiratory signals. Most of the sensor technologies adopted in this context are from electrical domain which may be constrained in their usage for bio-medical diagnostic applications. Especially, while monitoring cardiac activity and breathing rate in some critical medical procedures like Magnetic Resonance Imaging (MRI), patients have even suffered severe burn injuries from the use of electrical sensors [26]. Thermal or electrical burns associated with oximeter sensors, electrical cables, temperature probes and MRI surface coils during MRI examination and from diagnostic instruments during cardiothoracic surgery necessitate the development newer and safer sensors and investigative methods [27, 28].

Use of optical sensors like macro-bending optical fiber [29], optical interferometer [30] and Fiber Bragg Grating (FBG) which are minimally invasive and bio-medically safe have gained importance for use in medical applications in comparison with the electrical counterparts [31–33]. Optical fibers do not contain conductive parts and therefore, can even be used in and around high electromagnetic fields in hospital environment [34].

Most of the research in devising a method/technology for simultaneous measurement of cardiac and breathing activity confines its use only for the detection of cardiac and breathing frequencies and does not focus to retrieve the heart beat morphology which might aid in early diagnosis of many fatal cardiac diseases [35–40]. In addition, some of the works reported earlier are either minimally portable, or non-accommodative to subject's comfort [39, 40]. In the present work, we report a simple, standalone, portable, non-invasive, electromagnetically immune and bio-medically safe device for simultaneous measurement and real-time monitoring of cardiac and breathing activities using a Fiber Bragg Grating Heart Beat Device (FBGHBD) which provides unique signature and morphology of the heart beat and breathing effect on the pulmonic area on the chest along with its frequencies.

2. Theory of fiber bragg gratings

FBG is a periodic or a quasi-periodic modulation of refractive index of the core of a single mode photosensitive optical fiber, along its axis [41]. When a broadband light is launched into an FBG, a single wavelength which satisfies the Bragg's condition is reflected back while the rest of the spectrum is transmitted [42]. This reflected Bragg wavelength (λ_B) of the FBG is given by

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Here, Λ is the periodicity of the grating and n_{eff} is the effective refractive index of the fiber core. In the present work, FBG sensors with a gauge length of 3 mm have been fabricated in a photo sensitive germania-doped silica fiber, using the phase mask grating inscription method [43].

The effective refractive index, as well as the periodic spacing between the grating planes, will be affected by changes in strain and temperature. The shift in the Bragg grating centre wavelength due to strain and temperature changes is given by

$$\begin{aligned}\Delta\lambda_B = {} & 2\left[\Lambda \frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial \Lambda}{\partial l}\right]\Delta l \\ & + 2\left[\Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right]\Delta T\end{aligned} \tag{2}$$

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The first term in above equation represents the strain effect on an optical fiber and the second term represents effect of temperature. By interrogating the shift in Bragg wavelength, the external perturbation can be quantified [44–46]. For example, the strain effect on an FBG sensor is expressed as,

$$\Delta\lambda_B = \lambda_B\left[1 - \frac{n_{\rm eff}^2}{2}\left[P_{12} - \nu(P_{11} - P_{12})\right]\right]\varepsilon \quad (3)$$

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 [47]. The strain sensitivity of a FBG inscribed in a germania-doped silica fiber is approximately 1.20 pm $(\mu\varepsilon)^{-1}$ [48]. FBG sensors are known to react simultaneously for both strain and temperature. However several strain-temperature discrimination techniques and unique sensor encapsulation packages reported in literature have enabled FBG sensor technology to successfully employ in many commercial applications and harsh environments [49–51]. In the present set of experiments, the temperature effect on the FBG sensor is neglected as the experiment is conducted in controlled laboratory environment.

3. Design details of FBGHBD

The heart is located deep inside the thoracic cavity, medial to the lungs and posterior to the sternum between the two lungs of the body. The inflation and deflation of the lungs exert a high amplitude thoracic movement; whereas the effect of cardiac activity on the chest is diminutive. Hence, a novel mechanical package is designed using an intelligent combination of three simple components: A cone shaped structure, a micrometer and a flexible diaphragm which constitute the FBGHBD as shown in Figure 1. The smaller side of the cone shaped structure made up of Poly Vinyl Chloride (PVC) and is attached to the moving end of the micrometer which is translated by turning a micrometer bezel screw. The cone shaped structure provides the mechanical stability, whose larger side is tightly sealed with the silicon diaphragm whereas the smaller side is coupled by the micrometer assembly facing the diaphragm.

