Testing a Control Scheme for Multi-Frequency Oscillatory Ventilation

Bakir Hajdarevic[1,2], Jacob Herrmann[1,2], and David W. Kaczka[1,2,3]

[1] Department of Anesthesia, [2] Department of Biomedical Engineering, [3] Department of Radiology, University of Iowa, Iowa City, IA

Introduction

We have recently proposed multi-frequency oscillatory ventilation (MFOV) as an alternative modality of lung-protective mechanical ventilation for patients with heterogenous lung injury [1]. The distribution of ventilation in mechanically heterogeneous lungs is nonuniform and frequency-dependent, such that MFOV waveforms may be selectively filtered according to regional lung mechanical properties. The objective of this study was to design and test a closed-loop control scheme for generating broadband pressure and flow excitations with adjustable spectral content. MFOV waveforms were generated in healthy and injured lungs during a sequence of user-defined adjustments to set frequencies, amplitudes, and phases of airway pressure oscillations.

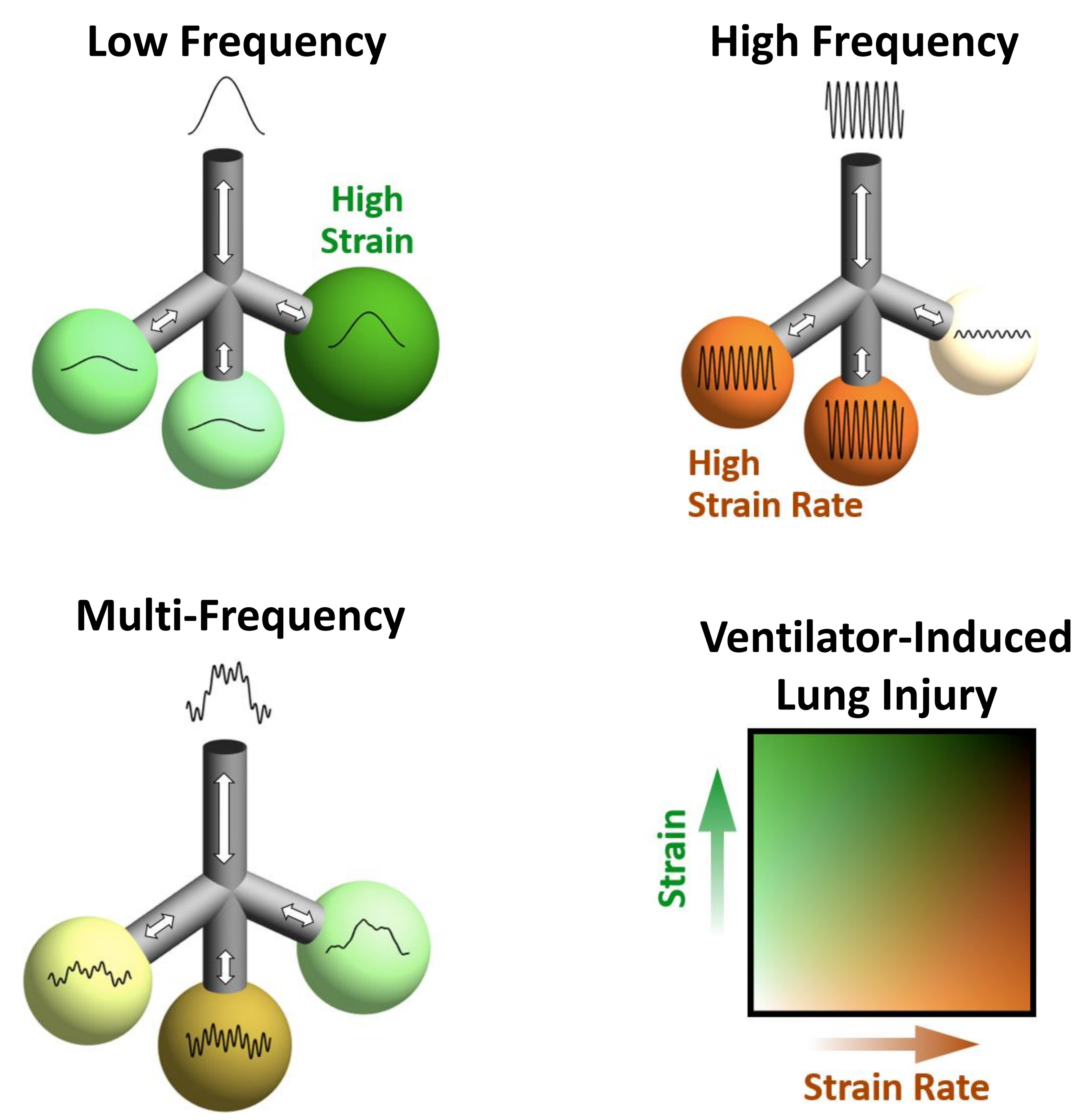

Figure 1. Illustration of heterogeneous strain and strain rate distributions during mechanical ventilation throughout three conceptual lung compartments with differing mechanical properties (resistive, elastic, and inertial). Each lung compartment selectively filters the flow delivered at the airway opening.

