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Multi-Sensor Cardio-Pulmonary Stethoscope for Quantitative Lung Water Measurement

Ruthsenne R.G. Perron*[(1)], Magdy F. Iskander[(1)], Todd B. Seto[(2)], Farhan A. Qazi[(1)], Darcy A. Bibb[(1)], and Eunjung Lim[(3)]
(1) Hawaii Center for Advanced Communications (HCAC), College of Engineering, University of Hawaii, Hon., 96822, USA
(2) The Queen's Medical Center, Hon. 96822, USA, (3) John A. Burns School of Medicine, Hon. 96822, USA

Abstract

This paper describes the development of a multi-sensor Cardio-Pulmonary Stethoscope (CPS) for measuring not only changes but assesses fluid status in lungs. CPS is a microwave device for noninvasive and continuous monitoring of vital signs and changes in lung water content (LWC). It contains a "chest patch" sensor that measures scattering parameters of 915MHz signal. Measurement results are wirelessly transmitted to a mobile device for remote patient monitoring. Excellent results were obtained in clinical trials at Queen's Medical Center with correlation factors of $r \geq 0.95$ for respiration and heart rates. Results from human clinical testing showed correlation factor of $r \geq 0.93$ with amount the of fluid extracted from hemodialysis patients. To examine the feasibility of using the multi-sensor CPS system, RF simulations on 3D human thorax were conducted. Obtained results demonstrated the effectiveness of such multi-sensor arrangement in assessing fluid content in lungs. An 8x8 RF multiplexing circuit was developed to experimentally validate simulation results and for use in clinical trials. Three-dimensional simulations and experimental validation results are presented.

1. CPS Device and Measurements

To overcome difficulties with presently available techniques for measuring lung water content including high cost, indirect, invasive and lack of bedside monitoring methods, we developed the CPS system which is a novel, noninvasive, "Chest Patch" multi-sensor based measurements, as shown in Fig. 1.

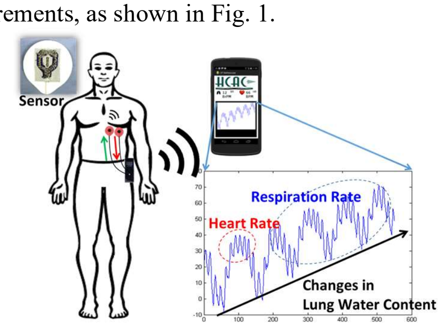

Fig. 1. Schematic of the multi-sensor CP-Stethoscope system with a micro-controller unit, and mobile App. Also shown is a typical waveform signal from a CP-Stethoscope measurement which contains the heart and respiration signals as well as changes in lung water content.

The CPS measurement method is based on continuous monitoring of the microwave scattering parameters to indicate changes in the dielectric properties of the lung tissue. An EKG-lead size sensor, based on a patented coplanar waveguide design [1-2], is placed in contact with the chest, scattering parameters are measured at 915 MHz, and multiple vital signs are derived from a single measurement using digital signal processing (DSP) algorithm [3]. This method has the advantage of using highly penetrating RF signals and electromagnetic waves that are scattered as they travel through the human body to provide in depth vital signs information including changes in lung water content.

2. Human Clinical Trial Results

CPS is noninvasive and can accurately measure the changes LWC as demonstrated by animal experiments [4-5] and experimentally tested on phantoms [3].

Recent human clinical trials on heart failure (HF) and hemodialysis (HD) patients were conducted at Queen's Medical Center, in Hon. HI. Simultaneous Pulmonary Capillary Wedge Pressure (PCWP) measurements using Swan-Ganz catheter were used for comparison of CPS data with HF patients, while change in weight of extracted fluid were used for comparison in HD patients. Thirteen HF patients and thirteen HD patients were included in this study. In all cases, HR and RR were monitored and compared with standard clinical methods.

Statistical analysis of the results showed excellent correlation, $r \geq 0.97$ for HR and $r \geq 0.93$ for RR. Detailed results of the statistical analysis of HR and RR is included in Table I. Similarly, the correlation factor between the CPS measurements and PCWP data were calculated and found to be 0.52 – 0.97 for heart failure patients, and 0.82 to 1.00 for the fluid removed from hemodialysis patients.

Example of results from a hemodialysis patient comparing fluid removed vs. trend of CPS signal during hemodialysis treatment is shown in Fig. 2.

