Performance analysis of an innovative sensory system based spirometer for diagnostic evaluation of COPD and CRPD diseases

Surajit Bagchi Dr. Madhurima Chattopadhyay
Heritage Institute of Technology;
Dept. of Applied Electronics & Instrumentation
Kolkata, India.
e-mail: sjb.prof@gmail.com; madhurima02@gmail.com

***Abstract*—This paper introduces an optics based sensory system to improve the performance of the conventional and modern (developed so far) spirometry in terms of cost, functionality, reliability for the diagnosis of two common respiratory diseases like chronic obstructive pulmonary disease (COPD) and chronic restrictive pulmonary disease (CRPD). In our present work, we have incorporated a cordless optics based sensing system which carries many unique features which include i) no external hardware interfacing circuit (for communication of signal to the computing device) thus reducing hardware complexity ii) A noise free computer compatible output. In order to analyze the output (coming out from the sensing system), we have derived an algorithm for faithful reproduction of the breathing pattern graphically. At the same time, the significant spirometric values are displayed numerically. This makes a more reliable approach by storing the information for future analysis to have a meaningful solution (by comparing with that of normal subjects) for the above mentioned respiratory disorders. The test results obtained from our experimental studies by using the proposed model are in good agreements with the actual clinical conditions of different subjects. In order to evaluate the performance of the device more precisely, the experimental results are further verified with the standard 'Pulmonary Function- Reference Normal Predicted Values Calculator' The investigation revealed a very good correlation between the two.**

***Keywords*— Spirometer, wireless optical sensor, spirometric values, respiratory disorders, COPD, CRPD, electrical isolation, shock hazards, Reference Normal Predicted Values Calculator.**

I. INTRODUCTION

Spirometry is the most commonly performed pulmonary function test (PFT). It is often the first test performed when a problem with lung function is suspected. The test produces a recording of the patient's ventilation under conditions involving both normal and maximal effort. The recorded output, called a spirogram, shows the volume of respiration. One can easily derive the rate at which the air travels into and out of the lungs. A spirometer can be used to measure the FVC (Forced vital capacity) and its derivatives (such as FEV1, FEF 25-75%), Forced inspiratory vital capacity (FIVC), Peak expiratory flow rate, Maximum voluntary ventilation (MVV), Slow VC, IC IRV, and ERV, Pre and post bronchodilator studies. From the spirogram obstructive and restrictive disorders can be accessed.

The optics based spirometer was first reported in 1975, Zdenek V. Kozak and Joseph Jaromir used a pair of light sources and a pair of photo sensitive elements to detect ventilation flow rates. In their particular set-up, a moving vane type air flow sensor had been designed as primary sensor for measuring inhalation and exhalation flow rates of the human lungs. The photosensitive devices are arranged in such a way that they can easily identify the rotational movement of the vane type transducer [1]. An optical digitizer for measuring spirometer output was patented by Hart at el. in 1980 which claims to generate an electrical signal which is proportional to the forced vital lung capacity [2]. Later on , in 1985, M D Morgan, A R Gourlay, D M Denison developed a method of three dimensional optical mapping that allows the shape and motion of the chest wall in recumbent patients. It uses a single camera at a fixed viewpoint to determine the three dimensional coordinates of the visible surface of the body, and hence to measure the volume and shape of the visible segment [3]. In 1998, Geoffrey M Weinberg and John G Webster designed, built and tested a proof-of-concept system based on optical encoder technology for measuring adult or infant ventilation [4] Afterwards in 2002, Cihat Ozhasoglu and Martin J Murphy observed breathing characteristics for five healthy subjects by optically tracking the displacement of the chest and abdomen and by measuring tidal air volume with a spirometer [5]. Nevine Mikhail-Hanna et.al assessed (2003) the potential for optical coherence tomography (OCT) for real-time imaging of pleural or peripheral lower airways as well as lungs in various states of inflation [6]. An optical fiber sensor, based on the macro-bending loss effect, was redeveloped for thoracic and abdominal circumference measurements. This non-invasive plethysmographic respiratory system used for health monitoring was reported by A.T. Augousti et al. in year 2005[7]. In the same year, a different proposal was given by Lay-Ekuakille, A. Scarano, A.V. Trotta, where they introduced a smart improvement in Pneumo-tachographic system via breath recognition and opto-isolation . They adopted optically coupled amplifier to allow inspiration recognition to select different patients: child, young, or old man breath to enhance the sensitivity of the differential pressure sensor [8]. An instrument to evaluate and calculate the volume of air inspired and expired by the lungs was devised by Tawa, H. et al. in 2009.

