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Analysis of Performance Limitations of a Widely Used Lung Simulator

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Abstract: The assessment of the efficacy of ventilators and sleep therapy devices requires either medical studies, whose reproducibility on patients is a challenge, or simulative bench tests using adequate hardware. The ASL5000 lung simulator (IngMar Medical, Pittsburg, USA) is one of the most widely utilized tools used by manufacturers of ventilatory devices and bench test groups for this purpose. This study systematically investigates for the first time its dynamic simulating accuracy in two operational modes: *flow pump mode* and *lung model* mode.

Our results indicate that in *flow pump mode*, the ASL5000 exhibits resonance phenomena and substantial attenuation at higher frequencies. These characteristics may constrain the simulator's accuracy, particularly when using test signals with rapid flow variations, such as flattening or snoring. In *lung model mode*, attenuation and resonance effects were observed at high frequencies depending on the lung parameter set used. The measured attenuation around 4 Hz is particularly critical, as many sleep therapy devices use this frequency for apnea classification.

Keywords: lung simulator, lung model mode, flow-pump, mechanic lung, bench testing, sleep therapy, ventilation, FOT, frequency response, simulation, simulation accuracy

1 Introduction

The ASL5000 is a breathing simulator designed for training healthcare personnel in respiratory management. Beyond training applications, the ASL5000 is widely used by researchers, bench test groups, and device manufacturers to evaluate the performance of sleep therapy devices, particularly Continuous Positive Airway Pressure (CPAP) devices and ventilators in noninvasive ventilation (NIV).

The ASL5000 offers two widely used operating modes: 1) *flow pump mode* and 2) *lung model mode*. The *flow pump mode* uses a pre-recorded flow signal as input. The mechanical lung then adjusts the position of the piston to generate the desired airflow at each time step. This mode is ideal for re-simulating challenging real-life breathing flow patterns that therapy devices must accurately detect. While it offers flexibility in reproducing various patterns, it does not respond to pressure variations created by the therapy device.

For scenarios requiring a response to pressure variations, the *lung model mode* is used. This is essential in NIV, where multiple pressure levels are used. This mode is also required to test apnea classification capabilities of CPAP devices. During apnea events certain CPAP devices apply low-amplitude pressure oscillations, within a frequency range of 3.5 Hz to 4.5 Hz [1] (FOT), to differentiate between central and obstructive apneas based on the flow response.

2 Related Work

Bench tests, such as conducted by Richard et al. [2], used the ASL5000 in *lung model mode* to assess the performance of auto-adjusting CPAP devices under real-life leak patterns. Zhu et al. [3] configured the ASL5000 in both *flow pump mode* and *lung model mode* to replicate patterns of sleep disordered breathing. In the context of NIV, several studies, including the one by Lebret et al. [4] employed a setup using the ASL5000 in *lung model mode* to evaluate NIV devices.

Although the ASL5000 is widely used to evaluate the devices mentioned, its limitations are not well studied. According to its user manual [5], the device has a 'small signal' bandwidth exceeding 15 Hz, but there is no guidance regarding the potential implications of using input signals with higher frequency and amplitude. Furthermore, it remains unclear whether these limitations apply equally to *flow pump mode* and *lung model mode*.

Stránská et al. [6] reported that the ASL5000 in *lung model mode* fails to accurately simulate the preset mechanical parameters for High-Frequency Jet Ventilation (HFJV) and volume control ventilation with a decelerating flow pattern in certain ventilators. This ventilation mode typically operates at a frequency of 420 bpm, equivalent to 7 Hz. The authors note that the simulator's unexpected behavior occurs when sharp peaks are present in the airflow signal. Additionally, it is reported that high-frequency resonance may arise, potentially leading to unexpected interactions between simulator and therapy device. Therefore, investigating the limitations of the ASL5000 is crucial, and this is the focus of the following discussion.

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3 Methods

3.1 General setup details

To assure synchronous and independent recording, the airflow rate and pressure at the simulator's outlet were measured with a sampling rate of 200 Hz using a CITREX H4 flow analyzer (IMT Analytics, Buchs, Switzerland). The CITREX H4 is a portable measurement device designed for verifying and calibrating ventilators and other medical gas flow devices. Additionally, valid calibration certificates for all ASL5000 units were present.

3.2 Flow pump mode setup

The *flow pump mode* test setup consisted of an ASL5000 unit connected to the flow analyzer at its outlet. The ASL5000 was configured to reproduce sinusoidal flow patterns with amplitudes ranging from 5 l/min to 60 l/min and frequencies spanning from 1/6 Hz to 50 Hz (from 10 bpm to 3000 bpm). Then, the input flow signal and the resulting output flow signal was resampled, synchronized, and the gain was calculated for each frequency and amplitude level. The test was conducted for *uncompensated residual capacity* (URC) settings of 50 ml, 500 ml (default), and 1000 ml to assess this parameter's impact.

