Measurement of Respiratory Acoustic Signals*

Effect of Microphone Air Cavity Width, Shape, and Venting

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Study objective: We have previously investigated the effects of microphone type and coupler air chamber depth on lung sound characteristics. We now report the results of experiments exploring the effects of air chamber width, shape, and venting on lung sounds. Design: We used a single electret microphone with a variety of plastic couplers. The couplers were identical except for the diameter and shape of the air chamber. We used cylindrical chambers of 5, 10, and 15 mm in diameter at the skin and conical chambers of 8, 10, and 15 mm in diameter. We compared the inspiratory lung sound spectra obtained using each of the couplers. We also examined the tendency of various needle vents to transmit ambient noise into the microphone chamber. Setting: Anechoic chamber.

Measurements and results: The shape and diameter had little important effect on the lung sound spectrum below 500 Hz. From approximately 500 to 1,500 Hz, the 5-mm diameter couplers showed slightly less sensitivity than the 10- and 15-mm diameter couplers. All conical couplers provided approximately 5 to 10 decibel more sensitivity than the cylindrical couplers. All vents allowed some ambient noise to enter the chamber but the amount was trivial using the narrowest, longest vent.

Conclusions: These data suggest that the optimal electret microphone coupler chamber for lung sound acquisition should be conical in shape, between 10 and 15 mm in diameter at the skin, and either not vented or vented with a tube no wider than 23-g or shorter than 20 mm.

CHEST 1995; 108:1004-08

Key words: acoustics; lung sounds; microphone; respiratory sounds

Before the early 1960s the stethoscope and human ear were used to examine and study biologic sounds, including lung sounds. Subjective descriptions of sounds were used to infer physiologic and pathologic conditions in the respiratory system. This was based on the earlier work of Léonard who had correlated lung sounds with autopsy-demonstrated pathologic findings in his seminal book of 1819 as recently reprinted.\(^1\) In the 1960s, the expanding availability of signal analysis equipment, first analog and then digital, provided the opportunity for objective acquisition and measurement of lung sound signals.\(^2\) Since then, investigators have used a variety of microphones, filters, and signal analysis devices to analyze lung sounds.\(^3\) However, there is little standardization in the field and virtually no widely available commercial equipment for lung sound research. Few researchers use the same or demonstrably similar instrumentation. It is therefore difficult to compare the results of otherwise similar experiments. In some cases, results of experiments done by different investigators have been so divergent that the scientific questions were more clouded after the studies than before.\(^4\)

Of all the links in the signal acquisition and analysis chain, the microphone and its coupling to the skin are probably the least understood but most critical. Contact microphones, air-coupled microphones, and accelerometers all have been used to acquire lung sound signals.\(^6,7,15\) With air-coupled microphones, the chamber size and shape may be whatever is convenient or felt empirically to provide acceptable results. Venting may or may not be used and often is not mentioned at all. The purpose of the vent is to prevent pressurization of the chamber that could degrade the sensitivity or frequency response of the microphone element.\(^10,13\) Because a vent is a small hole in the chamber, its presence affords the opportunity for pressure fluctuations within the chamber to leak out, decreasing the sensitivity of the microphone, particularly at low frequencies. Also, it will allow ambient sound to reach the microphone element. For this reason, venting al-

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Manuscript received January 4, 1995; revision accepted April 24.
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ways is accomplished through a narrow needle or tube that behaves as an inductive element, allowing excess pressure to dissipate while impeding the entrance of sound into the chamber. To our knowledge, the effectiveness of different vent arrangements in lung sound research has never been examined.

In this study, we report the results of a series of experiments comparing the effects of coupler diameter, shape, and air chamber venting on lung sounds. Our objective in making these and the previously reported comparisons is to provide some basis on which to compare different studies and to help determine which sensors and couplers may be best for lung sound measurements and research.

**Materials and Methods**

We used a single electret microphone (Sony ECM-155) for all experiments. This microphone is 12 mm in height and 5.6 mm in diameter and is commonly used in various arrangements for lung sound research. The couplers that acoustically and mechanically joined the active element of the microphone to the sound source were custom manufactured of plastic material. They were identical except for the diameter and shape of the air chamber connecting the microphone element with the skin. We made some of the chambers cylindrical and others conical. The maximal depth of the air chamber was always maintained at 2 mm (Fig 1) so that the only variables were the chamber diameter and shape. We used chamber diameters (at the skin surface) of 5, 10, and 15 mm for the cylindrical couplers and 8, 10, and 15 mm for the conical couplers. This encompasses the range of air-coupled microphone housings commonly used in most lung sound investigations (Table 1). We manufactured but did not use a 5-mm coupler because the shape of the resulting chamber was nearly identical to that of a cylinder.