The idea behind the use of micrometer assembly is to provide selective and quantitative protrusion/stretch to the FBGHBD diaphragm and enable it to reach further inside the flush of the chest muscle with least discomfort to the subject. As mentioned earlier, a 9/125 μm diameter germania-doped photosensitive silica fiber has been used in the fabrication of FBG sensors of 3mm gauge length. However, methods like reducing the size of the fiber for inscribing the FBG sensor, etched FBG sensor usage etc. can increase the sensitivity and response of the FBG sensor [52, 53]. The fabricated FBG sensor is tightly bonded across the diaphragm using a thin layer of cyanoacrylate adhesive. A narrow supporting piece made of light weight balsa wood is attached to the FBGHBD to run/carry the fiber inscribed with FBG sensor on to the diaphragm and towards the FBG interrogator. Figure 1 shows the three dimensional diagrams of the developed FBGHBD and its photographed image along with the fusion spliced fiber.

Figure 1 Design schematics and pictorial representation of FBGHBD.

4. Experimental details

Previous studies have revealed that a direct relation exists between the respiration and cardiac activities on the wall of the chest [54, 55]. The lung expansion due to breathing and heart beating due to cardiac activity commonly lead to thoracic movements. A detailed experimental procedure is devised in the present work to demonstrate the uniqueness of FBGHBD in simultaneous extraction of respiratory and cardiac activity morphologies and the relevant frequencies by either recording of change in wavelength of FBGHBD or calculating the surface strain generated on pulmonic area on the chest of the subject.

4.1 Subjects

Four healthy subjects (2 female and 2 male) have volunteered for the present work. They are aged between 22 and 28 years and are of varying Body Mass Index (BMI mean: 25). The approval from the ethical committee has been obtained before the experiments and required ethical procedures have been followed during the experiments. The subjects have been examined by a general medical practitioner one day prior to the experiment. All of them have been declared to be in good health condition to participate in the experimental trials. To validate the FBGHBD developed in this work, an electronic stethoscope which detects and records sound pulses originated from cardiac activity is used and the data is recorded simultaneously from both the devices while the subject is comfortably lying flat on the ground.

4.2 Experimental setup

Experimental setup of the present study mainly involves FBGHBD as the sensor element, connected to an FBG interrogator (SM 130–700, Micron Optics Inc.) which records the thoracic movements of the chest wall. The schematic representation of the experimental setup with FBGHBD mounted on the subject with the help of a velcro strap on the chest of a subject is shown in Figure 2.

4.3 Methodology

The FBGHBD and the digital stethoscope (3M™ Littmann® Electronic Stethoscope Model 3200) are mounted on the chest of subject around 2nd and 3rd

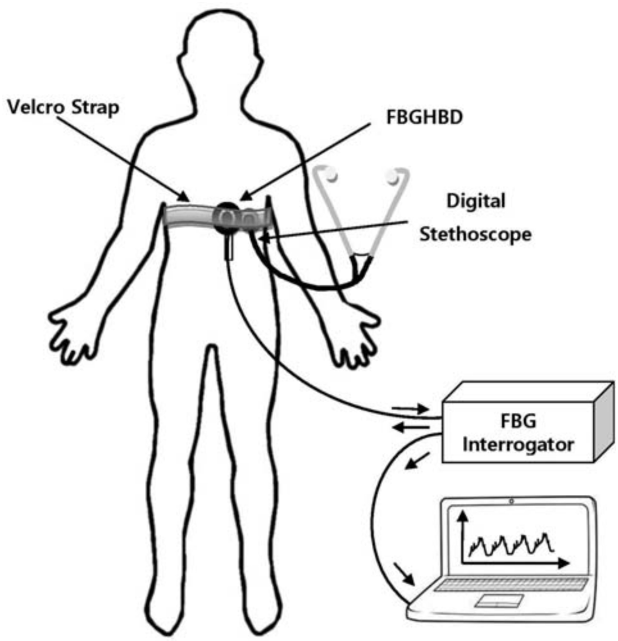

Figure 2 Schematic representation of the experimental setup.