The system was composed of an optical sensor (which was attached to the patient's chest and measures chest circumference), an accelerometer, a microcontroller, a Bluetooth module and a laptop computer [9]. In year 2010, Lipi Mohanty and Kevin S. C. Kuang invented a breathing rate sensor with plastic optical fiber, demonstrating the ability to quantify the breathing rate and monitor different breathing patterns up to a resolution of 1 breath/second (1 Hz). They applied the principle of coupling loss in designing this sensor to take advantage of the large core size of plastic optical fiber [10]. Wook Jae YOO et al. in 2010, proposed an optical fiber-based respiration sensor for a noninvasive respiratory monitoring gadget, where they fabricated two types of noninvasive nasal-cavity-attached fiber-optic respiration sensors. One is a silver halide optical-fiber-based respiration sensor that can measure the variations of infrared radiation generated by the respiratory airflow from the nasal cavity. The other is a thermochromic-pigment-based fiber-optic respiration sensor that can measure the intensity of reflected light which changes due to color variations of the temperature-sensing film [11]. In the same year, a non-contact type optical procedure was reported by Wolfgang Drexler et al for precise measurement of respiration rate and flow. This method was based on the measurement of external chest wall movement by a laser Doppler vibrometer [12].

In our present scheme, the sensory system translates the subject's breathing pattern into analogous radio frequency, which is compatible to the computer. The computer receives signal from the sensor directly and produces a spirogram by executing a dedicated software program. From this spirogram, we obtain the value of Forced Expiratory Volume of air in first one second (FEV1) and Forced Vital Capacity (FVC). The flow-volume pattern, a derivative of volume-time response, is generated for the evaluation of two respiratory parameters viz. Forced Vital Capacity (FVC) and Peak Expiratory Flow (PEF). The computer offers an easy means of data storage which further may be connected to LAN /WAN to enable a distantly located doctor to examine the subject online for necessary interpretation and medical advice. In this present study, we have started with the working principle of spirometer, followed by the schematic layout of our proposed scheme. The next section deals with results and discussions in which the performance assessments have been made with standard reference spirometric values. In order to perform such a bio-medical analysis, we are indebted to doctors and operators of various hospitals as mentioned in acknowledgement section. Finally the pros and cons of our designed instrument are discussed in conclusion.

II. WORKING PRINCIPLE

The working principle of our proposed device is described through a block diagram as shown in the Fig. 1. It relies on the transduction of the ventilation profile of the subject into analogous linear mechanical displacement which is further transformed into replicated radio-frequency signal by our advised cordless optical sensor. The computer captures and decodes the information sent by the sensor with the help of an algorithm written in C language. This high level language

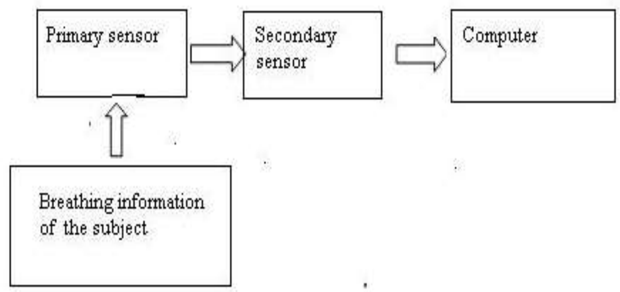

Fig.1: Block diagram of the proposed device

based program enables the processor to display the spirograms and their derivatives.

