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Computerized Multichannel Lung Sound Analysis

Development of Acoustic Instruments for Diagnosis and Management of Medical Conditions

BY RAYMOND MURPHY

The stethoscope has been so widely used by clinicians in the diagnosis and management of patients' illnesses that it has virtually become a symbol of the medical profession. Indeed, as pointed out by Reiser in *Scientific American*, the invention of the stethoscope by Laënnec revolutionized medicine, changing it from an art to a science [1]. Another revolution is now going on. Auscultation of the chest is now being computerized. One of the forces driving this computerization is that it offers the promise of providing improved instruments for noninvasive diagnosis, i.e., tools that do not invade the body or involve the harmful effects of radiation. Comprehensive reviews of the stethoscope's use in auscultation of the lung and of the development of computerized analysis of lung sounds have been presented [2]–[4]. There are also some more recent publications that report on employing advanced signal processing techniques for the detection of adventitious sounds that have been developed by a few groups in the field of lung sounds research [6], [7]. This discussion will focus on clinically important applications of this type of investigation and, in particular, on the development of multichannel lung sound analysis and its clinical importance.

The invention of the chest X ray had a large impact on the clinical utility of the stethoscope. There was no doubt that chest X rays were more reliable than auscultation with an acoustic stethoscope in the detection of important lung diseases such as tuberculosis and cancer. Physical examination of the chest also suffers from a variety of problems. Observer variability is a particularly troublesome one as has been shown in numerous studies. There are differences between clinicians in their education and in their use of nomenclature for sounds. There are even differences in the importance they place on auscultation in the first place. Consequently, it is difficult to know when an observation is made whether it is accurate or not; thus, in the medical literature, a number of derogatory statements can be found about the stethoscope. In the 1961 edition of Rubin and Rubin's *Textbook of Chest Medicine*, the following quote can be found: "The stethoscope is largely a decorative instrument insofar as its value in diagnosis of pulmonary diseases is concerned. Nevertheless, it occupies an important role in the art of medicine. Apprehensive patients with functional complaints are often relieved when they feel the chest piece on their pectoral muscles" [5]. There was even a radiologist who had a

framed stethoscope on the wall of a hospital in Boston under which was the following caption: "This is a stethoscope, an instrument formerly used in the diagnosis of lung diseases." One of the most famous investigators into the physiology underlying respiratory sounds, Paul Forgacs, claimed that auscultation had been reduced to a perfunctory ritual [8].

Despite these problems and opinions, the stethoscope remains one of the most common devices used by medical professionals. Physicians, nurses, and respiratory therapists routinely use stethoscopes in their daily practice to assess conditions that affect the lung. But as noted, its reliability is in question, presenting a paradox: an unreliable tool that everyone uses. Modern medical science has developed a host of more objective methods for the diagnosis and management of lung conditions. These include computed tomography (CT) scans, magnetic resonance imaging, chest X rays, a variety of blood tests, sophisticated pulmonary function tests, pulmonary arteriography, and radioisotope scanning techniques. Biopsy of the lung is also used in some instances to make definitive diagnoses of lung conditions. The general opinion is that these tests are more reliable and valuable than auscultation via the stethoscope. On the other hand, when a clinician is presented with a patient in severe acute respiratory distress, these tests are not likely the first ones to be used. In this situation, the stethoscope in the hands of a knowledgeable clinician can provide information that can be life saving. Auscultation, particularly when combined with the other modalities of physical diagnosis, can guide steps taken in patient management before any of the advanced technologies are employed. Examples are as follows:

- a sound called stridor can be heard when foreign bodies are in large airways (this is a potentially life threatening situation, and action can be taken to remove the offending material once this sound is recognized, e.g., a Heimlich maneuver can be performed)
- diffuse wheezing points toward a diagnosis of acute bronchial asthma and bronchodilators are often administered before other testing is done
- collapse of one lung can be detected by the absence or marked decrease of lung sounds on one side; treatment for this condition is often done immediately based on auscultatory findings
- fluid can be withdrawn from the pleural space reliably based on physical findings

- the presence of numerous crackles on auscultation in patients presenting with lung congestion secondary to heart failure is used to guide the administration of medications to reduce the fluid prior to more definitive testing.

These clinical applications, in part, explain why the stethoscope remains in common use despite its shortcomings. Computerized lung sound analysis has the potential of being applied in emergency situations such as the ones just described to improve diagnostic accuracy.

