

## Automated Lung Sound Analysis in Patients With Pneumonia

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**OBJECTIVE:** To determine whether objectively detected lung sounds were significantly different in patients with pneumonia than those in asymptomatic subjects, and to quantify the pneumonia findings for teaching purposes. **METHODS:** At a community teaching hospital we used a multi-channel lung sound analyzer to examine a learning sample of 50 patients diagnosed with pneumonia and 50 control subjects. Automated quantification and characterization of the lung sounds commonly recognized to be associated with pneumonia were used to generate an “acoustic pneumonia score.” These were examined in the learning sample and then prospectively tested in 50 patients and 50 controls. **RESULTS:** The acoustic pneumonia score averaged 13 in the learning sample and 11 in the test sample of pneumonia patients. The scores were 2 and 3 in the controls. The positive predictive value of a score higher than 6 was 0.94 in the learning sample and 0.87 in the test sample. The sensitivities in the 2 groups were 0.90 and 0.78, and the specificities were 0.94 and 0.88, respectively. Adventitious sounds were more common in pneumonia patients (inspiratory crackles 81% vs 28%, expiratory crackles 65% vs 9%, rhonchi 19% vs 0%). **CONCLUSION:** Our lung sound analyzer found significant differences between lung sounds in patients with pneumonia and in asymptomatic controls. Computerized lung sound analysis can provide objective evidence supporting the diagnosis of pneumonia. We believe that the lung-sound data produced by our device will help to teach physical diagnosis. *Key words:* lung sounds, physical examination, auscultation, pneumonia. [Respir Care 2004;49(12):1490–1497. © 2004 Daedalus Enterprises]

### Introduction

The diagnostic accuracy of the physical findings used to diagnose pneumonia is generally considered to be low. In one study, for example, 3 examiners’ clinical diagnosis of pneumonia had a sensitivity of 47–69%

and a specificity of 58–75%. The authors concluded that, “the traditional chest examination is not sufficiently accurate on its own to confirm or exclude the diagnosis of pneumonia.”<sup>1</sup> Another study showed, “a striking discrepancy between the stethoscope and [radiograph findings] in acute pneumonias.”<sup>2</sup> The chest examination, however, often shows signs that have been recognized, since the invention of the stethoscope by Laënnec, as consistent with pneumonia. There are, however, a variety of problems with clinical auscultation that make it difficult

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to reliably acquire the acoustic information that is associated with pneumonia. One major problem is substantial observer variability.<sup>1,3</sup> There has been a great deal of interest in using computer-based technology to circumvent the shortcomings of auscultation.<sup>4</sup> Computer-based technology has been developed that allows objective measurement, quantification, and display of auscultation

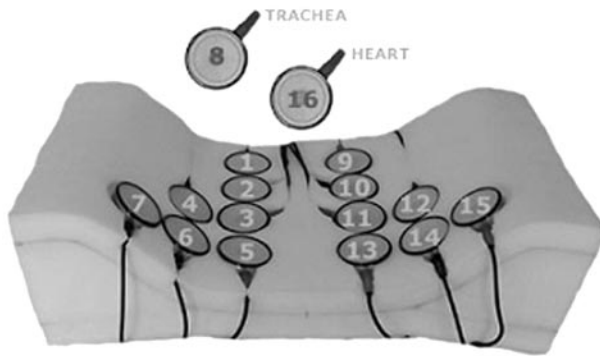


Fig. 1. Left: Placement of the microphones in the foam pad. Right: Placement of the pad against the subject's back.

tion findings.<sup>5-7</sup> We used a computerized multi-channel lung sound analyzer to determine whether objectively measured lung sounds differed significantly in patients with pneumonia versus asymptomatic subjects. We also were interested in quantifying the pneumonia sounds of patients for educational purposes.

**Methods**

All procedures were conducted in accordance with the ethical standards of the World Medical Association Declaration of Helsinki, and the study was approved by our institutional review board.

In our community teaching hospital we studied a convenience sample of 100 patients who were diagnosed by their physicians as having pneumonia. All the pneumonia patients had radiographic evidence consistent with the pneumonia diagnosis. The radiographs were interpreted by independent observers who were unaware of the bedside findings. Their charts were reviewed to confirm that they had findings consistent with symptoms of acute illness and the commonly reported criteria for pneumonia.<sup>3,8,9</sup> Fifty-eight percent were female.