interspace of pulmonic area to record thoracic movements/impermanent in real-time [56]. The real-time signal obtained from FBGHBD is a mixed signal which will have signatures of both cardiac and respiratory activities. The characteristic and largely dissimilar frequency variance between the respiratory and cardiac activity help in choosing frequency analysis for processing the mixed signal [57]. One of the dominant frequency component obtained from the mixed signal is compared against the digital stethoscope signal for cardiac activity validation. Among the five volunteered subjects, quantitative analysis for illustrating the consistency and reliability of the FBGHBD is carried out on one subject. Whereas, a comprehensive quantitative study is carried out on the results of FBGHBD obtained from all the subjects and compared against digital stethoscope recordings.

5. Experimental results

Simultaneous data acquired from FBGHBD and stethoscope for all the four volunteered subjects have been analyzed for the evaluation of the FBGHBD. Among the volunteered subjects, a typical subject has been chosen for demonstrating the analysis method of extraction of respiratory and cardiac activities from the obtained mixed signal. The mixed signal from the same subject has been analyzed for extraction of heat beat rate and breathing rate with preserved respective morphologies. Further, a quantitative analysis with comparison of FBGHBD results and stethoscope is carried out for all the subjects volunteered in the study.

5.1 Raw data/mixed signal

Figure 3 shows the plot of raw signals (mixed signal) obtained from FBGHBD for a sample trial of all four subjects; The *Y* axis of the plot shows the change in wavelength with offset *Y* values and the normalized time component of the experiment has been plotted along the *X* axis. The experiment has been conducted for about 60 seconds instructing the subjects to breathe in a relaxed manner. To test the developed sensor package rigorously for extreme cases of slow and fast breathing, two subjects are instructed to breathe differently. Subject 2 is advised to perform slow automatic inhalation and automatic exhalation and subject 3 is advised with forced inhalation and forced exhalation. Hence, a large variation in number of breathing cycles and the relevant change in breathing pattern can be observed from these two subjects with respect to plots of Figure 3.

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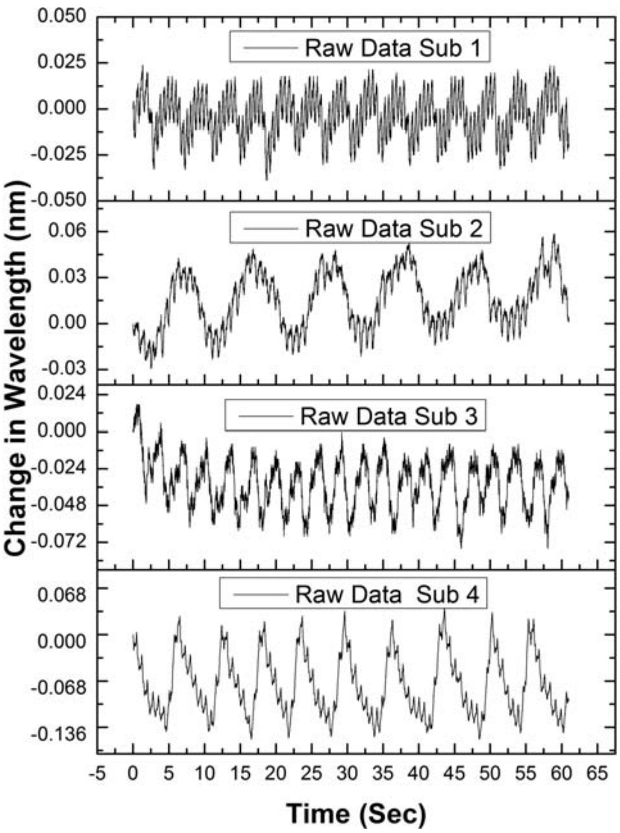

Figure 3 Raw signals acquired from FBGHBD for four subjects.

