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A Convenient Pulmonary Volume and Flow Detection System

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Abstract—**The pulmonary function test (PFT) is a widely used test in patients or for those who are at risk of respiratory dysfunction. In this study, we aimed to develop a more convenient system, namely, the impedance pulmonary function measurement system (IPFS), for overcoming the restrictions posed by the prevalent spirometric PFT. IPFS employs tetra polar electrodes that can measure pulmonary function using the subjects' hands alone. The impedance measured by IPFS extracts AC values of pulmonary impedance from DC values of body impedance in respiration. This system yields changes in the impedance of volume and flow. In order to verify IPFS, we compared the continuous waveforms obtained from the PFT module and developed IPFS using Pearson linear correlation coefficients ($p < 0.01$) for volume and flow. Further, we evaluated the potential application of IPFS for detecting pulmonary functions such as volume (FEV_1/FVC Ratio) and flow (PEF), and compared the measured parameters between IPFS and spirometric PFT. Our results demonstrate that the measurements obtained using IPFS reflect pulmonary function parameters.**

I. Introduction

THE pulmonary function test (PFT) is one of the essential tests for patients or for those who are at risk of respiratory dysfunction. With the increase in the number of patients with lung disease, the usefulness of this method has risen considerably, and many patients show abnormalities in the PFT even if their recent chest radiographs appear normal[1]. The PFT is a reproducible and qualitative evaluation method for identifying dyspnea, the severity and progress of which is otherwise difficult to grade by the symptoms alone.

Currently, the PFT includes testing the lung ventilation function while breathing through the mouth with the nose closed, the diffusive capacity in which a gas is distributed by penetrating the capillary membranes of the lung sac, and the cardiopulmonary function by heart catheterization. The PFT is very restrictive due to the long test time and the requirement of a specialist for performing it. Further, these methods may cause rejection and fatigue in the patient.

Therefore, to overcome these obstacles, previous studies have reported the use of electrical impedance plethysmography (EIP) as an alternative to PFT, resulting in a reduction in time, cost, and capital while monitoring and intensively treating pulmonary function [2]–[4]. However, a chest belt and electrode were applied on the thorax of patients in order to measure EIP, thus physically restricting the subjects' mobility. Goldensohn and Zablow [5] reported the relationship between the respired volume measured by spirometry and the corresponding changes in impedance measured on each arm above the wrist. Agarwal et al. [6] applied frequency analysis to the EIP signal and compared it to PFT parameters; however, they did not calculate PFT directly from the EIP signal. Current studies provide the tidal volume and respiration rate, but thus far, no previous investigations have estimated PFT parameters FVC, FEV_1, FEV_1/FVC ratio, and PEF using the impedance method.

Existing general impedance methods measure the static impedance such as body impedance, which is affected by the posture of the subject and the position of measurement. We developed the impedance pulmonary function measurement system (IPFS), which overcomes the restrictions posed by the currently used spirometric PFTs. Our system detects dynamic impedance, which is independent of static impedance because the static impedance extracted by the improved resolution part in our system.

II. Hardware Design and Implementation

A. Impedance Pulmonary Function Measurement System

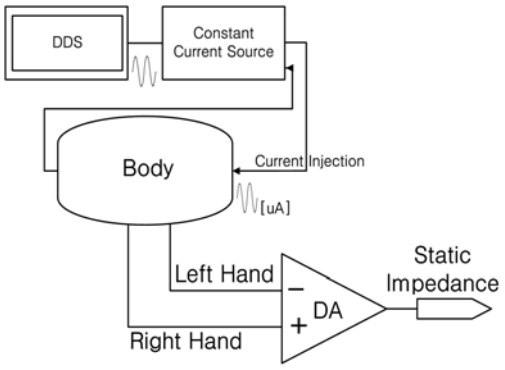

Fig. 1. Block diagram of Impedance System of IPFS.

The sine wave generated by a DDS (direct digital synthesis) is converted from a constant current source. As shown in Fig. 1, it is injected in both the hands of the subject to measure

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static impedance such as the body impedance. The measured static impedance includes the change in the volume and flow of lung impedance during respiration (Fig. 2). Therefore, the resolution of IPFS should be improved as compared to that of spirometric PFT. Through this method, it is possible to detect pulmonary function by measuring the impedance in the subjects' hands alone.