We also studied 100 subjects who had no clinical evidence of pneumonia. Forty-eight percent were female. All of these subjects were patients who presented themselves to an internist for annual physical examination. The basis of selection was solely that their age matched those of the pneumonia group. After obtaining informed consent the patients and control subjects were examined with a multi-channel lung sound analyzer (model STG-1602, Stethographics, Westborough, Massachusetts), as previously described.<sup>10</sup> Figure 1 shows the device, in which 14 microphones are incorporated into a soft foam pad. The microphone pad is covered with a custom-made, single-use, disposable interface that prevents transmission of

pathogens to the pad. One microphone was used to record tracheal sounds.

With nonhospitalized subjects the microphone pad was positioned on a stretcher or a plastic reclining chair and the subject was supine on the pad. Hospitalized patients were examined in their beds. All participants were asked to breathe more deeply than normal, with their mouths open. Two 20-s measurements were taken.

The STG system software was custom-developed to collect data and provide automated identification of wheezes, rhonchi, fine crackles, coarse crackles, and squawks, in accordance with published definitions, except as noted below.<sup>11</sup>

The computer performs the lung-sound analyses in several seconds. The validation of the device as a crackle counter has been reported.<sup>6</sup> Its validation as a wheeze and rhonchus detector appears in the Food and Drug Administration's approval document.<sup>7</sup> In the present study a crackle was defined according to published criteria,<sup>11</sup> except that patients with  $\leq 2$  crackles per breath were considered normal. A rhonchus (ie, a low-frequency continuous adventitious lung sound) was defined acoustically as an abnormal sound, present in at least 4% of the respiratory cycle, with a sinusoidal waveform and a frequency of  $\leq 180$  Hz. A wheeze was defined as an abnormal inspiratory or expiratory sound, present in at least 4% of the respiratory cycle, with a sinusoidal waveform and a frequency of  $> 180$  Hz. The computer rapidly performed time-expanded waveform analysis of each channel, and the waveform analysis was used to verify the automated analysis.<sup>5</sup> The quantified adventitious sounds were used to generate an "acoustic pneumonia score." To derive the acoustic pneumonia score we studied reported findings in textbooks and journal articles and reviewed the findings of a previous investigation by us.<sup>12</sup> It was clear from that review that crackles and rhonchi were commonly reported findings and that higher rates of crackles and rhonchi per

# AUTOMATED LUNG SOUND ANALYSIS IN PATIENTS WITH PNEUMONIA

Table 1. Summary of the Automated Acoustical Data Analysis

	Pneumonia ( <i>n</i> = 100)	Controls ( <i>n</i> = 100)	<i>p</i>	
Age	69 ± 18	69 ± 7	0.87	
<i>Average Rhonchi Rate</i>				
Inspiration	Patients With Rhonchi (%)	18	1	< 0.0001
	Rate (%) (range)	30 ± 20 (5–79)	5	N/A
Expiration	Frequency (Hz)	138 ± 46	101	N/A
	Patients With Rhonchi (%)	19	0	< 0.0001
Expiration	Rate (%) (range)	35 ± 25 (4–80)	-	NA
	Frequency (Hz)	127 ± 30	-	NA
<i>Mean Number of Crackles per Breath</i>				
Inspiration	Patients With Crackles (%)	81	28	< 0.0001
	Mean ± SD crackles/breath (range)	8 ± 5 (2–19)	4 ± 2 (2–13)	< 0.0001
	Frequency (Hz)	309 ± 63	387 ± 91	0.57
Expiration	Patients With Crackles (%)	65	9	< 0.0001
	Mean ± SD crackles/breath (range)	6 ± 5 (2–17)	4 ± 3 (2–13)	0.26
	Frequency (Hz)	278 ± 70	402 ± 104	< 0.0001

breath are associated with a higher likelihood of pneumonia. An acoustic pneumonia score was calculated for each subject by adding each of the individual scores. These scores were defined as follows. The rhonchus rate was defined as the proportion of the breath cycle occupied by rhonchi. The rhonchus score was calculated as follows: a rhonchus rate of 4–5% received a score of 3; a rate of 6–10% received a score of 5; and a rate of 11–100% received a score of 6.