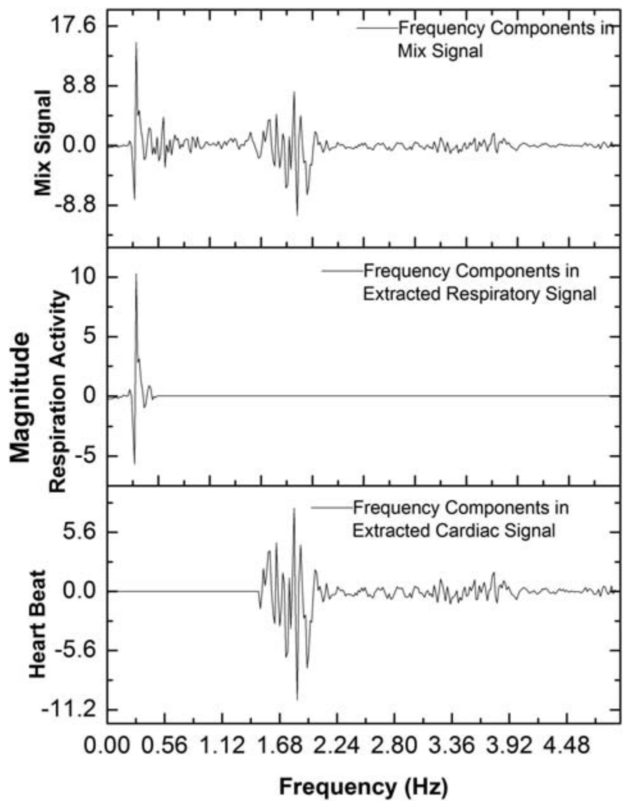

Figure 4 Plots processed in frequency analysis method representing the mixed signals in frequency domain for extraction of respiratory and cardiac activity.

From the plot it is clear that the shown trials are consistent and repeatable upon observing beat to beat signal. Further, the first trial of the subject 1 is considered for illustrating the extraction of respiratory and cardiac activity.

5.2 Frequency analysis of the mixed signal

Figure 4 shows the plot processed in frequency analysis method representing in frequency domain and Figure 5 represents the mixed signal in time domain. Generally, for healthy subjects, the respiratory activity should not exceed about 0.5 Hz, whereas the cardiac activity should not be less than about 0.7 Hz [58, 59]. The recorded mixed signal obtained from FBGHBD has been passed through a low pass filter of cut-off frequency 0.5 Hz and a high pass filter of cut-off frequency 0.5 Hz. First plot of Figure 4 shows the mixed signal in frequency domain whereas the subsequent plots below shows the independent frequency components for respiratory (0.28 Hz corresponding to 17 Cycles Min^{-1}) and cardiac activity (1.7 Hz corresponding to 102 Beats Min^{-1}) respectively. Correspondingly, the first plot of Figure 5 shows the raw mixed signal in time domain whereas in subsequent plots, its magnitudes with characteristic morphology of respiratory and cardiac activities extracted from frequency analysis of the mixed signal are shown.

Figure 6 shows the expanded view of two respiratory cycles from Figure 5, for illustrating the quality of preserved independent morphologies of respiratory and cardiac activities from mixed signal obtained from frequency analysis. From Figure 6 it is evident that the respective morphologies of respiratory and cardiac activities are accurately reconstructed from the extracted frequency components of the mixed signal obtained from FBGHBD on the chest of the subject.

5.3 Evaluation of FBGHBD with stethoscope

Figure 7 shows the simultaneously recorded signals from FBGHBD and stethoscope mounted around the pulmonic area on the chest of the subject for about 60 seconds. The change in wavelength of the FBGHBD and magnitude variation of the sound sig-