Methods

Control Scheme for MFOV Ventilation

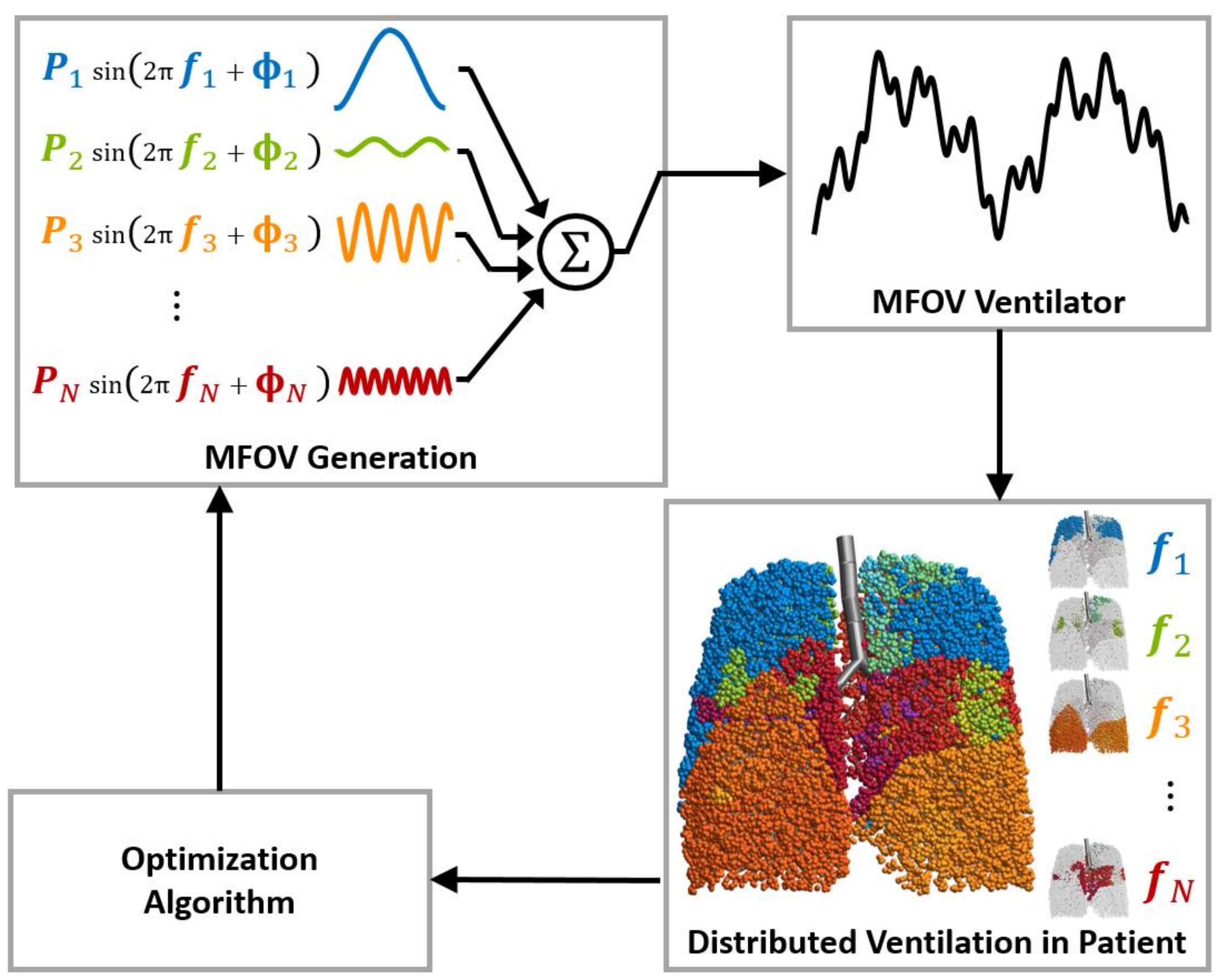

Figure 2. Block diagram of the MFOV control scheme. Sinusoidal waveforms with varying frequency, phase, and pressure-amplitude are generated to form a multi-frequency waveform. Ventilation is distributed throughout the lung in accordance with regional mechanical properties. An optimization algorithm tunes the spectral content of the MFOV waveform based on distributed ventilation.

Methods

Data Acquisition Protocol & Setup

Data was acquired from 3 subjects. Overall, the method was implemented in one healthy and four injurious lung conditions.

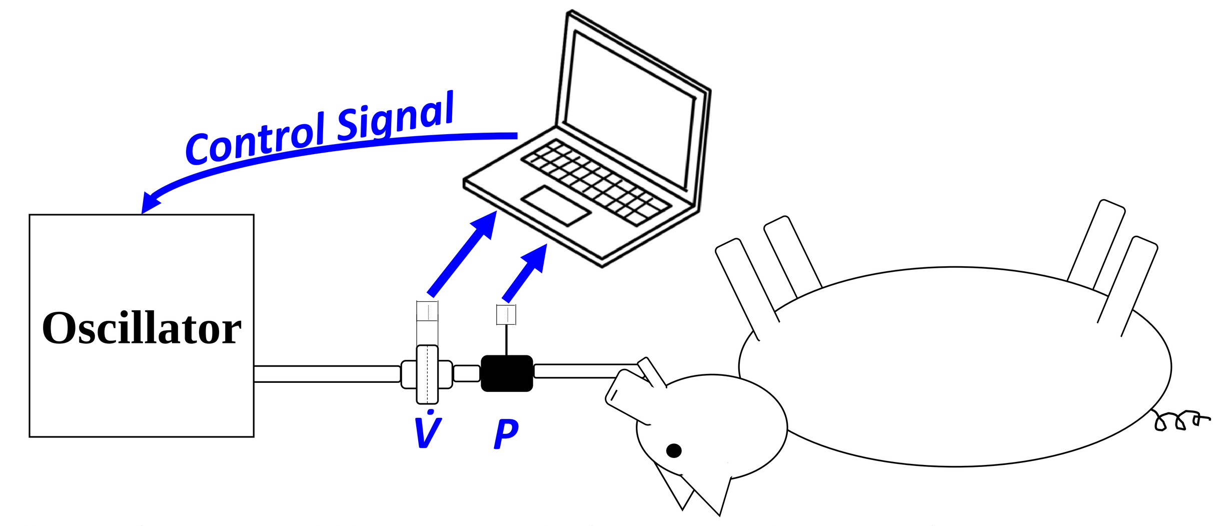

Figure 3. Block diagram of the data acquisition setup. A device for creating oscillatory waveforms was connected to a breathing circuit to the subject. A personal computer implemented the optimization algorithm from the flow ($\dot{V}$) (L/s) and pressure (P) (cmH_2O) transducers.

	Waveform 1			Waveform 2			Waveform 3			Waveform 4			Waveform 5		
Frequency (Hz)	9	6.25	1.6	**3**	6.25	1.6	3	6.25	1.6	3	**2.5**	1.6	3	**8**	1.6
Amplitude (cmH_2O)	2	2	2	2	2	2	2	**0.5**	2	2	0.5	2	**1**	0.5	2
Time (s)	~35			~25			~20			~15			~25		

Table 1. The data acquisition protocol used for all subjects and lung conditions. A triple frequency waveform was used for all waveforms. In total, 5 waveforms were generated with varying set frequency (Hz) and pressure-amplitude (cmH_2O) over specified approximate length of time (s).