The crackle score was calculated separately for inspiration and expiration and was defined as the number of crackles per respiratory phase, except that the maximum crackle score was 10 for inspiration and 10 for expiration. The minimum and maximum possible acoustic pneumonia scores were zero and 26, respectively. We examined the performance of this score in the first 50 subjects in each group (learning sample). We then examined the performance of the score in the remaining 50 patients in each category.

### Statistical Analysis

The results are presented as mean ± SD, unless otherwise stated. Paired *t* tests were used to compare the variables between the groups for the variables on a continuous scale. The McNemar test was used to compare categorical data. Differences were considered statistically significant when *p* < 0.05.

### Results

Table 1 shows the results of the automated analysis of the abnormal sounds in the 100 pneumonia patients and

control subjects. As expected, abnormal sounds were more common in the patients with pneumonia. Only 7% of patients with pneumonia were free of rhonchi and crackles, compared to 69% of controls.

The inspiratory crackles in the pneumonia patients were classified by the computer as coarse in 63% and both coarse and fine in 99%. Fifty percent of the expiratory crackles were classified as coarse; only one patient with pneumonia had expiratory fine crackles; the remainder had a mixture of fine and coarse crackles. The presence of crackles in the control group was age-related. None of the controls who had crackles were younger than 60 years old. Wheezing was more common in the pneumonia patients: it was present in 14% of patients during inspiration and in 21% during expiration. Three controls (3%) had inspiratory wheezing; 1 had expiratory wheezing. All pneumonia patients in this study had chest radiograph opacifications consistent with pneumonia. The opacifications were unilateral and basilar in the majority of patients. Right-sided pneumonia was more common than left-sided pneumonia. Upper-lobe involvement in the absence of lower-lobe involvement was uncommon.

Figure 2 shows examples of waveform plots, one from a patient with pneumonia, the other from a normal control subject. Figure 3 shows the crackle summary and the chest radiograph of the same patient.

### Acoustic Pneumonia Score

The acoustic pneumonia score averaged 13 ± 6 in the learning sample and 11 ± 5 in the test sample of pneumonia patients. It was 2 ± 2 and 3 ± 4 in the control subjects (Fig. 4). The sensitivity and specificities in the