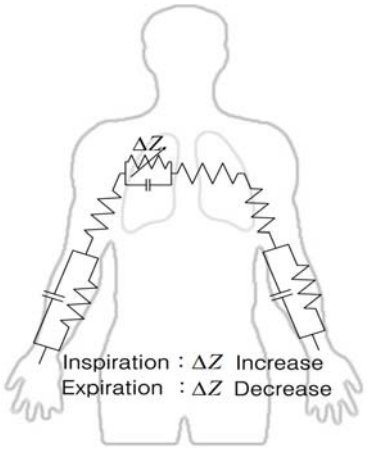

Fig. 2. Measuring lung volume and flow using both hands by IPFS.

When used with a constant current source, IPFS should be within the intensity and frequency range that does not cause any tissue reaction [7], [8]. Therefore, the lower part of the stimulus intensity-time curve should be used to measure body impedance (Fig. 3). The lower part of the curve refers to high frequency and minimal intensity. Therefore, this study used 50 kHz [9], 500 μA RMS, and 1.4 VPP.

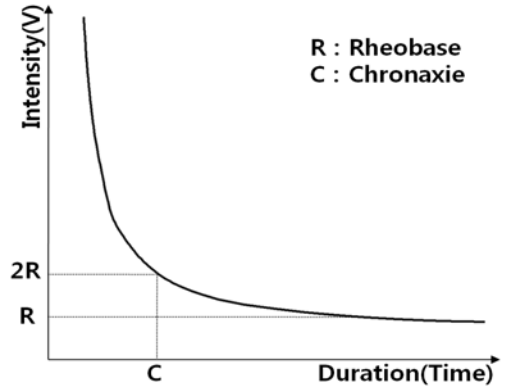

Fig. 3. Diagram of stimulus intensity-time curve

B. Improvement in the Resolution of IPFS

In case of spirometry, volume is derived from changes in flow. However, in case of IPFS, flow is extracted by changes in the volume. The impedance measured by IPFS extracts AC values of pulmonary impedance from DC values of body impedance during respiration. The impedance of a normal body is ±100 Ω; however, the range of pulmonary impedance requires a resolution of ±5 Ω. IPFS sets a high system gain to extract the pulmonary impedance. To this end, the static body impedance, minus the pulmonary impedance, is measured first using a 0.003 Hz low pass filter.

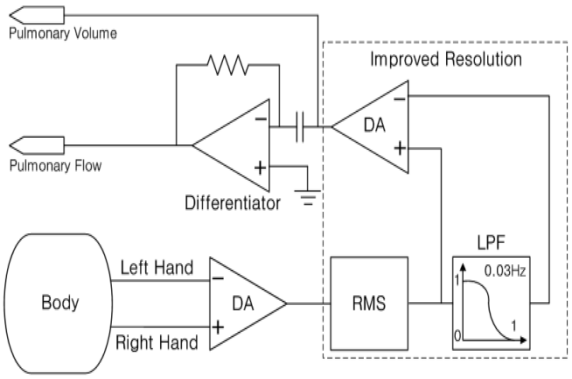

Fig. 4. Diagram of PFT with the use of IPFS.

Next, only the pulmonary impedance is extracted by subtracting the static body impedance from the body impedance by using a differential amplifier (Fig. 4). From this system, changes in the impedance of volume and flow can be acquired.

C. Clinical Experiment for verifying IPFS

A total of 4 men and 7 women (mean age: 46.36 ± 23.83 years, mean height: 159.36 ± 8.03 cm, mean weight: 59.55 ± 9.76 kg, mean body mass index: 23.50 ± 3.92) were recruited for this study. The participants were asked to avoid alcohol, caffeine, smoking, and intense physical activity for at least 12 h prior to the experiment. The protocol was reviewed and approved by the Institutional Review Board of the Wonju College of Medicine, and informed consents were obtained from all study subjects.