Results

Acquired Flow and Pressure

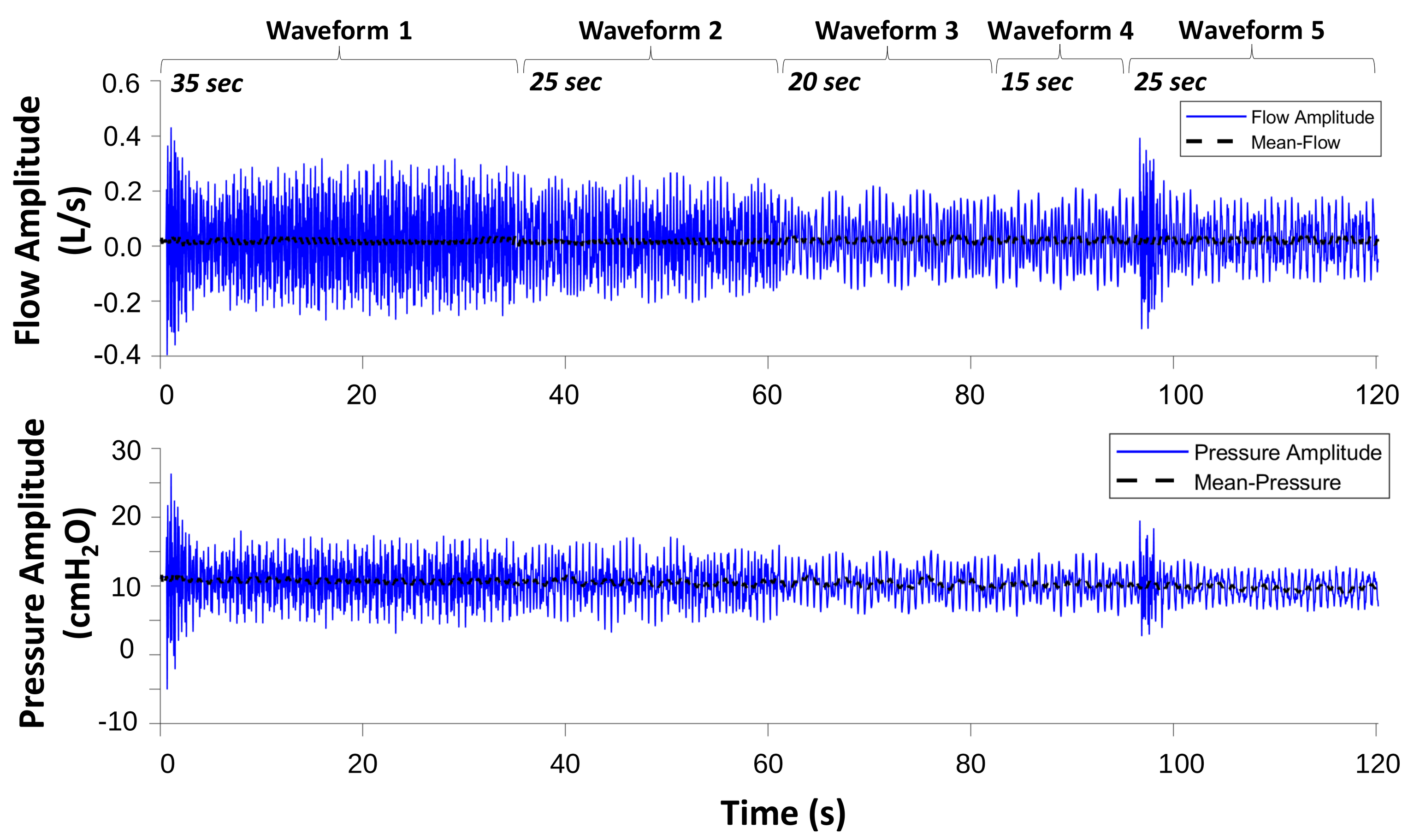

Figure 4. Flow (L/s) and pressure (cmH_2O) data recorded during the implementation of the protocol for a single injurious lung condition.