The lung sounds were amplified, passed through a band-pass filter between 20 and 2,500 Hz (sixth order Butterworth), and digitized at 10,240 samples per second using a 12-bit analog-to-digital converter. The digital data were parsed into 2,048-point segments with 50% overlap between consecutive segments. Each segment was windowed with a Hanning function and processed by a fast Fourier transform algorithm. The resulting power spectra were averaged in the frequency domain. For each recording, the standard error of the mean (SEM) of each 5-Hz point in the averaged power spectrum was calculated as an index of variability of the measurements that were averaged. The spectra from different chambers and venting arrangements were compared by plotting them using an overlapping format and then observing the differences at various frequencies.

The study protocol was approved by the Purdue University Committee on the Use of Human Subjects. All studies were per-

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**Figure 1.** Cross-sectional schematic diagrams of the microphone enclosures.

**Table 1—Chamber Geometry**

<table>
<thead>
<tr>
<th>Diameter at Skin, mm</th>
<th>Surface Area at Skin, mm²</th>
<th>Chamber Volume, mm³</th>
<th>Surface Area/Volume, mm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>20</td>
<td>47</td>
<td>0.43</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>...</td>
<td>0.70</td>
</tr>
<tr>
<td>10</td>
<td>79</td>
<td>71</td>
<td>0.84</td>
</tr>
<tr>
<td>15</td>
<td>177</td>
<td>94</td>
<td>1.04</td>
</tr>
</tbody>
</table>
formed within a soundproof chamber. One of the investigators (Y. O.) served as the subject after providing informed consent. He was 32 years of age, 172 cm in height, 68 kg in weight, and a healthy, lifetime nonsmoker. He had no history of asthma and had normal pulmonary function. The microphone and its coupler were attached over the right lower thorax at a single point marked by indelible ink. Each coupler was attached at precisely the same location using double-sided electrocardiographic adhesive rings. We took care to assure firm, circumferential adhesion of the couplers, and a new ring was used each time a coupler was replaced.

With a coupler placed at the study location, the subject was instructed to breathe regularly through a Fleisch pneumotachograph attempting to achieve a peak inspiratory flow of 2 L/s as displayed on an oscilloscope screen in front of him. A computer program automatically limited the analysis to sounds occurring between 1.5 and 2.5 L/s inspiratory flow. A mean of 64 spectra (range, 38 to 76) was averaged for each measurement.

To examine the effects of several venting arrangements, we used one cylindrical, 10-mm diameter coupler and performed recordings using a variety of vents summarized in Table 2.

We assessed the tendency of the vent to transmit ambient noise to the microphone by measuring the intensity of the airflow sound emanating from the mouth through the pneumotachometer during breathing, compared with the lung sound. This sound created by airflow at the mouth is an extraneous sound frequently encountered during lung sound studies and is easily distinguished from the lung sound by its spectral characteristics. We also recorded lung sounds while a low-intensity, 50-Hz square wave was fed to a small speaker within the soundproof chamber. The square wave harmonics provided a sound that was easily distinguished from the lung sounds on the power spectra. For one of the vents, we took sequential measurements with the vent open and then occluded (no vent).

RESULTS

The SEMs were so small that they rarely departed from the thickness of the average spectrum line and were therefore not plotted.

Figure 2 shows the overlapping spectra recorded using the conical and cylindrical couplers.

Figure 3 shows direct comparisons between the spectra recorded using the cylindrical and conical couplers of each chamber diameter. These figures also display spectra recorded during breathhold which

Table 2—Vent Sizes

<table>
<thead>
<tr>
<th>Diameter, mm</th>
<th>Length, mm</th>
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<tbody>
<tr>
<td>0.35*</td>
<td>20</td>
</tr>
<tr>
<td>0.35</td>
<td>13</td>
</tr>
<tr>
<td>0.35</td>
<td>7.5</td>
</tr>
<tr>
<td>0.64†</td>
<td>7.5</td>
</tr>
<tr>
<td>0.90†</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*0.35 mm = inner diameter of thin-wall 23-g needle.
†0.64 mm = hole drilled in plastic casing by a thin-wall 23-g needle.
‡0.90 mm = hole drilled in plastic casing by a thin-wall 20-g needle.

