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A virtual instrument for trans-thoracic impedance investigations

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Abstract- Impedance pneumography is a technique that allows the monitoring of respiratory activity through the measurement of variations in the impedance between two points located on the thoracic surface. In this paper, a low-cost, easily portable, and re-configurable measurement system is presented, suitable to perform impedance pneumography investigations, based on virtual instrumentation employing a data acquisition card controlled through a LabVIEW program. A possible approach for a metrological characterization of the system is proposed, showing a base uncertainty of the order of 0,4 % in the measurement of the resistive part of the impedance, in the range of interest. Some preliminary investigations have been performed in order to assess the influence on measured trans-thoracic impedance both of the kind of electrodes adopted for current injection and simultaneous voltage measurement and of the frequency of injected sinusoidal currents. Finally, acquisitions made on a volunteer are presented, evidencing the feasibility of the proposed system in monitoring the breath activity of a patient and in extrapolating relevant diagnostic parameters.

I. Introduction

Impedance pneumography is a technique which exploits the tight correlation existing between the different phases of respiratory activity and the variations in the impedance measured between two points located on the thoracic surface. The measurement of such impedance is extremely simple, requiring only the application of electrodes on the thoracic surface. As a consequence, this methodology does not pose any constraint to the respiration and mobility of the patient under examination, as opposed to traditional spirometric techniques which require a relevant cooperation from the patient.

The first impedance pneumography studies date back to 1944 and were based on the application of a sinusoidal current to a couple of electrodes, placed on the thorax, and on the recording of temporal variations of voltage between the electrodes themselves [1]. Later researches were devoted to the study of the connection between impedance variations and the inspired air volume, also as a function of the electrodes position [2]. The results of these studies showed that the optimal position of the electrodes, in order to achieve impedance variations as large as possible, was on the sixth intercostal space along the midaxillary line. Also in [2], the possibility to correlate the impedance variations to the inspired air volume was also demonstrated. Other literature papers aimed to study the optimal geometry for the electrodes [3]. The main problem with impedance pneumography, indeed, is to perform measurements which are not influenced by the low impedance of the thoracic surface and which are free from artifacts. The available studies showed that the solution able to minimize artifacts consists in using circular electrodes having a large area and surrounded by a metallic ring kept at the same potential of the central conductor (guard ring). Finally, it is worth mentioning that, apart from the monitoring of normal respiratory activity, impedance pneumography can also be effectively used for the diagnosis of pathological conditions, such as pulmonary edema [4].

In the present work, some numerical evaluations of trans-thoracic impedance on an anatomical model of the human thorax will be presented, with the aim to assess the optimal electrode geometry and to evaluate the entity of expected impedance variations, so as to be able to correctly design an experimental system for trans-thoracic impedance measurement. After that, a low-cost, easily portable, and re-configurable measurement system will be introduced, suitable to perform impedance pneumography investigations. A possible approach to a metrological characterization of the system will be reported and some sample recordings obtained with the proposed system on a volunteer will be finally illustrated, evidencing the effect of electrode type and frequency on measured impedance values and showing the performance of the system in monitoring normal respiratory activity.

II. Trans-thoracic impedance simulations on anatomical models

The numerical study of trans-thoracic impedance has been carried out making use of the admittance method [5]. Simulations have been performed on a three-dimensional anatomical model of the human thorax, developed starting from an atlas of tomographic images, considering a couple of electrodes located on the sixth intercostal space along the midaxillary line, one electrode for each side [6]. In order to simulate the effect of respiration, the air volume inside the lungs has been incremented by one liter (tidal volume) as compared to the residual functional capacity, equal to about three liters, obtained at the end of a normal expiration. Simulations have been performed for different frequencies of the sinusoidal excitation signal, varying between 10 and 100 kHz. As an example, simulations carried out at the frequency of 35 kHz have shown, in good agreement with experimental data available in the literature, that, as the electrode area is increased from 1 cm^2 to 31 cm^2, the basal trans-thoracic impedance decreases from values of the order of 600 Ω to approximately 100 Ω. The variations of such basal impedance, following inspiration of one liter of air, are of the order of 10 Ω for the electrodes having the smallest area and of about 9 Ω for those with the largest area considered. Altogether, the use of electrodes having a larger area results in a slight reduction in the absolute variation of trans-thoracic impedance due to respiratory activity, but in a large increase in the percentage variation of the impedance itself as compared to its basal value.