D. Detection of Impedance Pulmonary Function Characteristic Point

Since the impedance baseline differs across all subjects, the baseline was first detected using impedance from a stable initial state. When the flow signal crossed the baseline zero value, the volume was determined from the peak and trough obtained. We detected the impedance forced vital capacity (IFVC) using the difference between the peak and trough, and detected impedance forced expiratory volume in 1 s ($IFEV_1$) by measuring the amplitude of the volume 1 second away from the volume peak. The impedance peak expiration flow (IPEF) was detected using the maximum flow signal.

III. Experimental Results

A. Verification of Significance in IPFS

The signals for flow and volume measured using the spirometric PFT and IPFS methods are presented in Fig. 5.

The correlation coefficient between the PFT (reference) and IPFS signals were confirmed to be significant if $p < 0.01$. The p values were as follows: (a) volume inspiration, 0.981; volume expiration, 0.972; (b) flow inspiration, (i) 0.930 and (ii) 0.966; and flow expiration, (iii) 0.947 and (iv) 0.982.

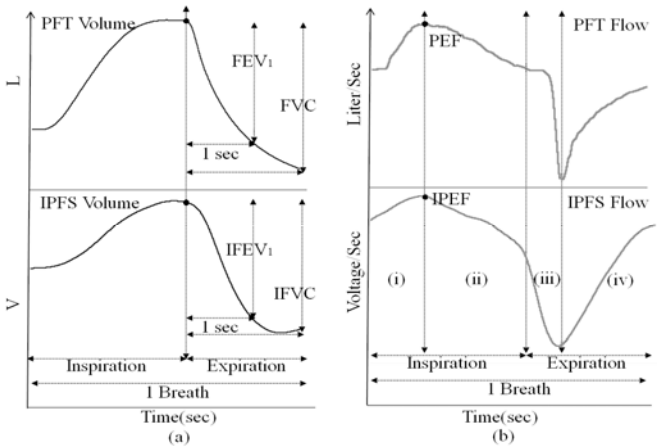

Fig. 5. Compare PFT signal with IPFS signal ; (a):Volume, (b):Flow

B. Verification of Possibility in PFT through Basic Clinical Experiment

Figs. 6 and 7 illustrate the changes in the FEV_1/FVC ratio as measured by PFT and IPFS on the volume, which is used to assess the pulmonary function. In the case of the $IFEV_1$/IFVC ratio, depending on the ratio of $IFEV_1$ and IFVC, IPFS can be used to compare the results obtained from the existing PFT (reference) without volume calibration.

FVC refers to the volume of air available for maximum exhalation after breathing in to the fullest lung capacity. FEV_1 refers to the maximum volume of air that is exhaled in one second, and this value is used primarily as the index for evaluating the main airway.

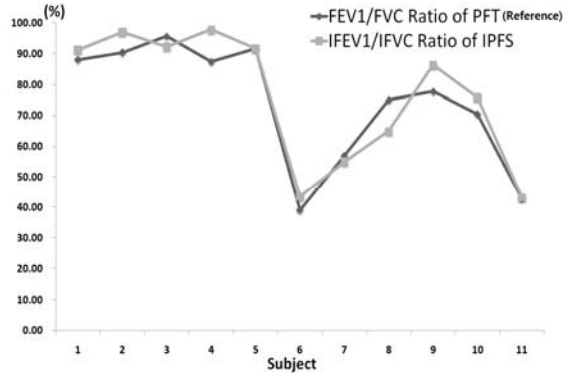

Fig. 6. Trend of FEV_1/FVC ratio between PFT and IPFS.

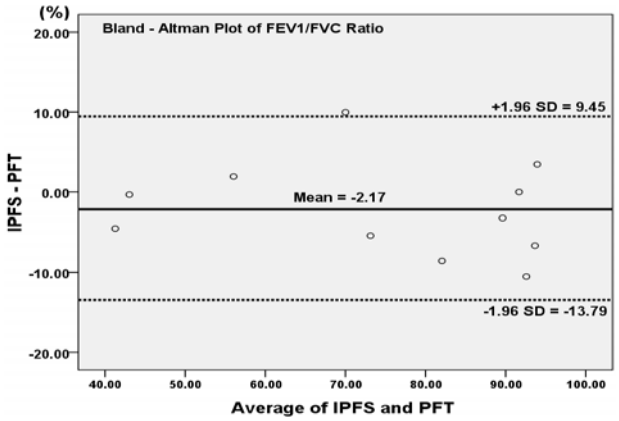

Fig. 7. Bland-Altman Plot of FEV_1/FVC ratio between IPFS and PFT signal.