III. SCHEMATIC OF THE DEVICE

The schematic diagram of the developed device is shown in the Figure 2. We have designed the primary sensor to compose of two coaxial cylinders, made-up of plastic. One end of the stationary outer cylinder is open to atmosphere and its tapered end goes to the mouth of the subject (nose is kept clipped off throughout the experiment). The inside cylinder undergoes linear and bidirectional movement responding the inhalation and exhalation pattern. This movement is sensed by the optical sensor as secondary transducer. It has been reported that such cost-effective optical sensors are used extensively for displacement measurement in different applications [13].

The wireless optics based sensor communicates a noise free signal to the computing device. The computer after computation provides a graphical impression suggesting the respiratory disorder like COPD or CRPD, if any. The patient is electrically isolated from the computing device thus no fear of electrical shock hazards.

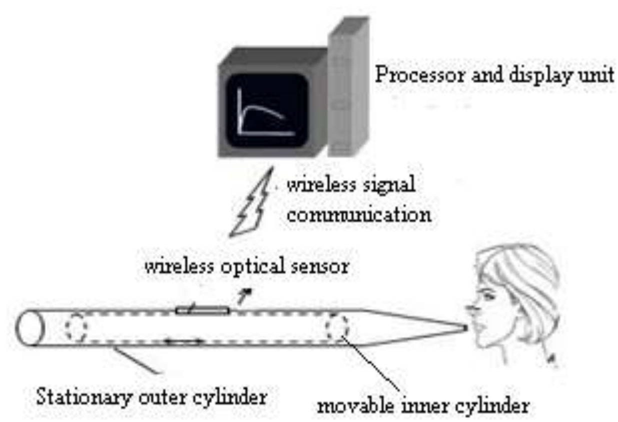

Figure2:Schematic set-up of the proposed device

IV. STATISTICAL DATA OF THE SUBJECTS

We studied the respiratory activities of 30 male volunteers. As per their age, weight, height and ventilator status, the subjects were divided into three groups. Group-I consisted of 10 non-smoker subjects whose respiratory systems were clinically reported as normal. Group-II was formed with another 10 patients each with the clinical diagnosis of chronic obstructive pulmonary disease (COPD). Rest 10 subjects, categorized as group III, were suffering from CRPD as summarized in Table I.

Table I: Statistical data of the subjects

Group	**Respiratory status of the subjects**	**Age group (Years)**	**Height limits (Cms.)**	**Weight limits (Kgs.)**
I	Normal	30-45, mean $\pm$ 4.7	150-180, mean $\pm$ 5.8	55-75, mean $\pm$ 4.5
II	COPD	30-60 ,mean $\pm$ .3.4	150-180, mean $\pm$ 7.8	50-80, mean $\pm$ 9.8
III	CRPD	30-60 ,,mean $\pm$ 2.8	150-180, mean $\pm$ 2.1	50-80, mean $\pm$ 3.7

V. RESULTS AND DISCUSSIONS

In this study, two different types of abnormal ventilation responses have been observed. One is Chronic Obstructive Pulmonary Disease (COPD) and other one is Chronic Restrictive Pulmonary Disease (CRPD). These obstructive and restrictive patterns can be identified from spirograms. Here, ventilation volume in liters (along vertical-axis) versus time in seconds (along horizontal-axis) is plotted for normal. COPD and CRPD affected subjects as shown in Fig. 3 to Fig.5. The flow-volume profile is the derivative of the spirogram. In this case, air flow in liters/sec. (along vertical-axis) versus volume in litters (along horizontal-axis) is plotted for each of the cases as stated above shown in Fig. 6 to Fig. 8. We have observed patterns for three different cases as discussed below. After discussing these three cases, finally we have given a summary of the experimental results of important spirometrc values with the reference values in a tabular form in Table II.

