Multilead impedance pneumography and forced oscillation technique for assessing lung tissue mechanical properties

Javier Gracia, Ville-Pekka Seppä and Jari Viik

***Abstract*—Forced oscillation technique measuring transfer impedance (Z_{tr}) is a traditional method to assess mechanical properties of the respiratory system. Lung tissue and airways mechanical properties are of clinical relevance, but difficult to distinguish from the Z_{tr} measurand.**

We propose a novel method that replaces the plestymographyc chamber in Z_{tr} by a multilead impedance pneumography (MLIP) system. We hypothesise that mechanical properties of the lung tissue should be more evident in the new method that in Z_{tr}.

We applied pressure oscillations at the mouth from 2 to 27 Hz in one sitting healthy subject holding breath at residual volume. Thoracic electrical resistivity changes where simultaneously recorded at three different heights of the thorax by a MLIP system. Lung volume changes were extract from the MLIP signals by subtracting the cardiac component calculated by means of ensemble averaging. Consequently, mechanical impedances at the three thorax levels were calculated as the complex ratio of mouth pressure (P_{ao}) and the time integral of the lung volume MLIP signals ($\dot{Q}_{IP}$): $Z_{IP} = P_{ao}/\dot{Q}_{IP}$.

We found a decrease in the real part of Z_{IP} from the upper to the lower areas of the chest. This is coherence with the known pleural pressure gradient distribution. Moreover, we observed Z_{IP} to share similarities with Z_{tr} at low frequencies, (i.e. same resonance frequency). However, Z_{IP} for the upper and lower regions of the thorax differed greatly with Z_{tr} for frequencies over 10 Hz.

Results need deeper investigation and larger clinical study samples. Nevertheless, this preliminary study shows the potential of Z_{IP} for assessing lung tissue mechanical properties.

***Index Terms*—Transfer impedance, lung mechanics, impedance pneumography, multilead impedance pneumography, forced oscillation technique.**

I. Introduction

THE forced oscillation technique (FOT) was introduced in the 1950's as a non-invasive approach to measure the mechanical properties of the respiratory system.

Two methods are commonly used: input impedance (Z_{in}), where pressure oscillations are imposed at the airway opening and the complex ratio between airway opening pressure (P_{ao}) and the resulting flow ($\dot{Q}_{ao}$) is measured ($Z_{in} = P_{ao}/\dot{Q}_{ao}$); and transfer impedance Z_{tr} where pressure oscillations are still imposed and measured at the airway opening, but patient is placed in a plestymographyc chamber and the displaced flow ($\dot{Q}_{tr}$) is measured ($Z_{tr} = P_{ao}/\dot{Q}_{tr}$) [1], [2].

The mechanical impedances contain a combination of the mechanical properties of all the elements of the respiratory system, i.e. lung tissue, thoracic wall, main and peripheral airways, etc. Mathematical models have been developed to extract the mechanical properties of lung tissue and the airways, being these two of more clinical interest. However, uncertainty in some of the parameters input into the models often compromise the accuracy of the results. Specially, under structural changes caused by respiratory diseases and diseases worsening.

Impedance pneumography (IP) is a noninvasive lung function measurement technique. IP uses four surface skin electrodes to record changes in the thoracic electrical resistivity. The thoracic resistivity signal has cardiac and a respiratory components. The cardiac component is caused by the blood redistribution within the thorax during each heart beat. In IP it is consider an interference and removed from the signal. The respiratory component emerges from structural changes in the lung tissue during respiration. Specifically, the thinning of the alveolar walls with increasing air leads to a proportional increment in tissue resistivity density [3].

We propose a novel FOT method that calculates the complex ration between the airway opening pressure (P_{ao}) and the airflow entering the lung tissue ($\dot{Q}_{IP}$), ($Z_{IP} = P_{ao}/\dot{Q}_{IP}$). $\dot{Q}_{IP}$ is calculated as the time integral of lung tissue volume changes measured with IP.

We hypothesise that IP signal solely reflects lung tissue changes and thus chest wall and diaphragm mechanical properties should not contribute to the IP impedance Z_{IP}. Studies showed that mechanical properties of the tissues are more evident in Z_{tr} that in Z_{in}. We conjecture that tissue contribution should be even more evident in Z_{IP}.

In this article we present a study case for one healthy patient using FOT and a multilead impedance pneumography MLIP system. MLIP allows to record three IP signals simultaneously in different locations of the thorax [4]. The article describes the set up, data analysis, and compares the results with transfer impedance studies found in literature.