Figs. 8 and 9 illustrate the changes in the normalized PEF of PFT (reference) and IPFS on the flow. PEF is the maximum expiratory flow achieved from maximum forced expiration, starting without hesitation from the point of maximal lung inflation [10]. PEF was compared to the regularized IPFS data.

The FEV_1/FVC ratio and normalized PEF values are considered important parameters in the evaluation of pulmonary function.

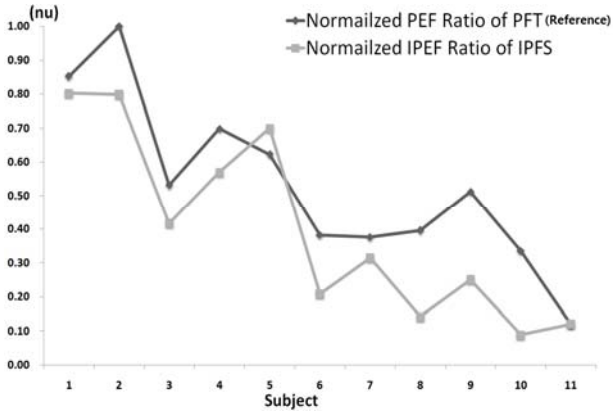

Fig. 8. Trend of normalized PEF between PFT and IPFS.

Spirometry was used to confirm the FEV_1/FVC ratio (mean: 2.17, standard deviation: ±5.93) and normalized PEF (mean: 0.13, standard deviation: ±0.11) parameters obtained by IPFS. On the basis of the trends of FEV_1/FVC ratio, normalized PEF, and Bland-Altman analysis, we confirmed that IPFS could reflect pulmonary functions as changes in the PFT parameters of volume and flow.

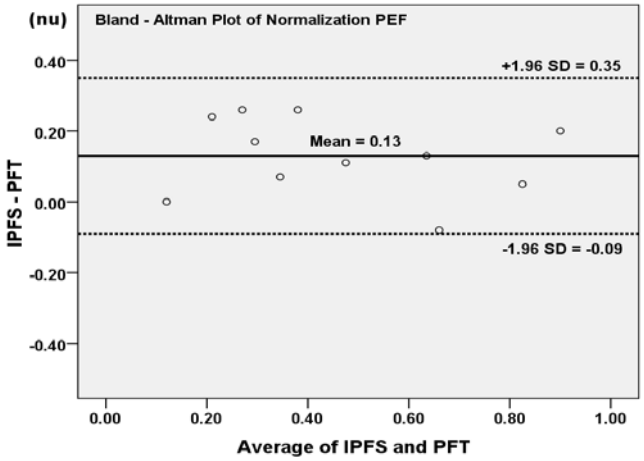

Fig. 9. Bland-Altman Plot of normalized PEF between IPFS and PFT signal.

IV. Conclusion

In this study, we developed IPFS to overcome the restrictions of the PFT performed using disposable respiratory kits (nose clip, bacterial filter, and mouth piece).

IPFS was developed using electrical impedance methods and a tetra-polar electrode system that measured changes in impedance according to the respiration of subjects by detecting the impedance on the subjects' wrists. The IPFS measures

changes in the impedance during respiration to detect the volume and flow signal with improved resolution.

The pulmonary function parameters were compared with parameters measured in a PFT module (ML-311, AD Instrument), and the results were found to be significant.

Further, we compared the pulmonary functions such as volume and flow measured by IPFS and spirometry (Vmax Encore, VIASYS Health care Inc., Hoechberg, Germany) in order to determine the potential usability of IPFS. IFVC and $IFEV_1$ were detected from the volume signal of IPFS, and the $IFEV_1$/IFVC ratio was then calculated from the obtained parameters. The IPEF detected from the flow signal of IPFS was normalized. Finally, the calculated $IFEV_1$/IFVC ratio and normalized PEF values were compared with correspond- ing PFT parameters.

In the future, achieving more detailed calibration of IPFS will enable detection of the volume-flow curve and the forced expiratory volume at 25 – 75% and evaluation of local airway function.

ACKNOWLEDGMENT

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