

Assessment of Terminations of a Branched Lung Model Using Acoustic Impedance Measurements

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ABSTRACT

The measurement of acoustic impedance at frequencies up to 6,400 Hz has been proposed as a diagnostic tool to yield more detailed information about lung condition. A three generation branching system of plastic Y-tubes has been constructed. The impedance of the branched system is measured by an impedance tube using the two-microphone technique. The impedance spectrum is used to calculate the reflection coefficient spectrum, which is converted to an impulse response by an inverse FFT. The area function is extracted from the impulse response by the Ware-Aki algorithm. Measurements of acoustic impedance of the branched system were made for several different end conditions of the eight terminal outlets. The outlets were either blocked with modeling clay, plastic packing material, or aluminum blocks or were unblocked. Six measurements were made of each configuration. In general, the more outlets blocked, the larger the shift to the right of the impedance magnitude peaks for frequencies above 3000 Hz. The impedance magnitude peaks for the plastic packing material were shifted in frequency to the right relative to the peaks of the other system terminations. The impedance magnitude peaks for the clay and aluminum system terminations were significantly different in magnitude but not shifted in frequency. The area functions at the end of the branched system were significantly different ($\alpha > 99\%$) for most of the end conditions. Area functions for the modeled branched lung systems between the end of the impedance tube and the termination outlets of the branched system were similar but distinctively different for the various end conditions. These results indicate that the two-microphone technique can sense small changes in the terminating end conditions of a rigid system of branched tubes and thus may sense impedance changes due to lung disease in the conducting airways.

Keywords: acoustic impedance, lung model, area function.

INTRODUCTION

The measurement of lung acoustic impedance at low frequencies has been studied by several researchers. One of the first studies of lung

acoustic impedance was conducted by DuBois *et. al.* [1] using the forced oscillation technique to measure the impedance of human lungs. This technique involves superimposing random noise over a bias flow into the lungs. The typical frequency range of the forced oscillation technique is between 0.5 and 10 Hz. Peslin *et. al.* [2] modified the forced oscillation technique to obtain a frequency range between three and 70 Hz. Hayes *et. al.* used forced oscillations to reveal significant differences between the acoustic impedance spectra of non-smokers, smokers, and patients suffering obstructive pulmonary disease. Depeursinge *et. al.* [4] measured the lung acoustic impedance between 10 and 40 Hz during left ventricular failure. The imaginary impedance showed distinct differences between left ventricular failure and the control. Thus, the lung acoustic impedance at low frequencies changes according to lung health and other physiologic conditions.

Further studies by van den Ber [5] revealed that the lung reflected higher frequency sounds (between 100 and 10,000 Hz) instead of behaving as an anechoic termination. This discovery has led to several studies of the acoustical properties of human lungs at high frequencies. Ishizaka *et. al.* [6] measured the input impedances of laryngotomized human subjects using a two-microphone technique. This study reported peaks in the impedance magnitude at 640, 1400, and 2100 Hz. Hudde and Slatky [7] measured the acoustic impedance of excised human lungs between two and 5,000 Hz. The measured impedances from this study were matched to a theoretical model of the human lung to recover acousto-mechanical parameters. While the methods of measuring the acoustic impedance at higher frequencies vary, the most widely accepted technique is the two-microphone technique developed by Blaser and Chung [8].

The basis of area recovery from a discrete impulse response is credited to Claerbout [9]. Ware and Aki [10] developed the continuous analogy to Claerbout's work. Both of these techniques were primarily used in geophysics until papers by Jackson *et. al.* [11] and Sidell and Fredberg [12] applied area recovery techniques to lung airway areas. Typically, a pulse is introduced into an

impedance tube connected to a lung. A single microphone records the reflected signal, directly measuring the impulse response needed for the area recovery technique. Succeeding papers [13-16] further refined the area recovery method for lung airways and examined the technique's accuracy and repeatability.

While studies have shown that acoustic impedance changes with different lung conditions, the exact conditions of the lung causing the impedance changes are speculative. The lung is a complicated acoustic system. Many factors may contribute to the impedance changes: airway branching, lung volume, mechanical characteristics of tissue, or boundary conditions between the lung and chest cavity.

