A telemedicine system based on the forced oscillation technique for remote monitoring of patients with chronic respiratory diseases

N V Oliveira¹, M H N Santos¹, L M Aligleri¹ and P L Melo¹,²
¹Biomedical Instrumentation Laboratory, Institute of Biology Roberto Alcantara Gomes and Laboratory of Clinical and Experimental Research in Vascular Biology, State University of Rio de Janeiro, BR

E-mail: plopes@uerj.br

Abstract. Home telemonitoring is of great interest in respiratory medicine where a large number of people have long term conditions. We developed a telemedicine instrument for home monitoring of subjects with chronic respiratory diseases. The instrument measures respiratory impedance and connects to the Internet through a notebook. The development of the hardware and software used in the instrument is described, as well as initial in vivo results obtained in a normal and an asthmatic subject. These results were in close agreement with the physiology, confirming the high scientific and clinical potential of this system. Internet transmission tests showed adequate results. We concluded that the developed system could be a useful tool for the implementation of telemedicine services, contributing to reduce the costs of the assistance offered to patients with chronic respiratory diseases.

1. Introduction
The elevated prevalence of respiratory diseases has been leading to a growing demand of medical assistance services in the last years. This increase also results in a progressive elevation in the admission of patients, which is particularly important in case of chronic respiratory diseases, whose incidence will increase in a near future [1, 2]. The respiratory function exams are usually performed in specialized centers, which very often are distant from the patient’s houses and workplaces.

In the last decades continuous advancements were observed in the telecommunication and computer science areas, allowing an important cost reduction and providing a significant opportunity for improving the efficiency of the health care. Thus, health services were developed using the concept of home care and telemedicine. However, the quality of these services highly depends on the use of portable instruments, which projects a growing demand for new instruments that allow a detailed analysis of respiratory parameters out of the hospital environment. Aiming to contribute in this direction, our research group have been developing portable systems for monitoring of respiratory parameters via the Internet [3-5].

The Forced Oscillation Technique (FOT) allows a detailed approach to investigate biomechanical characteristics of the respiratory system. This method is based on the application of sinusoidal excitation during normal respiration using an external pressure generator, allowing the measurement...
of respiratory system impedance. For the patient, the main advantage of the FOT is the simplicity of
the test administration, which requires little cooperation. This analysis provides parameters describing
the resistive and reactive properties of the respiratory system that are complementary to traditional
pulmonary assessment methods [6, 7]. These characteristics make FOT a potentially useful method in
telemedicine.

In this context, the present work describes the development of a system for monitoring the
respiratory impedance via Internet through the forced oscillation technique.

2. Materials and Methods

2.1. System development

2.1.1. Hardware design. Figure 1 describes a simplified block diagram of the instrument. The first
stage consists of a sinusoidal oscillator with a 6 Hz frequency and approximately 1Vpp based on the
PIC16F84A. The oscillator is controlled by the digital output of the data acquisition module. The
resultant sinusoidal signal is connected to a DC power amplifier with voltage gain of 47 implemented
with the IC LM3886 (Texas Instruments) coupled to a heatsink with thermal resistance of 1.72 °C/W
(HS12643, Wasting HS). The output of the amplifier, in its turn, is adapted to a loudspeaker of 8”
(Selenium, 140W) what converts the electric signals in pressure. The pressure signal produced by the
loudspeaker excites the measurement systems of flow and pressure. The flow measurement system is
composed by a pneumothacometer coupled to a differential pressure transducer (Honeywell 176PC),
whose signal is amplified by an instrumentation amplifier (AD620, Analog Devices) and subsequently
processed by a low-pass filter (Butterworth, 4th order, 6 Hz) and connected to one of the data
acquisition system inputs. The pressure measurement system is composed by an identical pressure
transducer, which is attached straightly to the tube that drives the oscillations to the patient’s mouth.
The signal processing is identical to that used one in the flow measurement system. The A/D conversion
system (NI USB-6009, National Instruments, Austin, Texas, USA) presents a resolution of 14 bits and
allows a maximum sampling frequency (fs) up to 48 kHz. In the present project the used fs was 1024
Hz. A touch screen notebook (Dell Inspiron series 137000, Intel, Core i5, 4G of RAM, hard disk of
456 GB) was employed as a hardware platform.