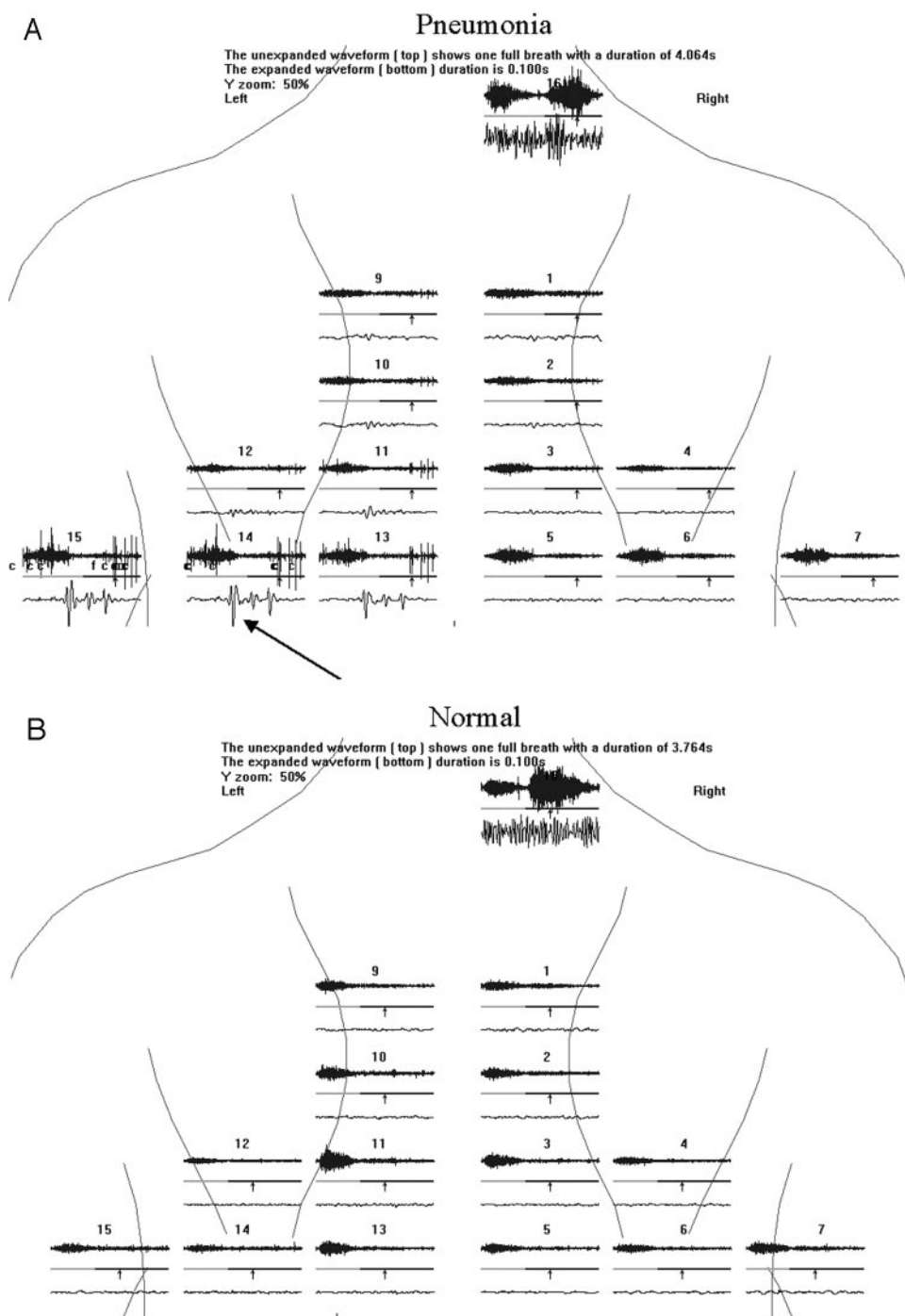


Fig. 2. Time/amplitude plots of a single breath, as they appear at multiple sites. The waveforms are presented in both the unexpanded mode (upper wave in each of the 2-wave sets) and expanded mode (lower wave in each of the 2-wave sets). The unexpanded waveform shows one full breath. The solid bars under the unexpanded waves mark the respiratory cycle. The thinner (light) part of the bar demarks the inspiratory phase, and the thicker (dark) part marks the expiratory phase. The small arrows indicate the location of the expanded interval. The duration of the expanded interval is 100 milliseconds. A: In this subject, who had left-lower-lobe pneumonia, crackles were heard over the left lower lobe. The time/amplitude pattern shows crackles on channels 13, 14, and 15 (large arrow). Note the coarse crackle waveform on the expanded time/amplitude plot. B: In this normal subject, there are no wheezes or crackles. The time/amplitude pattern is relatively uniform from site to site across the chest. Note that the waveform recorded by the tracheal microphone is longer and louder than those from over the chest wall.