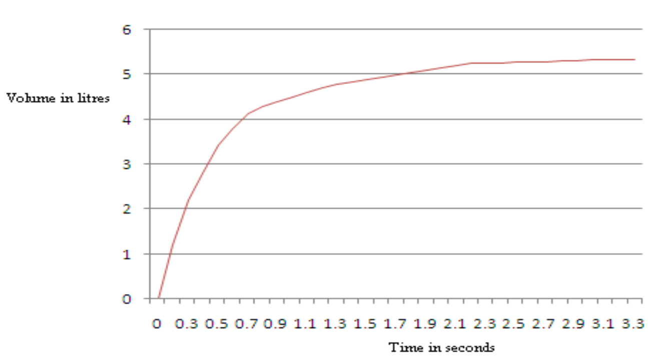

Figure 3: Normal volume –time curve

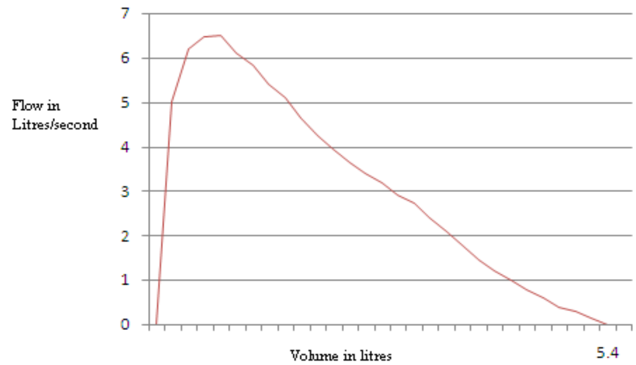

Figure 4: Normal exhaled flow-volume response

Table II shows the comparative study of the spirometric values (FEV1, FVC and PEF) as recorded using our proposed device (of the three types of subjects, with the reference values. The observed values are all within the specified standard ranges and very close to the reference values.

Case1: Spirograms showing normal respiratory behaviors.

We have obtained the spirograms of ten healthy male volunteers (Table-I: for statistical data). Fig. 3 shows the exhaled volume –time response of a normal subject, using our proposed device. With the help of our proposed algorithm the computing device generates flow-volume pattern as shown in the Fig. 4 from the spirogram (Fig. 3).
We have observed that the curve rapidly mounts to a peak point giving peak expiratory flow (PEF) initiating from origin (0, 0). We have found that the curve then descends almost through a straight line to a value where flow is zero and air volume is Forced Vital Capacity (FVC). We have found that the observations are in satisfactory agreement with the actual clinical condition.

Case2: Spirograms showing obstructive respiratory behaviors

We have studied ten male subjects, suffering clinically from obstructive diseases (most common forms are asthma and COPD).

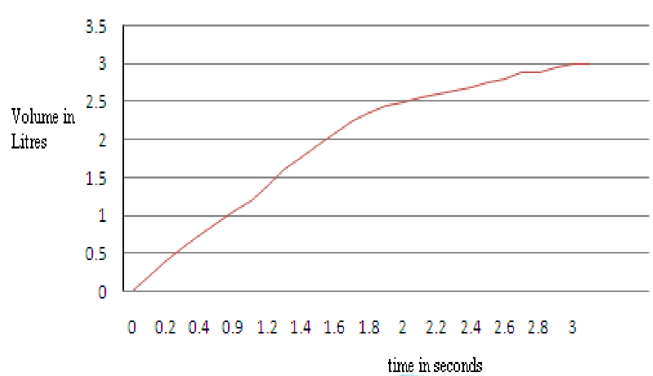

Figure5: Obstructive volume-time curve

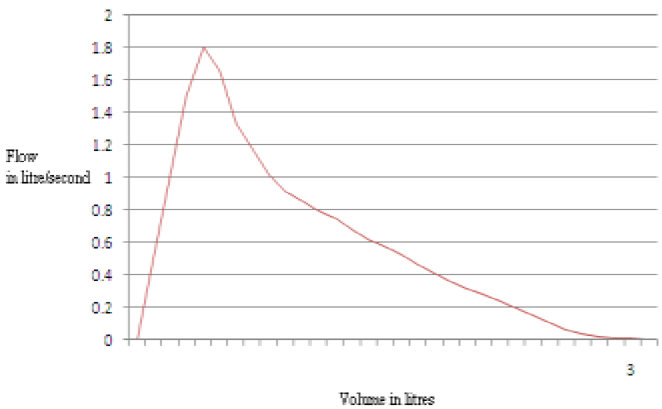

Figure 6: Obstructive exhaled flow-volume curve

In patients with obstructive lung disease, the small airways are partially obstructed by a pathological condition. Fig. 5 represents the volume-time response of a patient as we have examined by our proposed instrument.