III. The proposed trans-thoracic impedance measurement system

A. Description of the system

The need to develop algorithms for the processing of recorded trans-thoracic impedance data which are both complex and innovative suggested to base the measurement system on programmed virtual instrumentation. The schematic of the implemented solution is reported in Figure 1.

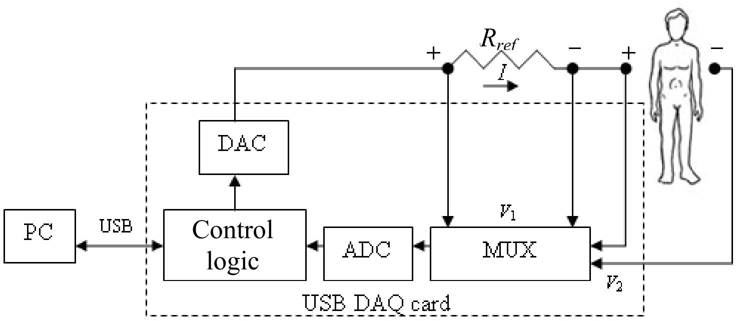


Figure 1. Block diagram of the proposed system for trans-thoracic impedance measurements

The employed data acquisition (DAQ) card (National Instruments NI USB-6251) is controlled by a PC through a USB connection and can also be powered by using a battery, thus making its direct use on the human body safe. The card itself generates a sinusoidal test signal whose frequency can be varied by the user, normally between 10 and 100 kHz. The parameters (amplitude and phase) of the injected current I are evaluated by measuring the voltage V_1 across a reference resistor, having a nominal resistance R_{ref} = 464,0 Ω comparable with that of the human body at the considered frequencies. Starting from such parameters and from the amplitude and phase of the voltage V_2 measured between the two electrodes placed on appropriate points of the patient thorax it is possible to obtain the trans-thoracic impedance value.
One of the key points of the proposed measurement approach, particularly as concerns the evaluation of the impedance phase and hence of the capacitive component of the trans-thoracic impedance, is the synchronization of the two voltage acquisition channels, which must be multiplexed (the adopted DAQ card makes one single ADC available). A preliminary investigation of this topic showed that the best solution is not to rely on the DAQ card internal multiplexer, which introduces an ill-defined time shift between the two channels and also presents settling time problems when the two voltage levels are far apart, but rather to acquire alternatively 10 periods of each voltage signal, triggering the acquisitions with the beginning of the output generated sinusoidal signal.
The whole acquisition system is controlled and managed through a LabVIEW program which, besides visualizing and recording the temporal evolution of the measured impedance signal, also allows a real-

time extrapolation of characteristic parameters from the signal, such as breath rate and rise time, which can be correlated to the health state of the patient.

B. Approach to a metrological assessment of the system

The uncertainty contributions which affect a trans-thoracic impedance measurement carried out with the proposed system are due both to the intrinsic uncertainty of the virtual impedance measurement instrument (DAQ card and LabVIEW processing) and to random effects related to electrode contact resistance, artifacts resulting from patient movements, etc. Even though the second effects are expected to produce much larger uncertainty on the measured values as compared to uncertainty of the virtual instrument, it is important to assess the baseline accuracy of such an instrument. Since the most predominant and useful part of the measured trans-thoracic impedance signal is the resistive one, a series of measurements have been carried out, at the frequency of 10 kHz, on a decade resistance box (Samar Type CR-E/7DC1) in order to evaluate the uncertainty due to the virtual instrument.

In particular, the resistance has been varied between 100 and 1000 Ω (the range of expected trans-thoracic impedances) in steps of 100 Ω. For each nominal resistance value, the resistive component of the box impedance has been measured, at the frequency of 10 kHz, by means of an automatic RCL meter (Philips PM6304), which has a measurement uncertainty for the resistive component, in the considered range, within 0,1 %. This way, a reference value for each resistance has been established, to be compared with the one measured through the proposed virtual instrument.