Analyzing the Frequency Content of Acquired Pressure

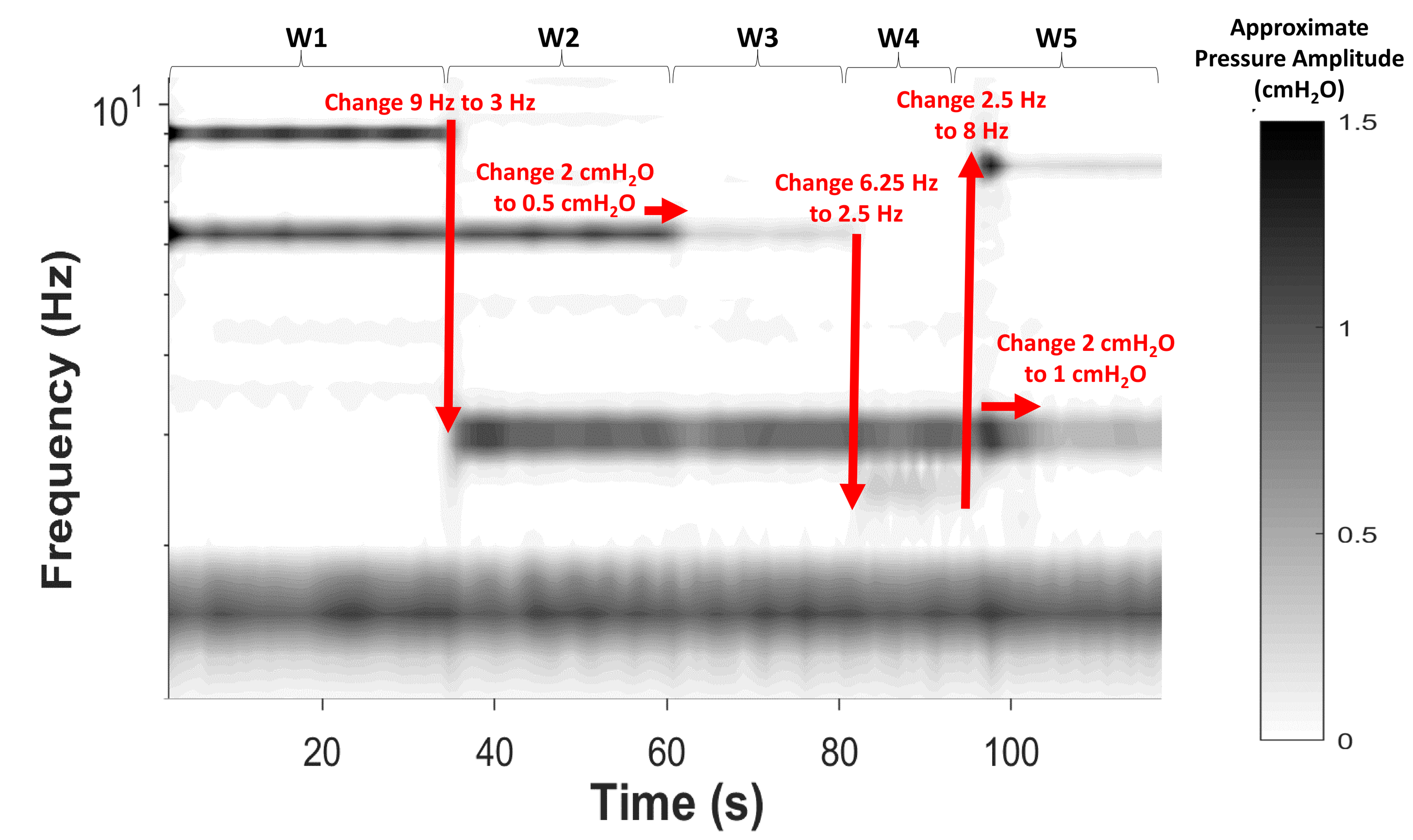

Figure 5. A spectrogram of acquired pressure data for a single injurious lung condition. This visualization distinguishes the various frequency components of each waveform and their respective pressure amplitudes.