The most intriguing of these factors is the mechanical parameters of tissue. Several diseases of the lung change these mechanical parameters. At what point will changes in the mechanical parameters cause an observable change in the lung's acoustic impedance? Will the change in impedance happen early enough in the course of the disease to implement corrective treatment?

The objective of this study is to find the changes in the impedance spectrum of a greatly simplified model of the lung caused by changing the end conditions. The model consists of three generations of branching rigid plastic tubes, terminated by various arrangements of aluminum blocks, plastic packing material, or modeling clay. The different conditions could be analogous to different mechanical parameters caused by disease. In addition, this study examines the area functions recovered from the impedance data to compare the relative complexity of interpreting the results of the two measurements.

MATERIALS AND METHODS

The impedance of the branched system is measured by an impedance tube using the two-microphone technique. The schematic diagram of the impedance tube facility is shown in Figure 1. Random noise is generated by a dual channel analyzer, amplified, and introduced into a impedance tube. The random noise causes standing waves to occur in the tube. Two microphones, placed 1.0 cm apart, measure the standing wave. From this data, the analyzer calculates the transfer function $H_{12}(w)$ at the first microphone as a function of frequency ($0 \text{ Hz} < f < 6400 \text{ Hz}$). The reflection coefficient, R , at the beginning of the transition section between the impedance tube and the lung model is given by the equation

$$R(w) = \frac{H_{12}(w) - e^{-jws}}{e^{jws} - H_{12}(w)} e^{2jw(\ell+s)}$$

where ℓ is the distance between the first microphone and the transition section, s is the microphone spacing, w is the circular frequency and j is $\sqrt{-1}$. The specific acoustic impedance z is related to the reflection coefficient by the equation

$$z = (1+R)/(1-R)$$

The specific impedance of each configuration is measured six times for statistical analysis.

The reflection coefficient spectrum is transformed into a time-dependent reflection signal (the impulse response) by the inverse Fourier transform. Using the algorithm described by Ware and Aki, the impulse response is deconvolved into a series of area changes; that is, the area function.

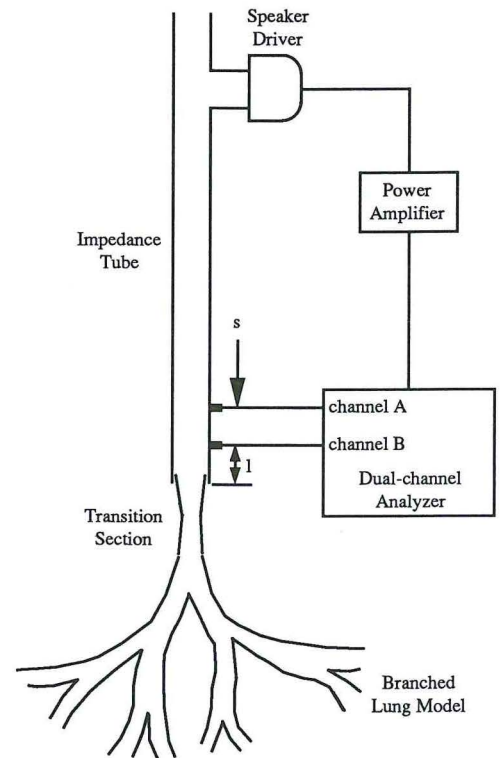


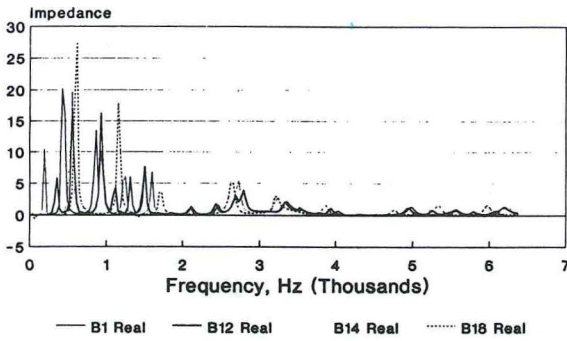
Figure 1. Schematic Diagram of Impedance Tube Facility with Attached Lung Model