The virtual instrument has then been used to make a series of measurements on each selected resistance, subsequently extracting from each series the average value and the interval encompassing 95 % of the measured values. Comparing, for each resistance value, the average with the measure obtained through the RCL meter the type B uncertainty has been evaluated. The 95 % interval, instead, allows to evaluate the type A uncertainty with a 95 % confidence level. The obtained results are summarized in Figure 2.

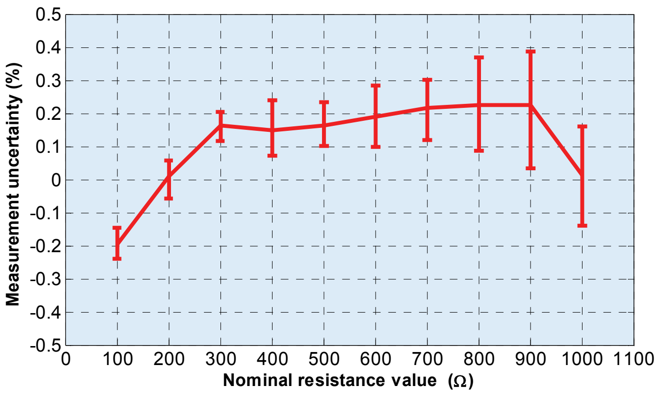


Figure 2. Type B (solid line) and type A (vertical bars) uncertainties on the measured resistance values

Analysis of Figure 2 evidences that both type A and type B uncertainties are lower than 0,3 % of the measured value. This results in an overall expanded uncertainty, with a 95 % confidence level, of about 0,4 %, that is definitely adequate for the purpose of making trans-thoracic impedance measurements.

It is worth mentioning that, besides the uncertainty of impedance measurement, one more important aspect for the proposed system is the uncertainty in the estimation of parameters extrapolated from the acquired signal, first of all the breath frequency which is the most important clinical parameter. The uncertainty of such parameter, derived from LabVIEW data processing, has been assessed by means of a Monte Carlo analysis [7]. In particular, a simulated resistance signal, having a sinusoidal time variation with a frequency of 0,4 Hz, average value of 400 Ω and peak-to-peak variation of 10 Ω, has been analytically generated and passed through the LabVIEW processing. Subsequently, a random noise has been added to each sample of the analytical resistance signal. This noise has been generated starting from the experimental probability distribution of measurements performed with the virtual instrument on a 400 Ω reference resistor, in order to characterize type A uncertainty of the instrument. Indeed, even though the resistance signal under examination is not constant, but varies in a sinusoidal fashion, its variations around 400 Ω are small enough to assume that type A uncertainty is the same as the one observed on a fixed 400 Ω resistor. The noisy signal thus obtained has been processed again through LabVIEW. Such investigation showed that the uncertainty in frequency estimation on the ideal (without added noise) signal is completely negligible, provided that the sampling frequency is at least 10 Hz, so as to correctly reproduce the real sinusoidal behavior of the resistance signal (no interpolation is performed on the acquired resistance samples). When realistic noise levels are added, no significant changes are observed, thus proving that the baseline uncertainty is definitely acceptable for the monitoring and diagnosis activity for which the system is designed.

IV. Experimental results

A. Effect of electrode type and measurement frequency

First of all, the proposed system has been used to measure the basal trans-thoracic impedance on a series of volunteers, so as to analyze its variations with frequency (in the usually adopted range between 10 and 100 kHz) and with electrode area. As an example, Figure 3 shows results obtained on one volunteer using two different types of electrodes: electrocardiography electrodes, which are composed of a large adhesive disk with a small electrode at the center, about 1 cm in diameter, and electro-surgery electrodes, which are silver adhesive electrodes which can be cut in any desired form. In particular, for the present study, electro-surgery electrodes have been cut in circular pieces having a diameter of about 4 cm. It is worth mentioning that, as opposed to electrocardiography electrodes, the latter have an active area which is exactly the same as the overall area. Data reported in Figure 3 show a trend which is very similar to the one obtained with the simulations on the anatomical body model. The basal impedance decreases as the electrode area is increased, essentially because of the larger cross section through which current flows. Curves reported in Figure 3 also clearly show a distinct variation with frequency which can be modeled as the series of a resistance (representing contact resistance between electrode and skin) and the parallel of a resistance and a capacitor, which is a first approximation electrical model of the human body in the considered frequency range.