Figure 2. Spectra recorded by the three conical and cylindrical couplers. Among the conical couplers, the solid line represents the spectrum from the 8-mm coupler.

Figure 3. Comparisons between cylindrical (solid line) and conical (dashed line) couplers. The lower amplitude spectra (dotted and short dashed lines) in each of the figures were recorded between breaths, at zero airflow and represent the background noise level. The low-frequency components of the background noise are principally of cardiovascular and muscular origin.
establish the background noise floor of the system. Below 500 Hz, there was little difference between couplers. However, between 500 and 1,500 Hz, the conical couplers were generally more sensitive. This difference approached 10 decibel in the case of the 15-mm couplers.

All of the above recordings were performed without the use of a microphone chamber vent. The effects of various vent sizes were assessed separately. Figure 4 shows the overlapping spectra of expiratory lung sounds using various vents including no vent. We used expiratory sounds to emphasize the upper airway sound contamination that is usually more apparent in expiration than inspiration. In this quiet environment, there was little contamination of the spectra below 800 Hz. Between 800 and 1,400 Hz, contamination became more evident as the vent width increased and length decreased. This sound contamination was identified as the breath sound emanating from the subject’s mouth through the pneumotachometer. The breathhold spectra using the harmonics of the 50-Hz square wave also revealed progressively greater contamination above 500 Hz using the 0.9-mm diameter and 7.5-mm length vent.

**Figure 4.** The effect of different vent sizes on expiratory lung sound spectra. Note the nearly complete absence of mouth noise contamination in the 1,000 to 1,500-Hz range when no vent is used (bottom graph). We noted the spectral peak at about 650 Hz in all expiratory lung sound recordings. This sound apparently emanated from within the chest and may represent central airway resonance although we are uncertain of its source or significance.

**Discussion**

Our previous experiments, comparing a range of microphones and chamber depths, revealed superiority of the shallowest chamber (2.5 mm compared with 5, 10, and 20-mm depths). This superiority was predicted by an acoustic model of the chest wall-chamber-microphone interface, in which a smaller chamber depth increases chamber impedance and yields improved system sensitivity, especially at higher frequencies. The present results showed less marked differences between different diameter chambers of similar geometry. All diameters gave equivalent spectra up to 500 Hz. The 10- and 15-mm diameter couplers were slightly more efficient at frequencies between 500 and 1,000 Hz (Fig 2). These observations were not surprising as changes in the diameter of the cylindrical chamber are predicted by the model to yield only small changes in sensitivity. However, the conically shaped couplers were clearly superior to the cylindrically shaped chambers of comparable diameter in the upper half of the lung sound frequency spectrum (Fig 3). From a theoretical perspective, this finding can be attributed to the conical coupler’s larger surface area (at the skin)-to-air chamber volume ratio.
compared with that of the cylindrical couplers. This makes the conical coupler a more efficient transducer of air pressure fluctuations from the chest wall to microphone. So, although it is desirable to keep the air chamber small to enhance the sound pressure generated from a given chest wall motion, it is also beneficial to maximize the chamber opening at the skin.

We chose the range of vent diameters and lengths based on what we have observed to be commonly used in previous lung sound studies. As noted, the reason for using a vent is to equalize the static pressure in the chamber to atmospheric pressure yet not affect the dynamic pressures generated by the vibration of the chest wall. Acoustically, the vent represents a parallel pathway for sound induced in the chamber by chest wall vibration. For the vent to have no effect on the lung sound measurements, its (parallel) impedance must be much greater than that of the air chamber within the frequency range in question. At typical lung sound frequencies (50 to 1,500 Hz), the vent can be represented as a small open pipe and the air chamber as an enclosure. If one desires the 200-Hz impedance of a 20-mm long vent to be 10 times greater than an air chamber of 100 mm³, the vent diameter would have to be <0.1 mm. This explains why the larger vents used in our study yielded significant corruption of the lung sound data by ambient breath sounds.

We urge great care in the use of microphone venting to avoid contamination by extraneous sounds. We also question the need for a vent at all when using self-adhesive microphone couplers. It is unlikely that the adhesive seal will be so efficient that the chamber gas compression created when the coupler is pressed to the skin will persist for more than a few seconds. Microphone couplers that are handheld or strapped to the chest would probably benefit from the use of a vent because of the intrinsically variable pressure exerted on the coupler during breathing. In either case, investigators should be aware of the effect that a vent may have on the acquired signal and its analysis.

REFERENCES