Table I
Statistical Analysis of Heart Rate (HR) and Respiratory Rate (RR) for Heart Failure and Hemodialysis Patients

Patient Type	Variable	Pearson	Concordance	Mixed	ICC
Heart Failure	HR	0.977	0.978	0.981	0.990
	RR	0.975	0.973	0.974	0.994
Hemodialysis	HR	0.974	0.972	0.970	0.996
	RR	0.934	0.931	0.926	0.991
Combined	HR	0.978	0.978	0.981	0.995
	RR	0.951	0.950	0.956	0.991

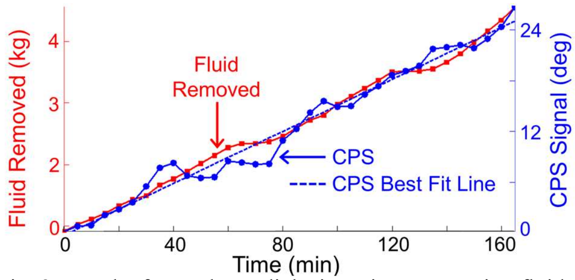

Fig. 2. Results from a hemodialysis patient comparing fluid removed and trend of the CPS signal.

3. Development of the Multi-Sensor CPS System

In its original form, the CPS is capable of monitoring vital signs and measure changes in lung water content using a pair of sensors in a chest patch arrangement [6]. To help with the development of a system that provides full screening of lung water content, a multi-sensor system was designed and fabricated. The multi-sensor system consists of an 8x8 RF-multiplexing circuit, shown in Fig. 3, that enables the RF signal to switch between sensors.

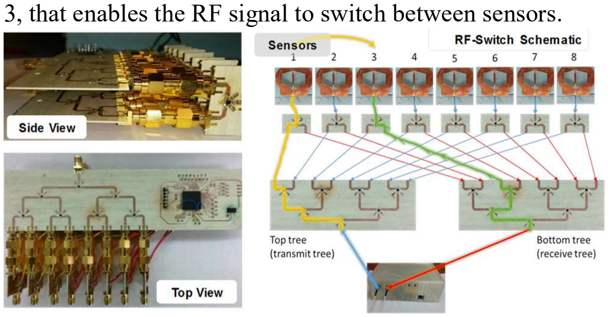

Fig. 3. Detailed view of the fabricated 8x8 RF-multiplexing circuit that will be used for the experimental validation of the multi-sensor system.

To evaluate the feasibility of using the multi-sensor system to determine status of water content in the lungs, we have conducted full 3D simulation with anatomically accurate model. Changes in the lung fluid content in both the left and right lungs were modeled similar to the previous simulations [7] from normal (20%) to edematous (40%) lung at rate of 2% increase for a total of eleven lung states. Setup and results of the 3D model is illustrated in Fig. 4. and 5, respectively.

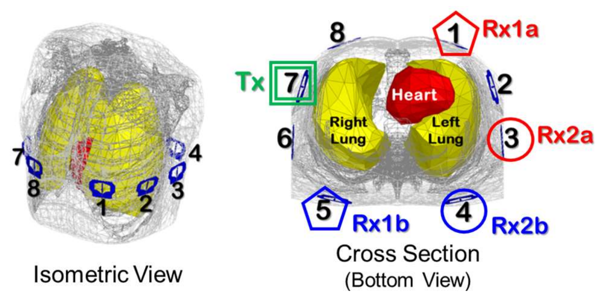

Fig. 4. Setup of multi-sensor simulation on a human 3D CAD model.

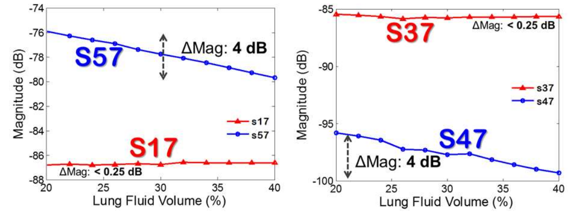

Fig. 5. S-Parameter results from multi-sensor 3D modeling.

4. Conclusion

Results from human clinical trials and simulations of a multi-sensor system on a 3D human CAD model illustrated the feasibility of using the Cardiopulmonary Stethoscope (CPS) measurement method in assessing lung water condition in addition to monitoring vital signs and measuring changes in lung water content. Development of this unique method and new multi-sensor capabilities with the 8x8 multiplexing circuit, promises a paradigm shift in pulmonary diagnosis and the development of a noninvasive system for continuous monitoring heart failure and dialysis patients.

5. Acknowledgements

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