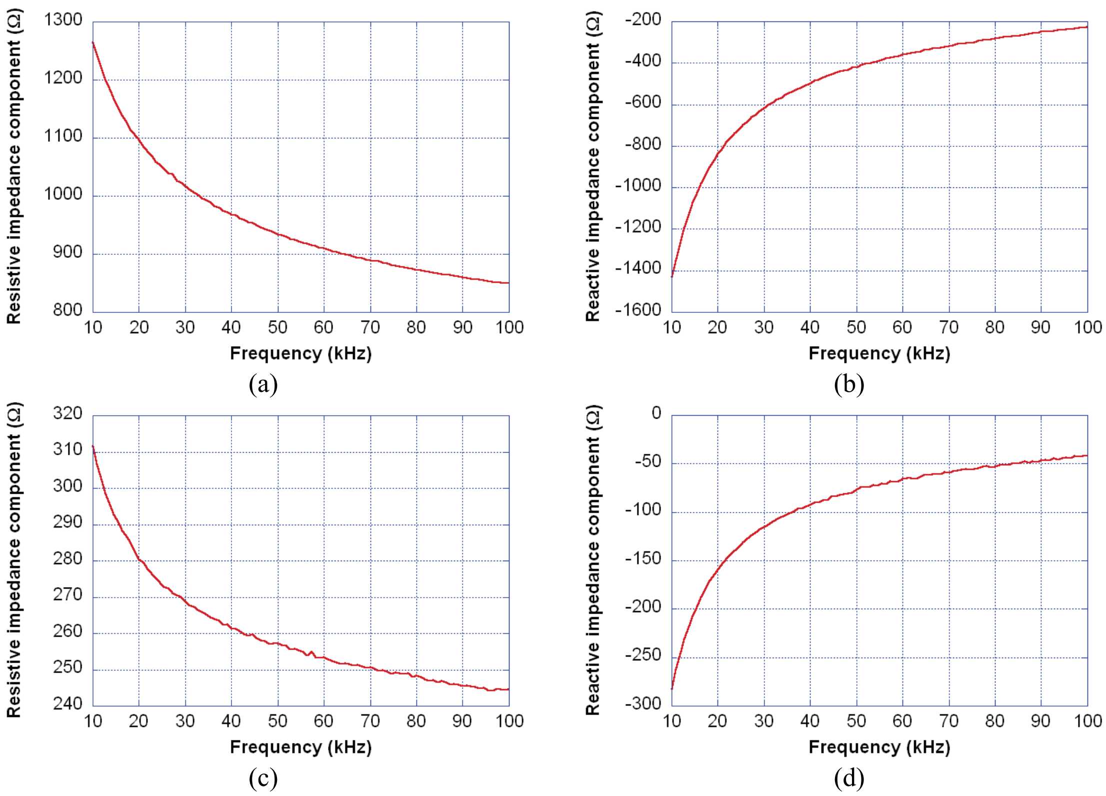
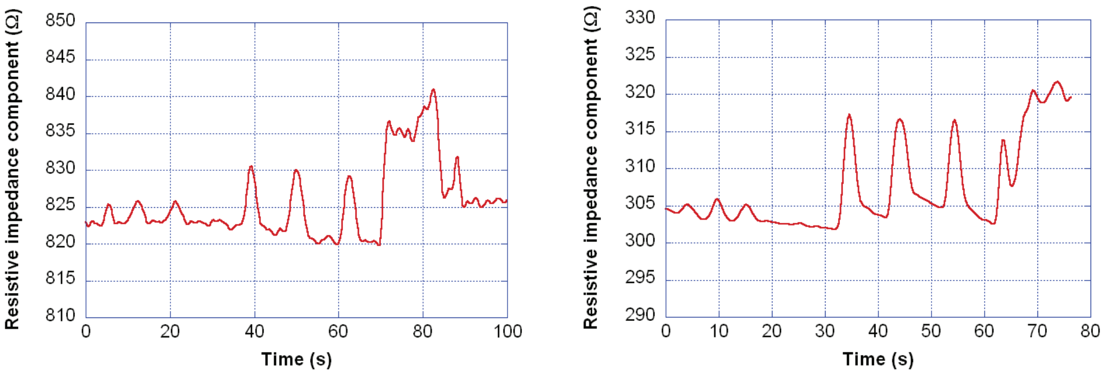