II. Material and Methods

A. Apparatus

Figure 1 shows a block diagram of the overall system. A personal computer (PC) provided, by a means of a digital to analog converter (DAC), an electrical sine signal with configurable frequency and amplitude. Using a self-made power amplifier (Amp.) (based on a TDA7266, STMicroelectronics), this signal drove a 250 mm diameter acoustic suspension loudspeaker mounted in a 50 mm high conical frustum ending in an opening of 30 mm diameter.

The pressure signal generated by the loudspeaker was transmitted to the subject thought a Fleisch pneumotachograph

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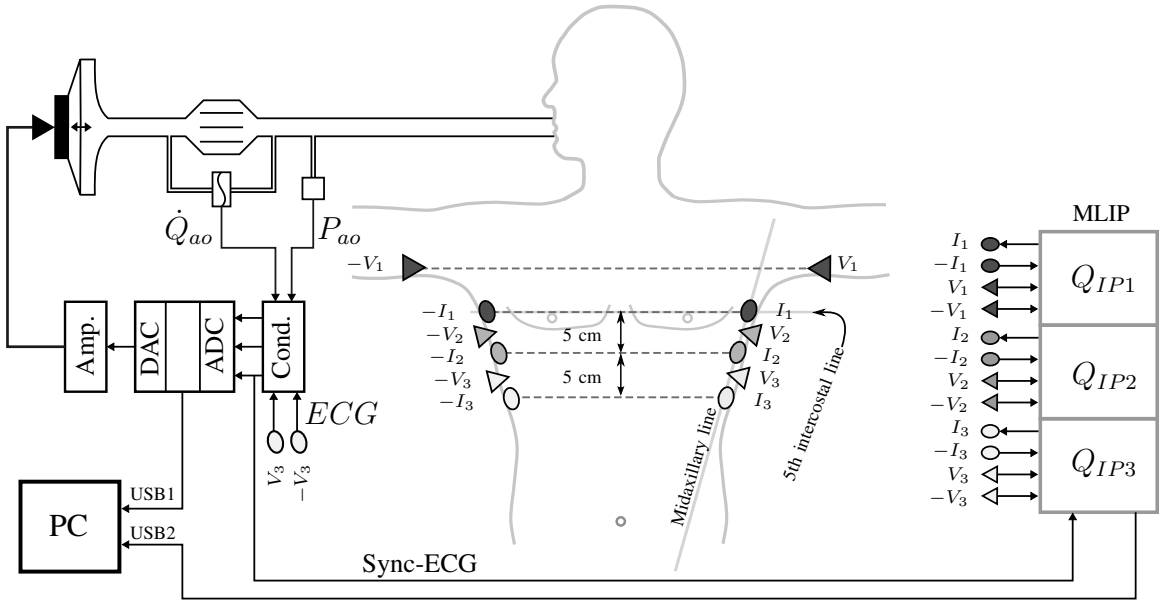

Fig. 1. Overall system block diagram and electrodes location. Filled triangles and circles over the subject's silhouette represent voltage and current electrodes respectively. Electrodes are labelled as the corresponding connector of the MLIP where they are connected. Im and $-Im$ for current feeding and Vm and $-Vm$ for voltage recording, where $m = \{1, 2, 3\}$ for the three differet leads. Recorded signals were: airway opening pressure (P_{ao}), airway flow ($\dot{Q}_{ao}$), thorax electrical resistivity changes (Q_{IPm}), and electrocardiogram signal (ECG)

and a mouth piece. The pneumotachograph was connected to a differential pressure transducer (HCLA02X5EB, SensorTechnics). Pressure at the mouth was measured by a pressure transducer (DCXL10DS, Honeywell). Transducers were connected to a conditioning circuit (Cond.) which included an electrocardiogram (ECG) amplifier. Conditioned signals were digitised by an ADC (usb6009, National Instruments) at 1 KHz connected to the PC.

Flow and pressure sensor were calibrated by a 3-litre piston. Frequency characteristics of the whole system were assessed from 0 to 35 Hz. We used the method suggested by *Brusasco et al.* [5], based in a reference impedance made of a bundle of pipelets whose impedance was predicted theoretically.

In order to make the amplitude of the pressure excitation signal independent of the load imposed, the amplitude of the electrical signal wave was controlled by a feedback control system by means of a proportional integral contol law acting in every sine cycle.