![Figure 1: Simplified block diagram of the instrument. PT: pressure transducer, PNT:
pneumothacometer, SR: shunt resistance, IA: instrumentation amplifier, LPF: low pass filter, PA:
power amplifier, SG: sinusoidal generator.](image)

2.1.2. Software design. The software was developed in LabVIEW 2012 environment (National
Instruments, Austin, TX). It is composed by two main modules, the first is devoted to the acquisition,
processing, presentation, quality control, saving the data and sending it to a server, aiming at remote
use.

The signal processing is similar to the one previously described in [6]. Basically, the signals are
separated in blocks of 1s, including blocks with 50 % of overlapping, multiplied by a Hanning window
and processed through the Fourier Transformer. It also allows the estimate of the respiratory resistance and reactance in 6 Hz (R6 and X6, respectively). The program also allows the measurement of the average values of R6 and X6 relative to the inspiratory and expiratory phases. The impedances of the biological filter and of the mouthpiece used between the equipment and the volunteers during the measurement are compensated. The system also allows to automatically identify incorrect values [R6 or X6 greater or less than the average ± 5 SD (standard deviation)] resulting from deglutition, speech or cough during the test, as well as errors due to the saturation of the input of the A/D conversion module and negative values of resistance. The system calibration was performed using a reference mechanical load (7100R5, 5.0 cmH2O/L/s, Hans Rudolph Inc., Coleparkway, Kansas, USA).

2.2. System evaluation

2.2.1. In vitro tests. Before using the system in humans, its appropriate functioning was valued using mechanical loads able to realistically simulate normal conditions (Rn=2.70cmH2O/L/s, \( \text{ln}=12.82\text{mcmH}_2\text{O/L/s}\)) and respiratory obstruction (\( \text{Rob}_{\text{s}}=6.42\text{cmH}_2\text{O/L/s}; \text{I}_{\text{pac}}=5.49\text{mcmH}_2\text{O/L/s}\)) \[8\].

2.2.2. In vivo tests in healthy and asthmatic individuals. The ability of the system to identify alterations associated with respiratory diseases was evaluated through a comparative analysis of the results obtained in a healthy individual that do not present history of respiratory diseases or tobacco use (male, 53 years, 171 cm, 70 kg, percentile of the forced expiratory volume in the first second - \( \text{VEF}_1 = 104.4 \)) and an asthmatic patient with slight respiratory obstruction (\( \text{VEF}_1 \% = 65.6 \% \), male, 44 years, 65 kg, 171 cm). During the exams, the two individuals remained seated, with the head in a neutral position. The studies using the FOT were approved by the Ethics Committee of the Pedro Ernesto University Hospital. The volunteer given a signed permission before the realization of the tests.

2.2.3. Statistical analysis. The results are presented as mean±SD. The comparison between the results was effectuated through the Wilcoxon test \[9\] using ORIGIN 8.0. Values of \( p<0.05 \) were considered significant.

2.2.4. Tests of data transmission/reception. The remote monitoring and information exchange was tested with typical measurements, realistically simulating clinical conditions. The system was used during 17 days, performing one measure a day in the morning (8:00-9:00hs) and sending/receiving simulated medical recommendations and information. This resulted in fifty-one typical archives. The volunteer was in his house in Rio de Janeiro. These test files were sent/received to/from our laboratory in the Rio de Janeiro State University, which is associated with our University Hospital.

3. Results

3.1. System development

Figure 2 illustrates the developed system, showing in (A) the front panel of the program used in the patient module, based on touch screen controls, and in (B) the case containing the circuits, transducers and pneumatic subsystems. The elements used during the measures (biological filter, mouth and the nasal clip) are also described.