Figure 3. Basal trans-thoracic impedance values with different electrodes: real (a) and imaginary (b) part for electrocardiography electrodes (1-cm diameter), real (c) and imaginary (d) part for electro-surgery electrodes cut in round pieces (4-cm diameter)

B. Monitoring performance for normal respiration activity

In order to validate the feasibility of the proposed approach, different measurement sessions have been carried out on the series of volunteers. As an example, Figure 4 shows a series of trans-thoracic impedance signals recorded on a volunteer and comprising a sequence of normal breathing, apnea, forced breathing, and movement artifacts (obtained by repetitively moving the arms and trunk). Measurements have been carried out at the frequency of 100 kHz and employing both kinds of electrodes previously discussed (electrocardiography and electro-surgery electrodes).
Analysis of Figure 4 shows that the best results have been obtained employing electro-surgery electrodes, mainly because of the larger active area. Indeed, as already evidenced by the simulations on anatomical models and by the previous measurements, by enlarging the electrodes area the basal impedance value decreases, but impedance variations with respiration remain almost the same, thus leading to a higher percentage variation of the trans-thoracic impedance. Moreover, Figure 4 also evidences that electrodes with a larger area tend also to reduce the effect of artifacts. In fact, impedance recordings with the smaller electrocardiography electrodes show that impedance variations due to artifacts are twice those due to forced respiration, while with the larger electro-surgery electrodes the effect of artifacts is comparable with that of forced respiration. As a final note, it is also worth mentioning that the second type of electrodes, not because of their larger area but rather as a result of their different constitution, give rise to a cleaner recording, removing some background noise visible in electrocardiography electrodes acquisitions.
Altogether, the amount of experimental data acquired confirmed the feasibility of the proposed approach for the monitoring of respiratory activity in patients through a trans-thoracic impedance measurement carried out with low-cost and flexible virtual instrumentation. Some efforts must still be undertaken in order to minimize movement artifacts. One possible solution, that will be tested in the future, is the use of a tetra-polar configuration, employing a pair of electrodes for current injection and a distinct pair for voltage measurement.



(a) (b)

Figure 4. Experimental trans-thoracic impedance measurements with different electrodes: (a) electrocardiography electrodes, (b) electro-surgery electrodes

V. Conclusions

A low-cost, highly portable, and flexible instrument for trans-thoracic impedance investigations, based on a DAQ card controlled via LabVIEW software, has been described.
A possible approach to a metrological assessment of the measurement system has been proposed, showing the ability to perform measurements of the trans-thoracic impedance resistive component, useful for breath activity monitoring, with a base uncertainty lower than 0,3 %, both for type B and for type A uncertainties.
The application of the proposed system on several volunteers confirmed its suitability to perform a monitoring of the respiratory activity of a patient, allowing the extraction of the relevant diagnostic parameters from the recorded trans-thoracic impedance data.
The next development of the presented work will be the comparison of the performance of the designed virtual instrument with currently available instruments of the same kind, with a series of trials in hospital environment. Some changes to the system leading to a possibly increased performance will be also tested. For example the adoption of a tetra-polar configuration will be investigated, in order to reduce the effect of movement artifacts. One further possible change which will be explored, that could

affect system performance in terms of acquisition rate, will be the transition to a scalar measurement system, acquiring only the magnitude of the impedance, instead of real and imaginary parts separately. Finally, an evolution of the presented research towards impedance tomography is foreseen, which will allow the reconstruction of an entire thoracic section image starting from impedance measurements carried out on a larger number of electrodes.

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