To record the three IP signals the MLIP system presented by *Gracia et al.* [4] was used. The ADC of the MLIP system was also configure to record the same ECG signal as the FOT's ADC. The common ECG signal was thereafter used as reference to synchronisedthe signals from the two ADCs.

B. Experimental set up

As show in Figure 1 each of the three leads of the MLIP system requiered a pair of electrodes for current injection ($I_m, -I_m$) and a pair for voltage measurement ($V_m, -V_m$). The first pair of current electrodes were placed on the sides of the thorax on the midaxillary line at the height of the 5th intercostal line. The two other pairs were placed lower with a separation of 5 cm. The first pair of voltage electrodes were placed on the arms between biceps and triceps brachii muscles.

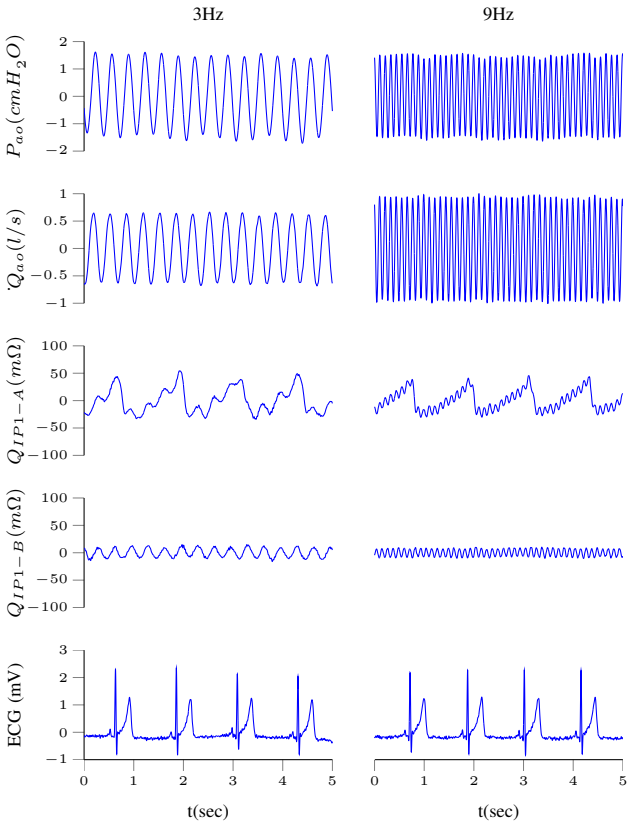

Fig. 2. Representative tracings obtained during pressure oscillations at 3 Hz (left) and 9 Hz (right) for a duration of 5 seconds; airway opening pressure (P_{ao}), airway flow ($\dot{Q}_{ao}$), upper thorax resistivity changes before (Q_{IP1-A}) and after Q_{IP1-B} CGO removal and electrocardiogram signal (ECG).

The two other pairs were placed between the three current electrodes [6]. The lower voltage electrodes pair was also use