The exams are initialized by pressing the button "Iniciar exame", and it is completed 35 seconds later. In order to identify measurement errors, associated with deglutition, speech or cough during the test, the pressure and flow signals can be visualized in the superior indicators of Figure 2A. The quality of the examination is evaluated through the coherence function (\( \gamma^2 \)) (Figure 2, indicator in the middle part of the panel), which analyses the interference of the respiratory signal in the signals of pressure and flow, and consequently, in the result of the analyses. Examinations without interference
results in $\gamma^2=1$, while more reduced values reflects higher interferences of the respiratory signal. In the present project, results obtained from procedures returning $\gamma^2$ values bellow 0.9 are discarded. At the end of the exam, the system offers the possibility to save the pressure and flow along the measurement time in txt format (“Salvar” option in Figure 2). The system allows the visualization of the $\gamma^2$ obtained along the examination, as well as the minimal value of $\gamma^2$ during the examination. An indicator changes its colour from green to red if the minimal $\gamma^2$ is below the stipulated threshold. Additionally, a message is shown for the patient asking that he/she remakes the examination. If this criteria is fulfilled, the program automatically send the results for a server, making the results available for the examination of the health care professional.

![Figure 2](image)

**Figure 2:** Frontal panel of the module associated with data acquisition (A) and picture of the portable instrument for monitoring respiratory patients by forced oscillations (B).

The second module was designed for the medical environment. It allows the registration of the patient (name, sex, register, telephone, date of birth etc.), as well as the storage of specific observations on the patient (disease, time from diagnostic etc.). This module contains subroutines of receiving the examination data and of sending answers back to the patient using TCP/IP.

3.2. System evaluation

3.2.1. In vitro tests. Table 1 describes these tests. The observed errors were smaller than 7 %.

|                     | Reference | Measured | Error (%) |
|---------------------|-----------|----------|-----------|
| $R_{\text{normal}}$ (cmH$_2$O/L/s) | 2.70      | 2.77     | 2.6       |
| $I_{\text{normal}}$ (mcmH$_2$O/L/s$^2$) | 12.82     | 13.53    | 5.5       |
| $R_{\text{patientes}}$ (cmH$_2$O/L/s) | 6.42      | 6.17     | -3.9      |
| $I_{\text{patientes}}$ (mcmH$_2$O/L/s$^2$) | 5.49      | 5.83     | 6.2       |

3.2.2. In vivo tests in healthy and asthmatic individuals. Figure 3A shows typical results of flow, respiratory resistance and reactance measured in the normal and the asthmatic individuals. Figure 4 presents the results obtained in the normal individual and in the asthmatic patient. Twenty one respiratory cycles were evaluated in the normal individual and twenty cycles in the asthmatic. The $R_{\text{exp}}$ was significantly more elevated than the $R_{\text{insp}}$ in the normal individual (p<0.05), while the values of $X_{\text{insp}}$ and $X_{\text{exp}}$ were not significantly different. In the asthmatic, The $R_{\text{exp}}$ was not significantly different from the $R_{\text{insp}}$, as well as the values of $X_{\text{insp}}$ and $X_{\text{exp}}$. The asthmatic presented values more elevated than the normal volunteer in terms of $R_{\text{insp}}$ (p<0.0001) and $R_{\text{exp}}$
(p<0.05). On the other hand, the Rexp-Rinsp was more elevated in the normal individual (p<0.01). The Xinsp was more negative in the asthmatic (p<0.02), while Xexp and Xexp-Xinsp were not different from that observed in the normal individual.

(p<0.05). On the other hand, the Rexp-Rinsp was more elevated in the normal individual (p<0.01). The Xinsp was more negative in the asthmatic (p<0.02), while Xexp and Xexp-Xinsp were not different from that observed in the normal individual.

**Figure 3:** Typical signals of airflow, resistance and reactance obtained in the normal (A) and the asthmatic individual (B).

**Figure 4:** (A) Box-plot description of the values obtained in the normal individual (left and blue) and in the asthmatic patient (right and in red). The top and bottom of the box represent the percentages of 25% and 75% of the sample, while the circle represents the mean value. The bar represents the value of 50%, while the markers out of the box represent the percentages of 10% and 90%. * P<0.05; ns = not significant. (B) Impedance values obtained during seventeen days of remote monitoring in the normal individual.

4. Discussion

*In vitro tests.* The observed errors considering mechanical loads simulating normal conditions, as well as respiratory obstruction, were small (Table 1). They may be considered appropriated to the intended application.