A system of branching tubes made of naglene Y-connectors (O.D. 0.5 inches) is attached to the end of the impedance tube via a smooth transitional connector. Measurements of acoustic impedance of the branched system were made for several different conditions of the eight terminal outlets. The outlets were blocked with modeling clay, plastic packing material (PPM), or aluminum blocks or left open. For aluminum blocks, measurements were made with one (BR1), two (BR12), four (BR1_4), and eight (BR1_8) outlets blocked. The same measurements were made with clay-terminated outlets (BC1, BC12, BC1_4, BC1_8) and with PPM-terminated outlets (BS1, BS12, BS1_4, BS1_8). In addition, mixed terminations were measured: one blocked with PPM and one blocked with clay (BS1C2); two blocked with PPM and two

blocked with clay (BS12C34); four blocked with PPM and four blocked with clay (BS14C58); and seven blocked with PPM and one blocked with clay (BS18C5).

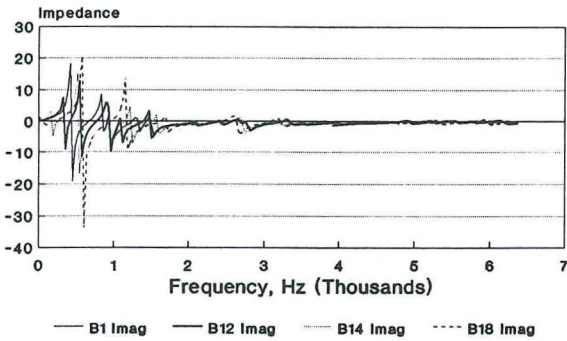
RESULTS

Figure 2 shows a typical impedance spectra of the branching system. Figure 3 shows an enlargement of the impedance spectra between 2,800 and 6,400 Hz. The five peaks labeled a,b,c,d and e show the typical shape of the spectrum between these frequencies. This range of frequencies shows the most repeatable differences in the impedance spectra of the various end conditions of



Ends blocked with clay

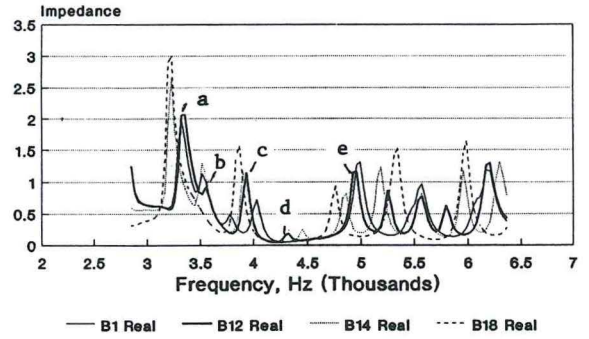
Figure 2a. Real Acoustic Impedance Spectrum (0 to 6400 Hz) for Model Terminations Closed With Modeling Clay.



Ends blocked with clay

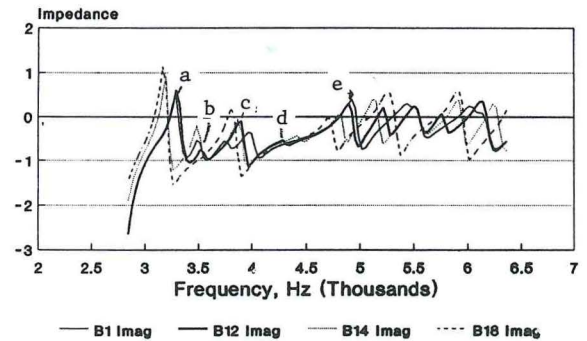
Figure 2b. Imaginary Acoustic Impedance Spectrum (0 to 6400 Hz) for Model Terminations Closed With Modeling Clay.

the branching system. Tables I, II, and III show the frequencies and amplitudes of the impedance magnitudes of the single-material blocked branched system.



Ends blocked with clay

Figure 3a. Expanded Real Impedance Spectrum (2800 to 6400 Hz) for Model Terminations Closed With Modeling Clay.



Ends blocked with clay

Figure 3b. Expanded Imaginary Impedance Spectrum (2800 to 6400 Hz) for Model Terminations Closed with Modeling Clay.