3.3 Lung model mode setup

The *lung model mode* test setup involved an ASL5000 configured in *flow pump mode* to provide a stimulus. This unit was connected to the flow analyzer, which, in turn, was linked to the simulator under test — a second ASL5000 configured in *lung model mode*. The stimulating ASL5000 was set to reproduce sinusoidal flow patterns with amplitudes ranging from 5 l/min to 40 l/min and frequencies spanning from 1/4 Hz to 15 Hz (from 15 bpm to 900 bpm). The frequency range was selected to ensure that the stimulating ASL5000 operates without resonant behavior. As demonstrated in Section 4.1, lower amplitudes still exhibit significant attenuation. While this affects the input signal amplitude, it does not impact the gain and phase relationships, as the evaluation relies on independently measured input and output signals recorded by the flow analyzer. URC was set to the default value of 500 ml.

Three commonly used lung parameter sets, consisting of lung resistance (R) and compliance (C), according to the linear single-compartment model, were tested:

1. Healthy lung: R: 5 $cmH_2O/l/s$, C: 75 ml/ cmH_2O
2. Obstructed lung: R: 20 $cmH_2O/l/s$, C: 60 ml/ cmH_2O
3. Restricted lung: R: 5 $cmH_2O/l/s$, C: 25 ml/ cmH_2O

Gain and phase relationships between the recorded flow and pressure signals were calculated for each tested frequency at each amplitude level using signals recorded by the flow analyzer. The obtained results were compared to the ideal response of the linear single-compartment model, implemented in MATLAB Simulink (MathWorks, Natick, USA).

4 Results

4.1 Flow pump mode results

Fig. 1: Output/input flow response of the ASL5000 in *flow pump mode* with an URC of 500 ml (default)

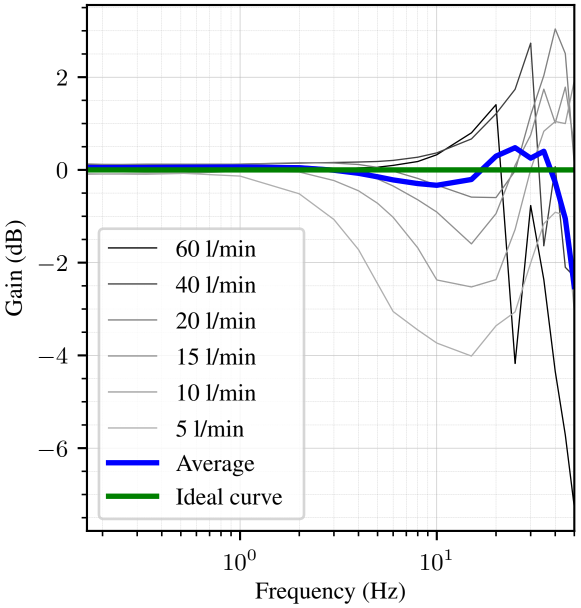


Figure 1 shows that for all URC settings, a gain close to 0 dB (100%) is observed for frequencies below 1 Hz, indicating accurate reproduction of the primary breathing frequency component. For amplitudes exceeding 20 l/min and frequencies above 10 Hz, the input signal is amplified by 2 dB (125%) to 3 dB (140%). For signals of amplitudes below 20 l/min, significant attenuation occurs beyond 1 Hz, with a maximum of -4 dB (63%) observed at 15 Hz for 5 l/min. Beyond 40 Hz the signal is dampened and high-pass behavior is observed. Using URC settings of 50 ml and 1000 ml, attenuation effects became more pronounced beyond 1 Hz, particularly using the 50 ml setting.

4.2 Lung model mode results

In case of the *lung model mode*, the ideal response, marked by the green curve, is defined by the lung parameters R and C and is not dependent on the different input signal amplitude levels. Beyond 6-10 Hz the phase estimation becomes unstable, likely due to noise, and therefore this range will not be further evaluated.

4.2.1 Healthy lung

Fig. 2: Flow-pressure response of the healthy lung using the ASL5000 compared to the ideal response of the PC simulation