*In vivo tests.* The observation of Re more elevated than the Ri in the normal individual, as well as the presence of similar values of Xi and Xe (Figure 4A), is consistent with previous works [10]. The pathophysiologic characteristics of asthma includes inflammation of the airways and bronchial hyperactivity, which results in airflow obstruction, and consequent alteration of the resistive and reactive properties of the respiratory system [11]. These alterations are coherent with the results described in the Figure 4A, which are also in line with works published previously [10]. It is important to emphasize that the studied asthmatic patient presents light asthma and is under adequate use of medication. This provides evidence of the high sensitivity of the impedance measurement method in the identification of the alterations in the respiratory mechanics of these patients.

*Transmission / reception tests.* During the tests it was observed an error in the transmission of the files (impedance: 3.1 MB; recommendations ≈ 1.0 kB) in only one of the examinations. It happened due to problems with the Internet connection. The measurements archive, however, was saved in the HD of
the netbook. This problem was subsequently easily solved by creating a to-do list, responsible for sending all files that were not properly transmitted to the server at the beginning of each exam.

5. Conclusion & future work
A new portable instrument was developed for acquisition and transmission of the exams in patients with respiratory diseases. The system allows sending the results to a server, as well as the information exchange between the health professional and the patients, contributing to improve the assistance offered to patients with respiratory diseases. Future plans include to integrate the FOT home monitoring instrumentation described in the present work with machine learning algorithms [12, 13] contributing to improve the understanding and management of respiratory diseases and its exacerbations.

Acknowledgments
This study was supported by the Brazilian Council for Scientific and Technological Development (CNPq) and Rio de Janeiro State Research Supporting Foundation (FAPERJ).

References
[1] Anonymous 2013 The juggernaut of respiratory diseases gains momentum The Lancet Respiratory Medicine 1
[2] GOLD 2016 Global Initiative For Chronic Obstructive Lung Disease – UPDATE (2016). “Global Strategy for the Diagnosis, Management, and prevention of Chronic Obstructive Pulmonary Disease.” (http://www.goldcopd.com: NHLBI/WHO)
[3] da Silva Junior E P, Esteves G P, Dames K K and Melo P L 2011 A telemedicine instrument for Internet-based home monitoring of thoracoabdominal motion in patients with respiratory diseases The Review of scientific instruments 82 014301
[4] Silva Junior E P, Esteves G P, Faria A C and Melo P L 2010 An internet-based system for home monitoring of respiratory muscle disorders Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference 2010 5492-5
[5] Esteves G P, Silva Junior E P, Nunes L G, Greco C S and Melo P L 2010 Configurable portable/ambulatory instrument for the analysis of the coordination between respiration and swallowing Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference 2010 90-3
[6] Miranda I A, Faria A C D, Lopes A J, Jansen J M and de Melo P L 2013 On the Respiratory Mechanics Measured by Forced Oscillation Technique in Patients with Systemic Sclerosis Plos One 8
[7] Oostveen E, MacLeod D, Lorino H, Farre R, Hantos Z, Desager K, Marchal F and Measurements E R S T F o R I 2003 The forced oscillation technique in clinical practice: methodology, recommendations and future developments The European respiratory journal 22 1026-41
[8] Lima A N, Faria A C, Lopes A J, Jansen J M and Melo P L 2015 Forced oscillations and respiratory system modeling in adults with cystic fibrosis Biomedical engineering online 14 11
[9] Dawson B and Trapp R G 2004 Basic & clinical biostatistics (New York: Lange Medical Books-McGraw-Hill, Medical Pub. Division)
[10] Paredi P, Goldman M, Alamen A, Ausin P, Usmani O S, Pride N B and Barnes P J 2010 Comparison of inspiratory and expiratory resistance and reactance in patients with asthma and chronic obstructive pulmonary disease Thorax 65 263-7
[11] World Health Organization W H O 2015 GINA – Global Initiative for Asthma.
[12] Amaral J L, Lopes A J, Faria A C and Melo P L 2015 Machine learning algorithms and forced oscillation measurements to categorise the airway obstruction severity in chronic obstructive pulmonary disease Computer methods and programs in biomedicine 118 186-97
[13] Amaral J L, Lopes A J, Veiga J, Faria A C and Melo P L 2017 High-accuracy Detection of Airway Obstruction in Asthma Using Machine Learning Algorithms and Forced Oscillation Measurements Computer methods and programs in biomedicine. In Press.