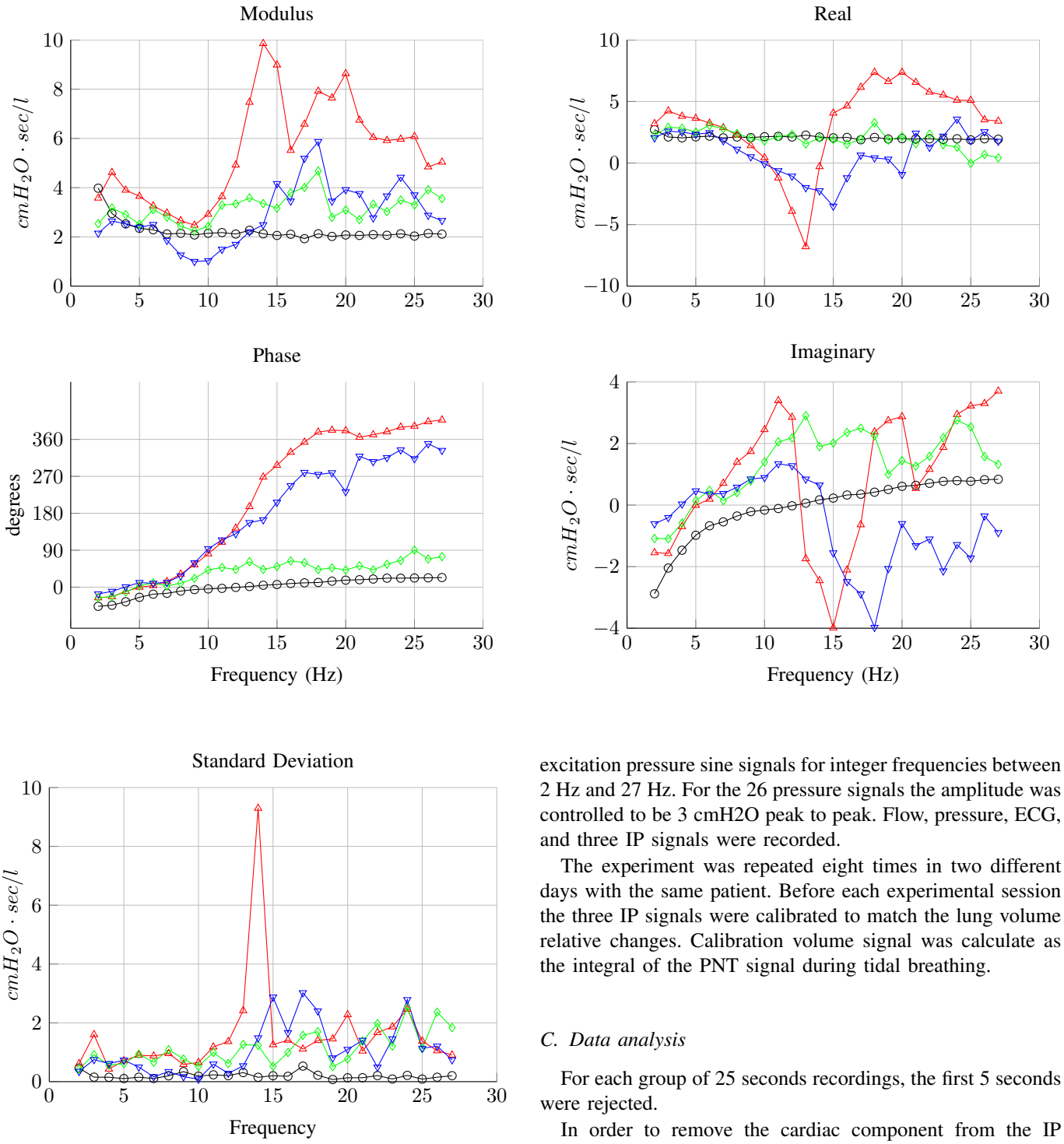

Fig. 4. Standard deviation of the eight recordings for the input impedance (Z_{in}, ◯) and the three IP impedances, from the recording at the upper (Z_{IP1}, △), $middle$(Z_{IP2}, ▽), and lower (Z_{IP3}, ◇) heights of the thorax

to record the ECG signal.

Test subject was sitting comfortably with the mouth at the height of the mouth piece opening. The patient was requested to cover the opening with the mouth for periods of 25 seconds at residual volume, keeping glottis open, and holding the cheecks with their hands. This action was repeated for 26 excitation pressure sine signals for integer frequencies between 2 Hz and 27 Hz. For the 26 pressure signals the amplitude was controlled to be 3 cmH2O peak to peak. Flow, pressure, ECG, and three IP signals were recorded.

The experiment was repeated eight times in two different days with the same patient. Before each experimental session the three IP signals were calibrated to match the lung volume relative changes. Calibration volume signal was calculate as the integral of the PNT signal during tidal breathing.

C. Data analysis

For each group of 25 seconds recordings, the first 5 seconds were rejected.

In order to remove the cardiac component from the IP signals the ensemble average method described by *Seppä et al.* was used [7]. Each IP signal was split in sections of a cardiac cycle duration, defined by the R-peaks of the ECG signal. Sections were resized to the same time duration and averaged into a cardiogenic oscillation (CGO) template. The CGO template was again resized to the duration each R-peak interval and subtracted from the original IP signal.

Results of the CGO filter are showed in Figure 2 for two different pressure excitation frequencies.

The input impedance Z_{in} and coherence function between flow and pressure γ^2_{in} was compute for each frequency as suggested by *Michaelson et al.* [8]:

$$Z_{in}(w) = \frac{G_{pf}(w)}{G_{ff}(w)} \quad (1)$$

$$\gamma^2_{pf}(w) = \frac{|G^2_{pf}(w)|}{G_{ff}(w) \cdot G_{pp}(w)} \quad (2)$$

Where G_{pf} is the cross spectrum between airway opening pressure (P_{ao}) and airways' flow signals ($\dot{Q}_{ao}$); G_{ff} is the autocorrelation spectrum of $\dot{Q}_{ao}$; G_{pp} is the autocorrelation spectrum of P_{ao}.