We have seen that FEV1 is lower than that he normal value. From the Flow volume characteristics (Fig. 6) as provided by our device, we have observed that the PEF is smaller here relative to its normal value and from the PEF the curve has started to descend following a concave pattern. Higher the concavity, severe is the disease.

Case3: Spirograms showing restrictive respiratory reaction

With the help of our developed instrument, we have examined ten subjects who are facing restrictive diseases. Comparing Fig. 7 with Fig. 4, we have observed that FEV1 is almost same thus concluding that the airways are normal. We have obtained the shape of the exhaled flow-volume response (Fig. 8) outline similar to the normal record (Fig. 4) but in reduced size. Over all shape is small and oval in outline. The curve descends in a straight line from the peak expiratory flow level to the volume-axis of the curve. We have studied the spirograms to obtain (FEV/FVC)% .We observe that the (FEV/FVC)% values are close to each other for normal and CRPD distressed subjects ,whereas, the COPD affected subjects have low (FEV/FVC)% values (Table II)

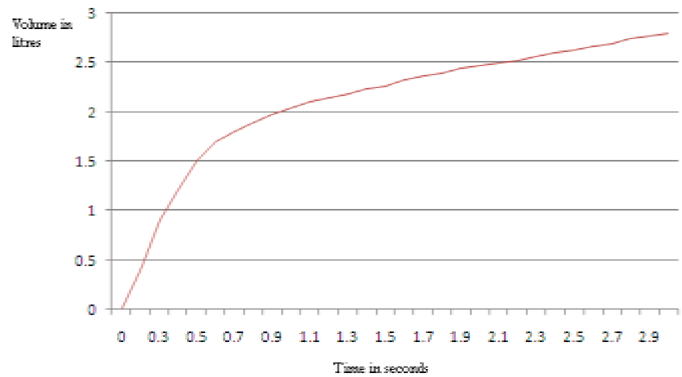

Figure7: Restrictive spirogram

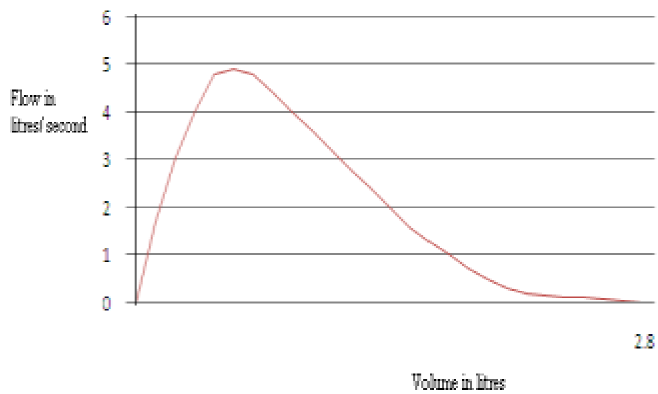

Figure 8: Restrictive exhaled flow-volume curve

VI. CONCLUSIONS

We have further verified our experimental data with that from the Pulmonary Function - Reference Normal Predicted Values Calculator [15.16]. Fig.9 and Fig. 10 depict the graphical comparison of these two for the normal FEV1 and FVC values of 10 subjects having similar statistical data. In these graphs, the red colored pattern shows our experimental data while the blue colored curve presents the values from Pulmonary Function - Reference Normal Predicted Values Calculator.

We have used the technique of correlation to verify statistical significance of the association. We further have applied the regression analysis method to check the relationship between the two by means of an equation. We have calculated the correlation and regression coefficients and derived the regression coefficient as depicted in Table-III.

We have observed a close agreement between these two (Pulmonary Function - Reference Normal Predicted Values and our proposed spirometer) as supported by the Table III.

The effectiveness of the optical sensory scheme along with the computational device has been verified with experimental studies on fifty different human respiratory systems. Though the experimental results are suggestive for qualitative diagnosis, still there is a scope to enhance the performance of the gadget by optimizing the design of the primary sensor .