Results

Convergence Behavior for 6.25 Hz

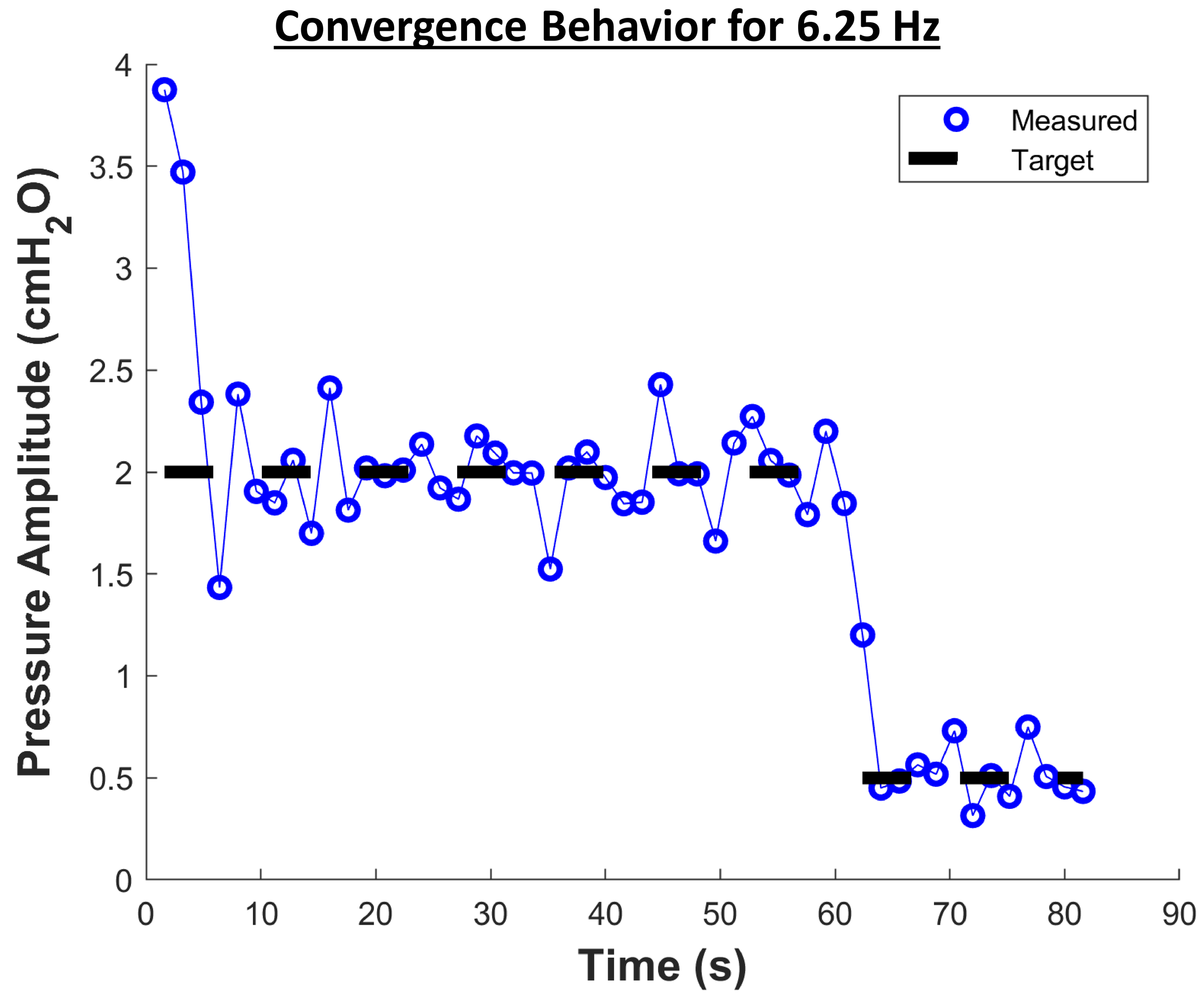

Figure 6. Convergence behavior for 6.25 Hz acquired during an injurious lung condition. The plot shows how the optimization algorithm attempts to predict the desired pressure magnitude.