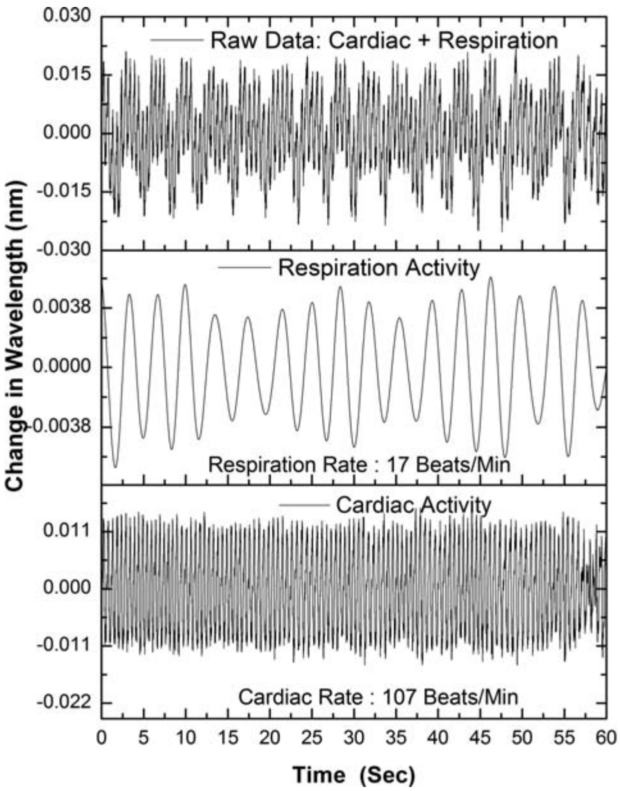

Figure 5 Plots processed in frequency analysis method representing the mixed signals in time domain for extraction of respiratory and cardiac activity.

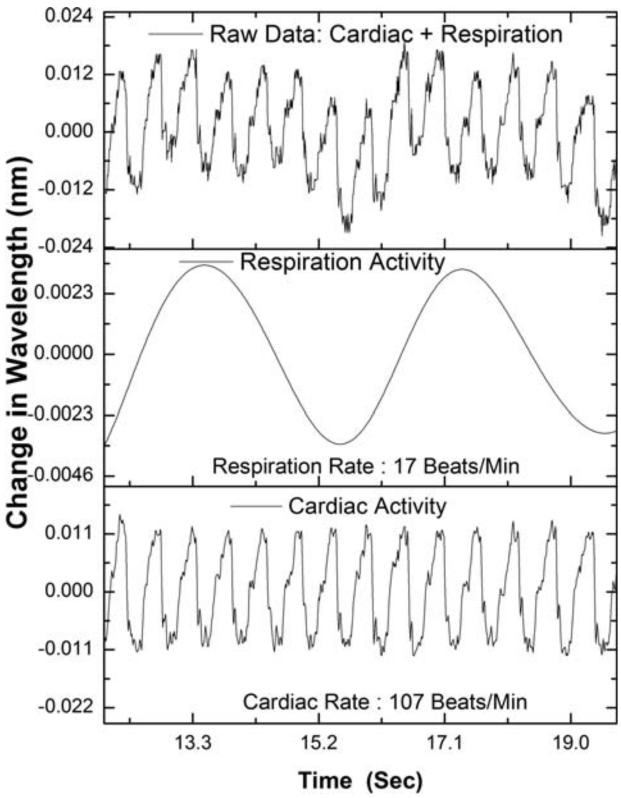

Figure 6 Expanded view of two respiratory cycles from Figure 5 which illustrates the quality of single recording and superiority of extracted morphology of each beat.

nal obtained from stethoscope is plotted in Y axis whereas X axis is the common real-time. Figure 8 shows the expanded view of FBGHBD and stethoscope response for 10 heart beat cycles. From Figure 8, it is evident that the heart beat envelopes obtained from FBGHBD and the spikes obtained from stethoscope match with each other in the entire stretch of the data signifying the correlation. It is pertinent to note here, that the stethoscope offers only the frequency of cardiac activity whereas the FBGHBD signal also provides the independent heart beat morphology.

5.4 Quantitative analysis of the subjects under test

A quantitative analysis of FBGHBD signals of all the trials recorded from all subjects has been carried out to extract the breathing and cardiac activity frequencies and the results of the cardiac frequencies are compared against stethoscope readings. Table 1 shows the individual trials of each subject and their corresponding breathing and heart rates to calculate average values per minute. From Table 1, it is evident that from all the trials of the subjects, the frequency of heart beat obtained from FBGHBD matches exactly with the heart beat frequency obtained from the stethoscope. The results of this table which comprises statistics of twelve trials of four subjects, signifies the reliability, accuracy and uniqueness of the FBGHBD in simultaneous extraction of respiratory and cardiac frequencies.