Table I. Comparison of impedance magnitude peaks of branched system terminated with clay.

	One blocked		Two blocked		Four blocked		Eight blocked	
	mag.	freq.	mag.	freq.	mag.	freq.	mag.	freq.
peak a	2.00	3328	2.08	3360	1.29	3520	1.56	3872
peak b	1.13	3520	0.92	3552	1.15	3904	0.94	4768
peak c	0.49	3776	1.13	3936	0.26	4448	1.53	5344
peak d	0.72	4032	0.19	4320	0.82	4864	0.64	5984
peak e	1.31	4992	1.16	4960	1.24	5184	—	—

mag : magnitude
freq: frequency

Table II. Comparison of impedance magnitude peaks of branched system terminated rigidly.

	One blocked		Two blocked		Four blocked		Eight blocked	
	mag.	freq.	mag.	freq.	mag.	freq.	mag.	freq.
peak a	1.58	3296	2.01	3328	0.82	3520	1.22	3872
peak b	1.04	3488	0.52	3552	1.01	3936	0.65	4800
peak c	0.34	3744	1.15	3936	0.21	4480	1.43	5312
peak d	0.89	4032	0.21	4320	0.80	4864	1.59	5952
peak e	1.74	4992	1.31	4960	1.18	5784	—	—

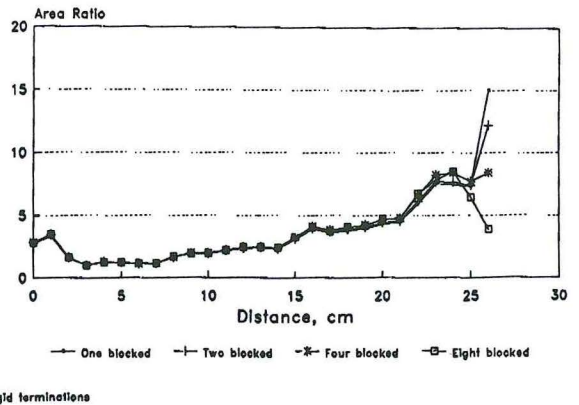
mag : magnitude
freq: frequency

Table III. Comparison of impedance magnitude peaks of branched system terminated with plastic packing material.

	One blocked		Two blocked		Four blocked		Eight blocked	
	mag.	freq.	mag.	freq.	mag.	freq.	mag.	freq.
peak a	1.28	3296	1.87	3328	0.82	3520	0.93	3840
peak b	0.76	3488	0.42	3552	0.91	3904	0.65	4832
peak c	0.24	3712	0.79	3936	0.18	4480	0.67	5312
peak d	0.78	4000	0.14	4288	0.78	4896	0.92	5920
peak e	1.52	4960	1.10	4928	0.61	5184	—	—

mag : magnitude
freq: frequency

Figures 4, 5 and 6 each show the recovered area functions for four of the 12 single-material blocked branched systems. A graph of the actual area ratio function for the branched lung model is shown in Figure 4. The acoustic length of the branched lung model was about 25 cm. Table IV displays the statistical comparison between normalized termination areas of several similar configurations.



Rigid terminations

Figure 6. Area Ratio Function For Model Terminations Closed With Aluminum Plugs.

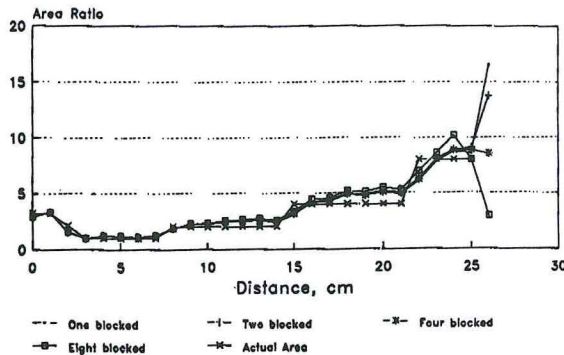
Table IV Comparison of Terminal Equivalent Areas, normalized with respect to throat area.