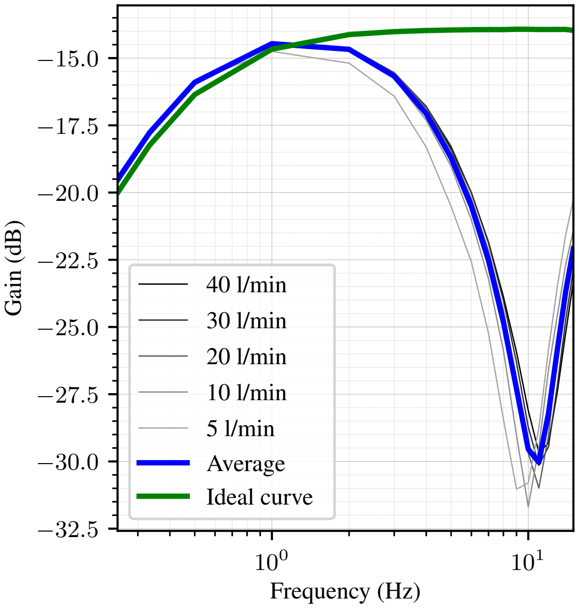
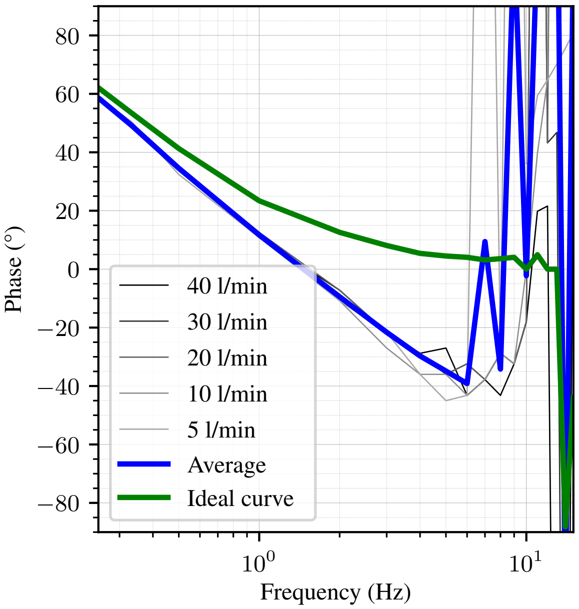


Fig. 3: Phase response of the healthy lung using the ASL5000 compared to the ideal phase response of the PC simulation



In Figure 2 the measured flow-pressure response closely follows the expected lung behavior up to 1 Hz for the healthy lung parameter set. Beyond this frequency, attenuation is observed, with a pronounced notch at 10 Hz. Phase reproduction in Figure 3 remains satisfactory up to 1 Hz, although we observe increasing phase shift as the frequency rises.

4.2.2 Obstructed lung

Fig. 4: Flow-pressure response of the obstructed lung using the ASL5000 compared to the ideal response of the PC simulation

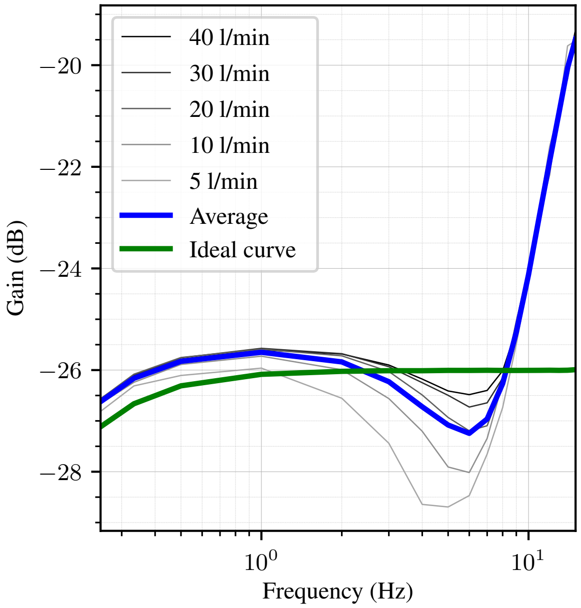
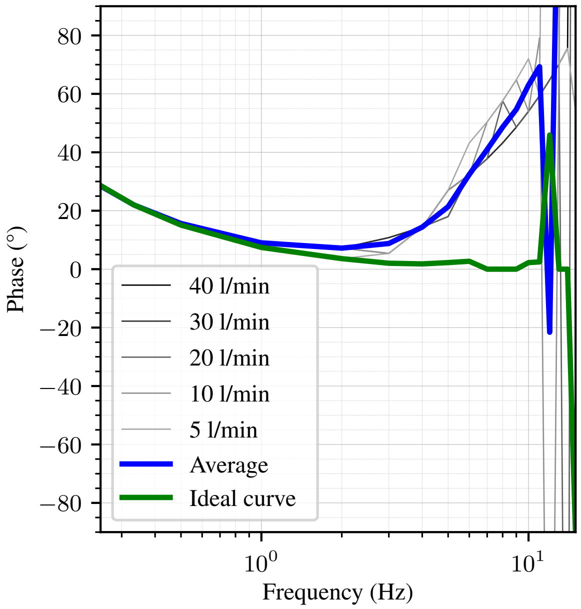


Fig. 5: Phase response of the obstructed lung using the ASL5000 compared to the ideal phase response of the PC simulation



In Figure 4 the measured flow-pressure response exhibits a strong correlation with the ideal response up to 2 Hz for the obstructed parameter set, although with less accuracy than in Figure 2. Beyond this frequency, first, an attenuation is observed, particularly strong for low flow amplitudes, followed by a significant gain increase at higher frequencies, indicating resonance. Regarding phase response, the simulated signal closely matches the ideal phase up to 1 Hz but increasingly deviates beyond that.