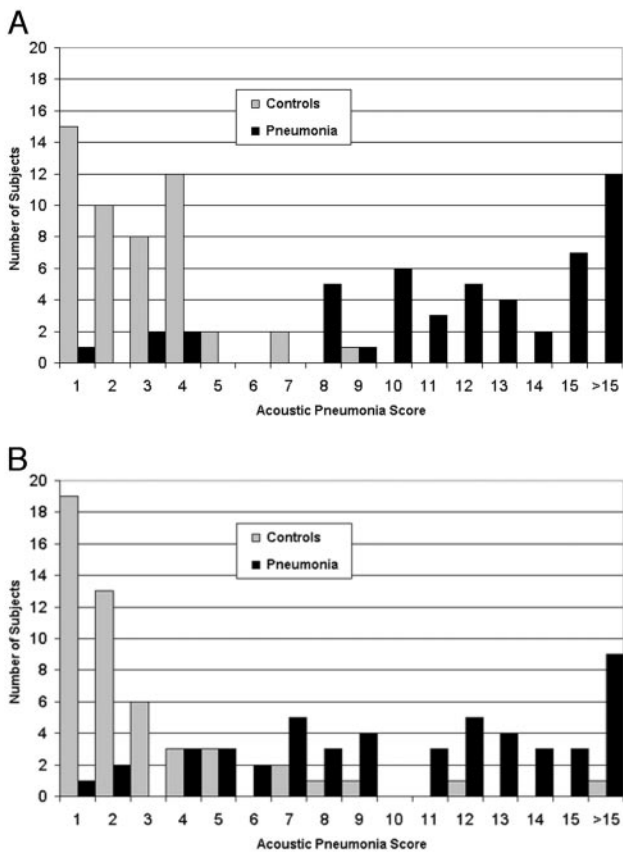


Fig. 4. Acoustic pneumonia score frequency distribution in control subjects and in patients with pneumonia. A: The first 50 controls and pneumonia patients. B: The second 50 controls and pneumonia patients.

clinically important information to help diagnose patients suspected to have pneumonia, who have no other substantial cardiopulmonary disorder.

Pneumonia is the leading cause of infectious-disease-related death and a leading cause of mortality in persons  $\geq 60$  years old in the United States.<sup>13</sup> Evidence has been presented that the sooner pneumonia is treated, the better the prognosis.<sup>5,14</sup> Unfortunately, the clinical presentation is often atypical, particularly in the elderly.<sup>15-17</sup> Accordingly, we became interested in ways to improve the diagnosis. In previous research, utilizing computer-assisted analysis, we demonstrated that adventitious sounds can be differentiated by their acoustic characteristics.<sup>5,18</sup> In addition, the patterns of objectively measured sounds in a variety of common illnesses are different.<sup>12,18-21</sup> Several of those studies reported on the acoustic characteristics of the sounds in pneumonia patients<sup>12,19-21</sup> As those studies involved only a small number of patients, we were interested in finding out if those preliminary observations would apply to a larger number of patients in a typical clinical setting. We observed significant differences in the lung sounds of pneumonia patients and subjects who were not

acutely ill. The sensitivity and specificity of this lung-sounds analysis method for distinguishing pneumonia from other illnesses is not known and requires further study. In addition, our choice of an acoustic pneumonia score of 6 as a threshold was somewhat arbitrary, although it was based on an extensive literature review and our experience. A prospective study of that score is also indicated.

**Accuracy**

Sixteen patients with pneumonia had acoustic pneumonia scores of  $\leq 6$  and thus were false negatives. Fourteen of those patients had a crackle rate that was lower than the threshold. One had markedly decreased breath sounds in the area where the pneumonia was present on chest radiograph. The other had diffuse wheezing that may have obscured the presence of crackles. Three of the 9 false positives had a technically unsatisfactory recording. The remaining 6 all had evidence of chronic pulmonary or cardiac disease.

The crackle rate in the control group of our study was much higher than the crackle rate in the normal subjects of previous studies.<sup>22,23</sup> However, those studies used much younger subjects, they included only subjects without lung disorders, and they did not involve measurements on as many sites.

From a clinical point of view, it would not be a problem to differentiate the false positives from the pneumonia patients. All of our pneumonia patients were acutely ill and had one or more of the usual clinical findings of pneumonia. All of the false positives, on the other hand, were undergoing routine annual physical examinations and none were acutely ill. Automated lung-sound findings, like other clinical evidence such as the chest radiograph, need to be viewed in terms of the total clinical picture to avoid over-diagnosis. With our lung-sounds-measurement system the results are immediately available at the bedside, the device is noninvasive and can be used even with critically ill patients, as we did in the present study, and the foam pad that contains the microphones is easily placed under the patient, even a patient on a ventilator.

**Advantages of Computerized Lung-Sound Analysis**

A good deal of the information obtained by computerized lung-sound measurement can be obtained by a skilled clinician using a stethoscope. In applying for Food and Drug Administration approval we presented the results of observations by board-certified pulmonologists compared to the automated measurements and analysis. There was close agreement in the recognition of wheezes, rhonchi, and crackles.<sup>7</sup> There was less agreement when lesser-trained clinicians were similarly tested. When evaluating a report of lung auscultation in a medical record, it is not always

easy to know if a particular observer is competent or places much value in auscultatory findings.