End ₁	A ₁	End ₂	A ₂	t _{statistic}	α_{max}
B1	16.52	B12	13.78	16.3	0.9995
B12	13.78	B1_4	8.52	57.3	0.9995
B1_4	8.52	B1_8	— *	—	—
BR1	15.05	BR12	12.20	2.88	0.99
BR12	12.20	BR1_4	8.39	8.20	0.9995
BR1_4	8.39	BR1_8	3.85	16.9	0.9995
BS1	15.22	BS12	12.49	8.35	0.9995
BS12	12.49	BS1_4	9.61	9.94	0.9995
BS1_4	9.61	BS1_8	5.86	23.5	0.9995
BS12	12.49	BS1C2	11.55	2.88	0.99
BS1_4	9.61	BS12C34	7.69	11.4	0.9995
BS1_8	5.86	BS14C58	3.22	19.1	0.9995
BS1_8	5.86	BS18C5	5.28	3.78	0.995

* data unavailable

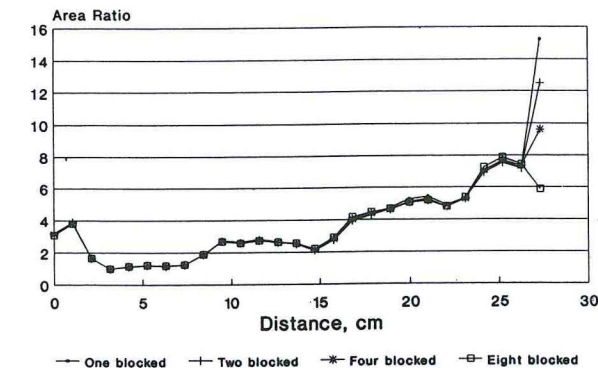
DISCUSSION

In general, the more outlets blocked by a material, the larger the shift of impedance magnitude spectrum to the right. This makes sense acoustically, since the impedance of a closed straight tube is the same as the impedance of an open straight tube except that the peak amplitude for the closed tube is shifted to the right. The impedance magnitude peaks of the plastic packing material terminated systems are shifted to the left relative to the corresponding peaks for the aluminum and modeling clay terminated systems. Again this is not surprising, as the packing material is more like an open end condition than the aluminum blocks or modeling clay. The size of the impedance magnitude peaks differ between the clay and aluminum terminated systems, perhaps showing a difference in the material stiffness and damping properties. The peaks, however, are not shifted in frequency. This shows that clay and aluminum are quite similar when analyzed by acoustic techniques.



Ends blocked with clay

Figure 4. Area Ratio Function For Model Terminations Closed With Modeling Clay.



Outlets blocked with packing material

Figure 5. Area Ratio Function For Model Terminations Closed With Packing Material.

While differences in the terminations of the branched system are difficult to detect by impedance, the terminal area function detects these differences very well. The t-statistics for the terminal area functions of related branched system terminations yielded confidence levels of 99.0% or greater. The comparisons of the terminal areas of BS12 versus BS1C2 and BS1_8 versus BS18C5 are especially interesting. In both cases, the termination of one outlet was changed from packing material to clay and the decrease in terminal area was detected at a confidence levels of 99.0% and 99.5%, respectively.

In conclusion, these findings show that area functions can detect changes in the terminal conditions with a 99% or greater confidence level. Acoustic impedance also detects these changes, but is more difficult to use. These results indicate that the two-microphone technique can sense small changes in the end conditions of a rigid system of branched tubes and may sense impedance changes due to lung disease in the conducting airways.

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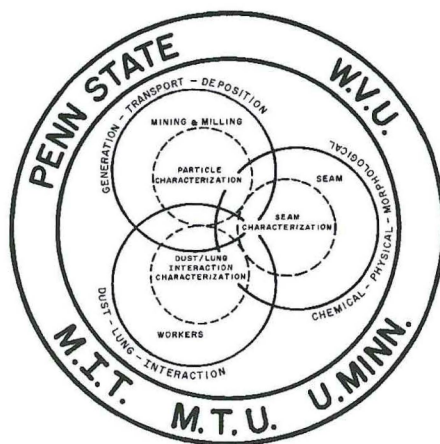
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