Moreover, the simplicity of the system (we have described in this paper), allows even unskilled technicians/ operators to capture the breathing information in remote parts of our country. The promising attribute of the device is that its cost is much less (US$150) compared to the prices of other such instruments available in the market (US$1500-$2500).The added advantages of our optical sensing scheme are to provide almost maintenance free device with complete electrical isolation between the patient and system which minimizes the electrical shock hazards.

TABLE II A summary of experimental results of three important spirometrc values and their agreement with the reference values

Groups	Average value of FEV1 (liters)		Average value of FVC (liters)		Average value of (FEV1/ FVC)%	PEF (liters/second)	
	Values obtained through our device	Recommended Values(range)	Values obtained through our device	Recommended Values(range)		Values obtained through our device	Recommended Values(range)
Normal	4.3	1.98 –5.35	5.4	2.16–6.45	80	6.5	5.28–13.95
COPD	1.2	0.41-2.72	3.1	0.71– 4.02	39	1.8	1.02–9.55
CRPD	2.1	0.95–3.01	2.8	1.08–4.13	75	5.0	2.35–10.80

Table III: Statistical analysis of FEV1 and FVC values between our device and the calculator [16] for normal subjects

Parameters	Correlation Coefficients	Regression Coefficients	Regression Equation
FEV1	+ 0.9587	0.9581	Y=1.129X-0.4376
FVC	+ 0.9693	0.9693	Y=0.8079X-0.7762

In the equations in Table-III, X and Y represent the recorded (by our device) and the calculator provided values respectively. We moved one step further to validate results obtained so far by comparative graphical displays of FEV1 and FVC values between the normal reference calculator and proposed spirometer (Fig.9 and Fig.10).

Hence the outcome of our study helps the medical practitioners to make better quantitative assessments of their patients' pulmonary health.

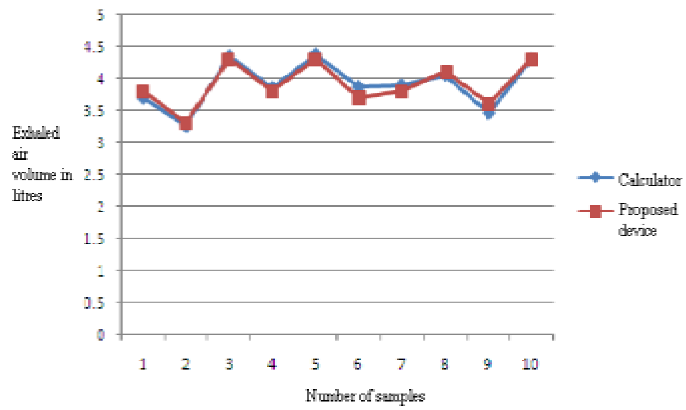

Figure 9: A comparative graphical display of FEV1 values between the normal reference calculator and proposed spirometer

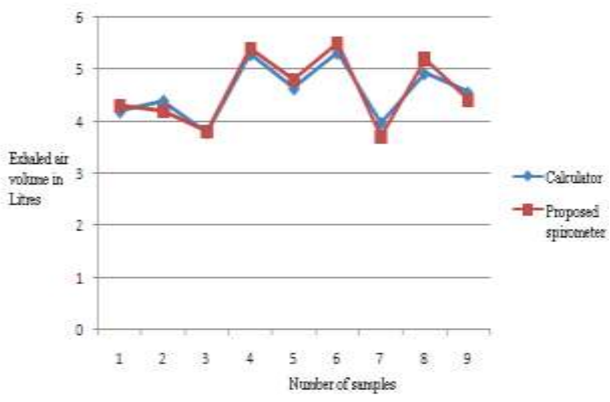

Figure 10: A comparative graphical display of FVC values between the normal reference calculator and proposed spirometer

ACKNOWLEDGMENT

The authors are willing to acknowledge the doctors of Ruby General Hospital, AMRI Hospital, Anadolok, Salt Lake, Kolkata and Mission hospital, Durgapur for data collection and necessary interpretation.