Pressure-Amplitude Accuracy Across all Subjects

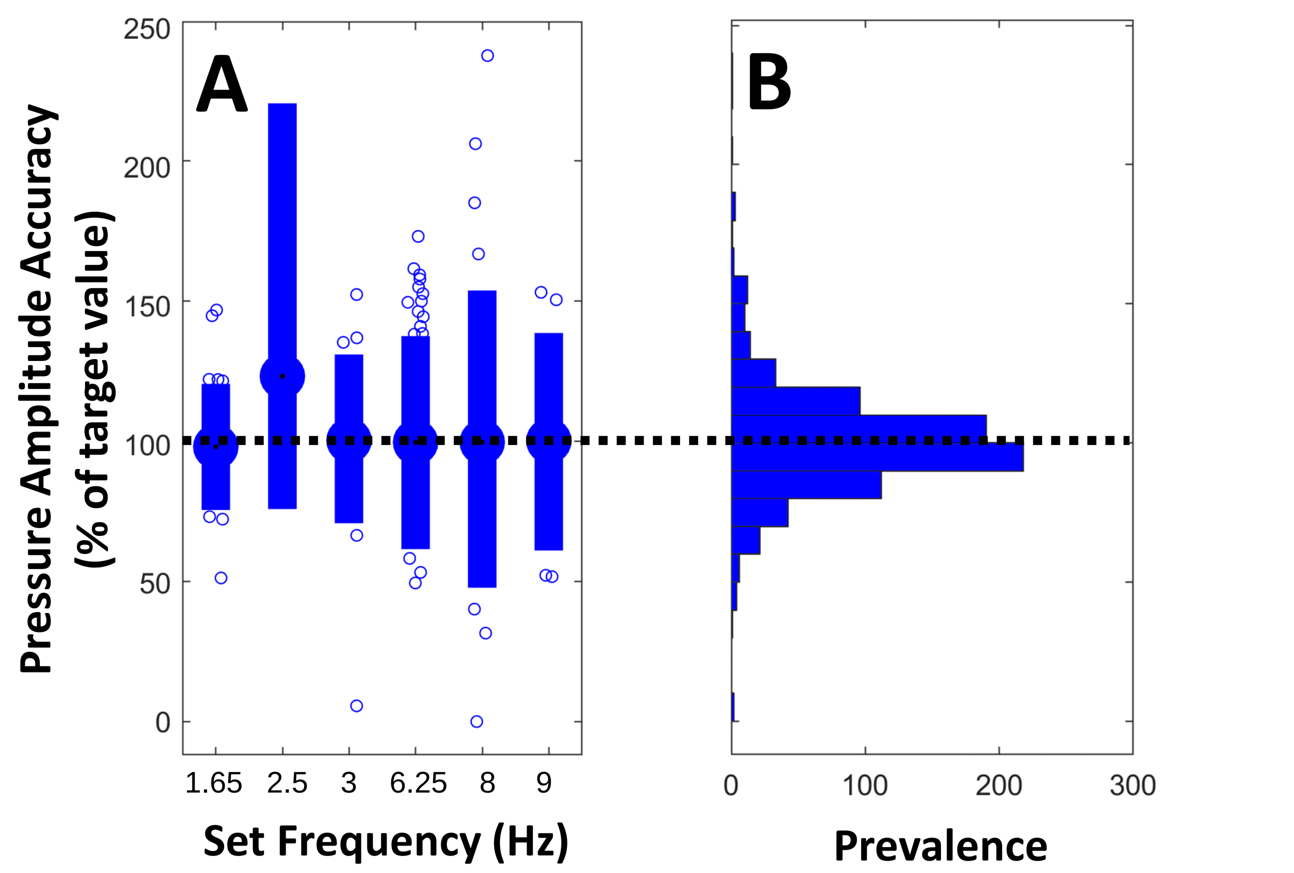

Figure 7. A) Boxplots for each frequency used after normalizing the pressure-amplitudes relative to the set amplitude for all subjects and lung conditions. B) Histogram of percent convergence for all frequencies. As indicated by the dashed line, the mean pressure-amplitude observed is approximately 100% in both plots.

Conclusions

- During 5 implementations in 3 subjects with healthy and injured lung conditions, our method ensured a mean pressure-amplitude accuracy of 100%.
- The control scheme developed in this study is scalable and translatable for clinical applications of MFOV.
- This method will enable clinicians to optimize the spectral content of ventilator waveforms for specific patient lung conditions.
- Future work will involve improving the initial convergence behavior and response to perturbations of the controls scheme.

Disclosures

D.W. Kaczka and J. Herrmann are co-founders and shareholders of Oscillavent, Inc.

References

1. D.W. Kaczka, J. Herrmann, C.E. Zonneveld, D.G. Tingay, A. Lavizzari, P.B. Noble, and J.J. Pillow. "Multifrequency oscillatory ventilation in the premature lung: effects on gas exchange, mechanics, and ventilation distribution." *Anesthesiology*, 123(6):1394-1403, 2015.