To calculate the IP impedances Z_{IPm} for the three IP signals ($m = \{1, 2, 3\}$) we used:

$$Z_{IPm}(w) = -jw \cdot H_{pq}(w) = -jw \cdot \frac{G_{pv}(w)}{G_{qq}(w)} \quad (3)$$

Where G_{pq} is the cross spectrum between P_{ao} and IP volume signals (Q_{IPm}); G_{qq} is the autocorrelation spectrum of Q_{IPm}; Multiplying the transfer function of pressure to IP volume ($H_{pq}(w)$) by $-jw$ is equivalent to differentiating the IP volume signal with respect to time [9].

Relationship between γ^2_{IPm} and the coherence function between pressure and IP volume (γ^2_{pq}) is :

$$\gamma^2_{pq} = \frac{|G^2_{pq}|}{G_{pp} \cdot G_{qq}} = \frac{w^2 \cdot |G^2_{f\dot{q}}|}{w^2 \cdot G_{ff} \cdot G_{\dot{q}\dot{q}}} = \gamma^2_{f\dot{q}} = \gamma^2_{IPm} \quad (4)$$

In the present study we considered only values with coherence function greater than 0.95.

III. Results

Calculated input impedances Z_{in} and the IP impedances Z_{IPm} from the eight recordings were averaged. Figure 3 shows in four different plots the modulus, phase, real and imaginary parts for the averaged values. The standard deviation of the averaged impedances is presented in Figure 4.

Input impedance Z_{in} results agree with those reported in literature for healthy patients [10]. Resonance frequency (f_0) reported to be in the range between 7.7 and 13.3 Hz, was found around 12 Hz in our case.

Comparing IP impedances Z_{IPm} with traditional transfer impedance Z_{tr} data in the literature, we observed that absolute values of Z_{IP} are smaller than Z_{tr}. *Lutcher et al*. [11] reported the real part of Z_{tr} to be 5 $cmH_2O \cdot s/l$ at $4Hz$ whereas we found it to be 3.8, 2.8, and $2.5 cmH_2O \cdot s/l$ for Z_{IP1}, Z_{IP2}, and Z_{IP3} respectively. Resonant frequency reported to be 4.9 Hz for Z_{tr} [11] was found between 4 and 5 Hz for Z_{IPm}.

IV. Discussion

Is not straightforward to compare absolute values between Z_{tr} and Z_{IP} as they may reflect different properties of the respiratory system. Moreover, the calibration assumed regional IP volume changes to be equal to the total lungs volume changes, what is not necessarily correct.

Nonetheless, real absolute values (at least at low frequencies) decreased for the middle and lower areas of the chest ($Re\{Z_{IP1}\} > Re\{Z_{IP2}\} > Re\{Z_{IP3}\}$). This agrees with the knowledge that pleural pressure gradient keeps alveoli more stretch in the apexes than in the bases of the lungs. Therefore, volume changes driven by FOT should be more noticeable in the lower unstretched alveoli.

More relevant that comparing absolute values is perhaps to compare the trend of impedance changes with frequency, or the phase plot. Phase is a relative parameter not affected by calibration . Z_{IP2} showed a similar trend with Z_{tr} at low frequencies. However, upper and lower IP impedances (Z_{IP1}, Z_{IP3}), presented a drop in magnitude for the real part and great deviation in phase for frequencies over 13 Hz. Perhaps, at these frequencies oscillations stop to produce changes in the tissue.

Standard deviation increased considerably for frequencies over 15 Hz. Amplitude of volume sine for a constant amplitude flow sine deceases at a rate of $1/2\pi f$. It lead to think that signals over 15 Hz may fall out of the resolution of the MLIP system.

V. Conclusions

We have conducted a preliminary study that, in our knowledge, shows for the first time the combined use of FOT and thoracic electrical impedance measurement. This novel idea needs further analysis of the results, improvement in the accuracy of instruments, and larger clinical study samples. Nevertheless, this new approach has the potential to obtain lung tissue properties with higher accuracy than Z_{tr}. Moreover, the lack of need for a bulky plestymography chamber could make of Z_{IP} a more accessible method.

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