REFERENCES

[1] Kozak et al, Zdenek Vaclav Kozak , Joseph Jaromir, Stupecky , Bidirectional spirometer, Patent Number: 3922525, Country: United States,Kind Code: A,File ;Date: May 13, 1974,Issue Date: Nov 25, 1975

[2] Russell F. Hart et al, 1981, “Optical digitizer for measuring spirometer output”, US Patent 4307729.

[3] M D Morgan, A R Gourlay, D M Denison, THORAX, an international journal of respiratory medicine, Thorax 1984;**39**:101-106 doi:10.1136/thx.39.2.101IK. Elissa,

[4] Geoffrey M Weinberg and John G Webster, Physiological Measurement Volume 19 Number 3 , 1998 Physiol. Meas19 441 doi:10.1088/0967-3334/19/3/013R

[5] Cihat Ozhasoglu, Martin J Murphy, “Issues in respiratory motion compensation during external-beam radiotherapy”; International Journal of Radiation Oncology*Biology*Physics, Volume 52, Issue 5, 1 April 2002

[6] Nevine Mikhail-Hanna, BS, David Mukai, MS, Naglaa H. El-Abbadi, BS, Wong-Gyu Jung, ME, Reza Mina-Araghi, MD, Zhongping Chen, PhD, Henri Colt, MD and Matthew Brenner

[7] A.T. Augousti, F.-X. Maletras, J. Mason, Technology, The use of a figure-of-eight coil for fibre optic respiratory plethysmography: geometrical analysis and experimental characterisation. *Optical Fiber Technology*, Volume 11, Issue 4, October 2005, , pp. 346-360. ISSN (print) 1068-5200

[8] Lay-Ekuakille, A. Scarano, A.V. ; Trotta, A. , Instrumentation and Measurement Technology Conference, 2005. IMTC 2005. proceedings of the IEEE, 16-19 May 2005, Volume: 1, on page(s): 381 – 383.

[9] Tawa, H. ,Yonezawa, Y. ; Maki, H. ; Ogawa, H. ; Ninomiya, I. ; Sada, K. ; Hamada, S. ; Caldwell, W.M. , Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE, 3-6 Sept. 2009, on page(s): 5179 – 5182.

[10] Lipi Mohanty and Kevin S. C. Kuang , “A breathing rate sensor with plastic optical fiber “, Appl. Phys. Lett. 97, 073703 (2010) http://dx.doi.org/10.1063/1.3480601

[11] Wook Jae YOO, Kyoung Won JANG, Jeong Ki SEO, Ji Yeon HEO, Jin Soo MOON,Jae Hoon JUN, Jang-Yeon PARK, and Bongsoo LEE, “Development of Optical Fiber-Based Respiration Sensor forNoninvasive Respiratory Monitoring"; School of Biomedical Engineering, College of Biomedical and Health Science, Research Institute of Biomedical Engineering, Konkuk University, Chungju 380-701, Korea,2010

[12] Jürgen Popp, Wolfgang Drexler, Valery V. Tuchin, Dennis L. Matthews “A non-contact optical procedure for precise measurement of respiration rate and flow” ,Proc. SPIE 7715, 77150G (2010); http://dx.doi.org/10.1117/12.854482

[13] T. W. Ng, “The optical mouse as a two dimensional displacement sensor, Sensors and Actuators” A 107(2003) 21- 25.

[14] R.O. Crapo, A.H. Morris, P.D. Clayton, C.R. Nixon, Lung Volumes in Healthy Nonsmoking Adults. Bull Eur. Physiopathol. Respir., 18:pp.419-425, 1982.

[15] D.W. Dockery et al., “Distribution of Forced Vital Capacity and Forced Expiratory Volume in One Second in Children 6 to 11 Years of Age”;American Review of Respiratory Disease, Volume 128, pp. 405-412, 1983.

[16] H. Hedenström, P. Malmberg, K. Agarwal. Reference Values for Lung Function tests in Females. Bull. Eur. Physiopathol. Respir. 21, pp. 551-557, 1985.

[17] H. Hedenström, P. Malmberg, H.V. Fridriksson. “Reference Values for Lung Function tests in Men: Regression equations with Smoking Variables”. Upsala J. Med. Sci., 91: pp.299-310, 1986