There is a great deal of information in lung sounds that is not easily obtained by even the best of clinicians. For example, at a single site the clinician can make at least 6 observations, such as the presence/absence, character, and timing of crackles, wheezes, and rhonchi; decreases in amplitude; and duration of the inspiratory and expiratory phases. The meaning of those observations is discussed elsewhere.<sup>24</sup> If the clinician listens in 10 sites, there are at least 60 possible sets of data. That is beyond the memory capabilities of most people. Computers greatly improve the efficiency of data collection and management. Two minutes of 14-site automated lung-sound analysis gathers as much data as 28 min of one-site-at-a-time listening by a human. The automated data are archived and easily retrievable, even years later, thus avoiding memory problems, potential difficulties with transcribing the data, and potential problems in deciphering handwriting.

Another reason for interest in lung sounds, as compared to the radiograph, is that the sounds provide more regional information. The chest radiograph is a summation shadowgram. Areas at the lung bases, particularly behind the heart, are not well visualized. This is particularly true in the intensive care setting, where only anteroposterior views are obtained and the patient is often unable to cooperate with instructions to take a deep breath. Computerized lung-sounds analysis has the advantage of providing results immediately at the bedside. It may be particularly applicable with children or pregnant patients, with whom radiography may have safety issues.

Although several studies (noted above) found objective differences in the lung-sounds of patients with pneumonia that allow them to be separated from those of other lung disorders, further study is needed to more precisely determine how well that separation can be done. Nevertheless, there are many clinical circumstances where those other conditions are unlikely and the data from acoustic lung sound analysis could potentially aid in diagnosis. Nonsmokers with no previous history of lung disease, for example, are unlikely to have crackles, particularly if the patient is < 60 years old. The case can be made stronger if baseline data (analogous to a baseline electrocardiogram) are available and show that the patient had no abnormalities on a previous examination.

### Limitations

In addition to the fact that we were comparing acutely ill patients to persons who were not acutely ill, there are some other limitations to the present study. We collected data from only 14 chest sites. There were only 2 microphones on the lateral chest and none on the anterior chest. One of the false negatives had radiographic evidence of

right-middle-lobe opacification. The microphone closest to the right middle lobe was abnormal, but the acoustic pneumonia score did not rise above our threshold for the pneumonia diagnosis. It is possible to place microphones on the anterior and lateral chest, but we did not do that in the present study because we have found that those locations give more artifacts and poorer-quality recordings. The fact that we had such a high sensitivity despite not having anterior microphones or more lateral microphones suggests that most of the information from pneumonia sounds can be detected on the posterior chest. It may be that in our elderly population the majority of the pneumonias are due to aspiration and therefore more likely to be posterior and inferior. Indeed, almost all of the radiograph reports indicated that the lower lobes were involved.

An additional limitation is that we did not take the pathologic stage of pneumonia into consideration. Early pneumonia is known to be pathologically much different than late pneumonia, which probably affected the sounds we measured, as the stage of pneumonia present when we made our measurements differed from patient to patient. It would require a much larger study to address that question.

We studied a convenience sample rather than consecutive patients. The patients with pneumonia were selected from the admitting diagnosis list or by asking the hospital nurses if any of their patients had a diagnosis of pneumonia. This was done only on the days when a technician was available. The charts and radiographs were subsequently reviewed and only those patients meeting published criteria were included. Ten patients were not included for that reason.

### Conclusion

This study provides evidence that the auscultatory findings in patients with pneumonia can be readily quantified by a computerized technique. The method is noninvasive and provides useful diagnostic information at the bedside to aid clinicians managing this common ailment.

### REFERENCES

1. Wipf JE, Lipsky BA, Hirschmann JV, Boyko EJ, Takasugi J, Peugeot RL, Davis CL. Diagnosing pneumonia by physical examination: relevant or relic? *Arch Intern Med* 1999;159(10):1082-1087.
2. Osmer JC, Cole BK. The stethoscope and roentgenogram in acute pneumonia. *South Med J* 1966;59(1):75-77.
3. Mehr DR, Binder EF, Kruse RL, Zweig SC, Madsen RW, D'Agostino RB. Clinical findings associated with radiographic pneumonia in nursing home residents. *J Fam Pract* 2001;50(11):931-937.
4. Pasterkamp H, Kraman S, Wodicka G. Respiratory sounds: advances beyond the stethoscope. *Am J Respir Crit Care Med* 1997;156(3 Pt 1):974-987.
5. Murphy RL, Holford SK, Knowler WC. Visual lung-sound characterization by time-expanded wave-form analysis. *N Engl J Med* 1977;296(17):968-971.