4.2.3 Restricted lung

The signals generated using the restricted parameter set exhibit similar inaccuracies to that of the healthy parameter set. Accurate reproduction is observed up to 2 Hz, beyond which significant attenuation and phase error emerge.

5 Discussion

5.1 Flow pump mode

The resonant behavior at higher frequencies using higher amplitudes could present a challenge for simulating rapidly changing flow patterns, such as flattening. Conversely, high-frequency, low-amplitude signals, such as snoring, may be significantly dampened. Therefore, accurate simulation can be expected only for frequencies below 1 Hz with the ASL5000.

5.2 Lung model mode

The observed attenuation beyond 1 Hz may present challenges for tests to evaluate apnea classification capabilities of sleep therapy devices. For the healthy lung parameter set, the signal exhibits an attenuation of approximately 3 dB compared to the ideal lung model at 4 Hz. For lower amplitudes, e.g. 5 l/min, this attenuation is increased to 4 dB, which can be translated to a perceived resistance of ~8.5 $cmH_2O/l/s$, instead of the set value of 5 $cmH_2O/l/s$. Moreover, the resonant behavior observed with the obstructed parameter set could pose challenges for testing ventilatory devices using multiple pressure levels with steep pressure ramps, as the rapid pressure changes may introduce high-frequency components that may lead to resonance phenomena between the device and simulator.

6 Conclusion

In this study, we assessed the simulation capabilities of the ASL5000 mechanical lung simulator. In *flow pump mode*, high flow amplitudes cause resonance phenomena, and low flow amplitudes cause significant attenuation, both limiting the ASL5000's accuracy in simulating signals above 1 Hz. These limitations may pose challenges when simulating flattening patterns and snoring. Additionally, the *uncompensated residual capacity* parameter was found to affect the reproduction accuracy of input flow signals, with the default value of 500 ml being optimal.

In *lung model mode*, the ASL5000 successfully replicates intended lung behavior up to 1 Hz. Beyond that, for all parameter sets, a higher resistance than expected is reproduced, which may impact apnea classification tests. When using the obstructed lung parameter set, the ASL5000 exhibits resonant behavior starting at 8 Hz. This may present challenges when testing ventilatory devices that rely on rapidly changing pressure signals, potentially leading to undesirable interactions between the device and simulator. The observed resonance and increase in resistance when used with rapidly changing patterns is consistent with the results of Stránská et al. [6].

While the ASL5000 demonstrates reliable performance up to 1 Hz, its limitations at higher frequencies should be considered. To ensure high-quality simulation in *flow pump mode*, we recommend analyzing the input flow signal for higher frequency components and applying appropriate filtering. In *lung model mode*, we advise independently recording flow and pressure signals, resimulating these using the corresponding lung model, and verifying the results for anomalies.

To the best of the authors' knowledge, this is the first study to systematically evaluate the simulation limits of the ASL5000 mechanical lung simulator.

Author Statement

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References

[1] Karin G. Johnson. Apap, bpap, cpap, and new modes of positive airway pressure therapy. pages 297–330, 2022.

[2] Mathéo Richard, Emeline Fresnel, Jean-Pierre Mallet, Raphael Gilson, Adrien Kerfourn, Maxime Patout, Carole Philippe, Dany Jaffuel, and Marius Lebret. Performances of auto-cpap devices under real-life leak patterns: A high-fidelity modeling approach. *Archivos de Bronconeumología*, January 2024.

[3] Kaixian Zhu, Gabriel Roisman, Sami Aouf, and Pierre Escourrou. All APAPs are not equivalent for the treatment of sleep disordered breathing: A bench evaluation of eleven commercially available devices. *Journal of Clinical Sleep Medicine*, 11(07):725–734, jul 2015.

[4] Marius Lebret, Emeline Fresnel, Nathan Prouvez, Kaixian Zhu, Adrien Kerfourn, Jean-Christophe Richard, and Maxime Patout. Responses of bilevel ventilators to unintentional leak: A bench study. *Healthcare*, 10(12):2416, nov 2022.

[5] Ingmar Medical. Asl 5000 user manual 3.6, https://www.ingmarmed.com/wp-content/uploads/2016/11/80-31-760-asl-5000-users-manualpv1-1.pdf. *Accessed: 2025-03-11*, 2016.

[6] K. Roubík Stránská, M. and M. Rožánek. Asl 5000 lung model fails to simulate preset mechanical parameters during hfjv and volume control ventilation with a decelerating flow waveform in some ventilators. 2014.