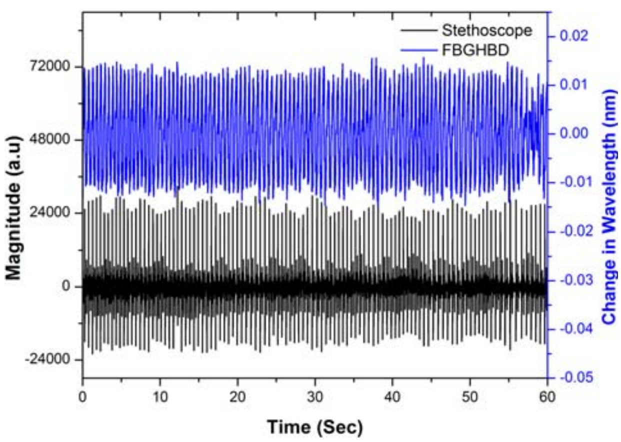

Figure 7 Comparison of FBGHBD and digital stethoscope.

Table 1 Quantitative analysis of FBGHBD results with stethoscope of all the volunteered subjects.

Sl No	Trials	Respiratory Rate/Min	Cardiac Rate/Min		Average Heart Rate/Min	
		FBGHBD	FBGHBD	Stethoscope	FBGHBD	Stethoscope
Sub 1	Trial 1	17	107	107	103	103
	Trial 2	16	99	99		
	Trial 3	17	103	103		
Sub 2	Trial 1	6	65	65	62	62
	Trial 2	7	62	62		
	Trial 3	6	58	58		
Sub 3	Trial 1	20	70	70	67	67
	Trial 2	18	72	72		
	Trial 3	16	67	67		
Sub 4	Trial 1	9	81	81	79	79
	Trial 2	11	77	77		
	Trial 3	13	79	79		

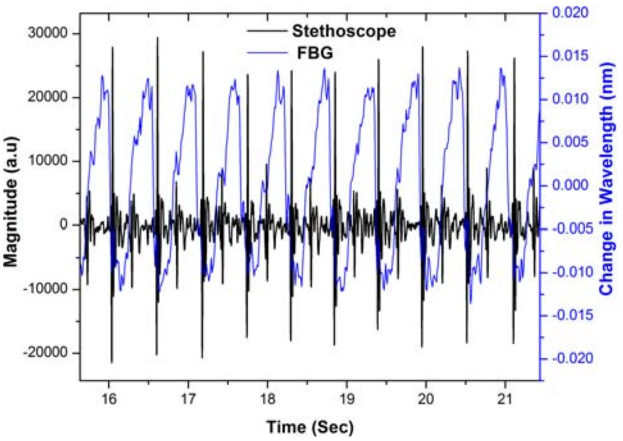

Figure 8 Expanded view of FBGHBD and stethoscope signal for10 heart beat cycle.

6. Conclusion

A novel, *in-vivo*, non-invasive, simple, portable technique for the simultaneous measurement of respiratory and cardiac activity using Fiber Bragg Grating Heart Beat Device (FBGHBD) is developed and illustrated in this work. The developed FBGHBD has the ability to simultaneously record respiratory and cardiac activities using a single FBG sensor. The obtained results of the FBGHBD have been compared with the results obtained from an electronic stethoscope which detects and records sound pulses originated from cardiac activity.

The unique design of FBGHBD provides additional critical information such as nascent morphology of cardiac and breathing activity, heart rate variability, heart beat rhythm etc. which can assist in early clinical diagnosis of many conditions associated to heart and lung malfunctioning. The developed FBGHBD is simple in design, robust, portable, repeatable, EMI proof, shock proof and non-electric in its operation which are desired features for any clinical diagnostic tool used in hospital environment. The inherent advantages of FBGHBD make it best suitable for measurements in biomechanics and biomedical settings involving human trials.

Author biographies Please see Supporting Information online.

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