6. Murphy RL, Del Bono E, Davidson F. Validation of an automatic crackle (rale) counter. *Am Rev Respir Dis* 1989;140(4):1017-1020.
7. FDA approval K012387. Available at <http://www.fda.gov/cdrh/pdf/k012387.pdf>. Accessed September 20, 2004.
8. Metlay JP, Kapoor WN, Fine MJ. Does this patient have community acquired pneumonia? Diagnosing pneumonia by history and physical examination. *JAMA* 1997;278(17):1440-1445.
9. Heckerling PS, Tape TG, Wigton RS, Hissong KK, Leikin JB, Ornato JP, et al. Clinical prediction rule for pulmonary infiltrates. *Ann Intern Med* 1990;113(9):664-670.
10. Bergstresser T, Ofengeim D, Vyshedskiy A, Shane J, Murphy R. Sound transmission in the lung as a function of lung volume. *J Appl Physiol* 2002;93(2):667-674.
11. Sovijarvi A, Vanderschoot J, Earis J. Computerized Respiratory Sound Analysis (CORSA) recommended standards for terms and techniques. *Eur Respir Rev* 2000;10(77):585-649.
12. Bettencourt PE, Del Bono EA, Spiegelman D, Hertzmark E, Murphy RL Jr. Clinical utility of chest auscultation in common pulmonary diseases. *Am J Respir Crit Care Med* 1994;150(5 Pt 1):1291-1297.
13. Marston BJ, Plouffe JF, File TM Jr, Hackman BA, Salstrom SJ, Lipman HB, et al. Incidence of community acquired pneumonia requiring hospitalization. *Arch Intern Med* 1997;157(15):1709-1718.
14. Holford SK. Discontinuous adventitious lung sounds: measurement, classification and modeling. ScD Thesis, Massachusetts Institute of Technology; 1982.
15. Battleman DS, Callahan M, Thaler HT. Rapid antibiotic delivery and appropriate antibiotic selection reduce length of hospital stay of patients with community-acquired pneumonia: link between quality of care and resource utilization. *Arch Intern Med* 2002;162(6):682-688.
16. Metlay JP, Schulz R, Li YH, Singer DE, Marrie TJ, Coley CM, et al. Influence of age on symptoms at presentation in patients with community acquired pneumonia. *Arch Intern Med* 1997;157(13):1453-1459.
17. Berman P, Hogan DB, Fox RA. The atypical presentation of pneumonia in old age. *Age Ageing* 1987;16(4):201-207.
18. Piirila P, Sovijarvi AR, Kaisla T, Rajala HM, Katila T. Crackles in patients with fibrosing alveolitis, bronchiectasis, COPD, and heart failure. *Chest* 1991;99(5):1076-1083.
19. Sovijarvi AR, Piirila P, Luukkonen R. Separation of pulmonary disorders with 2-dimensional discriminant analysis of crackles. *Clin Physiol* 1996;16(2):171-181.
20. Vanderschoot J, Helisto P, Lipponen P, Piirila P, Sovijarvi AR. Distribution of crackles on the flow-volume plane in different pulmonary diseases. *Technol Health Care* 1998;6(1):81-89.
21. Piirila P, Sovijarvi AR. Crackles: recording, analysis and clinical significance. *Eur Respir J* 1995;8(12):2139-2148.
22. Workum P, Holford SK, Delbono EA, Murphy RL. The prevalence and character of crackles (rales) in young women without significant lung disease. *Am Rev Respir Dis* 1982;126(5):921-923.
23. Thacker RE, Kraman SS. The prevalence of auscultatory crackles in subjects without lung disease. *Chest* 1982;81(6):672-674.
24. Loudon R, Murphy RL Jr. Lung sounds. *Am Rev Respir Dis* 1984;130(4):663-673.