An early application of computerized lung sound analysis was an outgrowth of an observation that a group of pipecoverers exposed to asbestos as a result of working in a shipyard was noted to have an abnormal number of crackling noises on auscultation. Initial investigations employed an acoustic stethoscope using a method of mapping the lung sounds at prescribed sites on the chest wall of the workers exposed directly to asbestos and comparing these findings to the findings in an age matched group of shipyard workers not directly exposed. Blinded auscultation, i.e., examinations in which the observer was unaware of the exposure history, clearly showed that the presence of fine end inspiratory crackles was significantly more common in workers directly exposed to asbestos [9]. Operating on the belief that the sounds heard over the chest were not random events but reflected the pathophysiology of the underlying lung and that if this information could be captured, it would be useful in the development of powerful tools for diagnosis and monitoring of cardiopulmonary conditions, a physician-engineering team began employing methods to make graphical displays of the sounds. They began to apply modern technology to the acoustical signal from the lung, in particular, advances in acoustical knowledge and computer science [10]. A series of investigations to explore the utility of quantifying lung auscultatory phenomena began. There were a number of other investigators worldwide with similar interests, and the International Lung Sounds Association was founded to promote investigation in the field of medical acoustic research in 1976 [11]. (The 31st annual meeting of this organization was held 6–7 October 2006).

An important observation was made that helped facilitate the computerized analysis of lung sounds. It was noted that in the time domain, expanding the time axis beyond the conventional methods of sound analysis (e.g., phonocardiograms and phonopneumography) provided a powerful tool for examining lung sounds [12] (see Figure 1).

Time expanded waveform analysis (TEWA) provided an objective tool that showed distinctive patterns of the common lung sounds that allowed them to be distinguished visually rather than only by ear [13]. TEWA was useful in characterizing the crackles of asbestos workers and training and validating technicians in detection of these crackles for surveillance of workers [14]. TEWA was also used to help clarify lung sound nomenclature [13], [15]–[17]. It has also been shown by British and Finnish investigators to be as good as CT scans in detecting asbestosis [18], [19]. Indeed, the pipecoverers mentioned above were followed for 18 years, and it was found that the ones who had crackles at both bases of the chest documented using this technology showed worse X rays and pulmonary function than those without crackles. These observations encouraged the pursuit of investigations that lead to the development of a multichannel lung sound analyzer [Stethograph (STG)] by the author and collaborators, which will be described in the remainder of this manuscript.

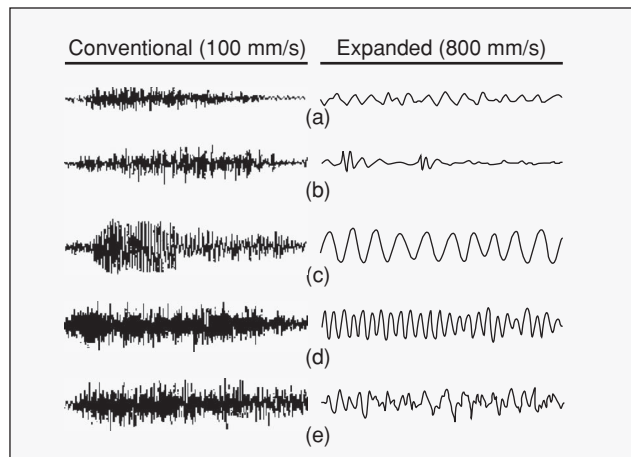


Fig. 1. Time domain plots are illustrated in both the time unexpanded and time expanded modes. (a) Normal vesicular inspiratory sound. (b) Inspiratory rales at posterior lung base. (c) Sonorous rhonchus. (d) Sibilant rhonchus (wheeze). (e) Normal tracheal inspiration. It is clear that the pattern differences between different types of lung sounds are seen more easily in the expanded mode. (Reprinted with permission from “Visual lung-sound characterization by time-expanded wave-form analysis,” by R. Murphy, S. Holford, and W. Knowler, *New England Journal of Medicine*, vol. 296 pp. 968–971, April 28, 1977.)

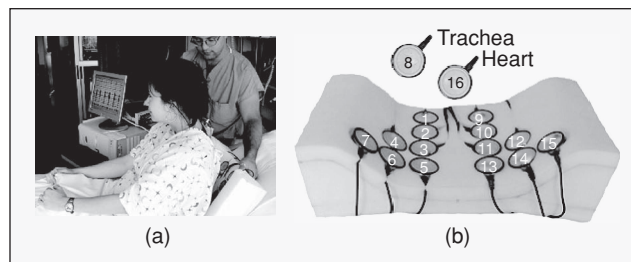


Fig. 2. (a) The 16-channel STG System. (b) Sixteen electronic stethoscopes in a backpad. A disposable, fluid impervious covering covers the pad during patient application.

Development of Multichannel STG

Sounds can be detected at many sites on the chest (up to about 60 depending on body size). This can provide a great deal of diagnostic information not easily obtained in other ways. However, the recording and analysis of sounds from multiple sites over the chest is a slow and tedious process. The use of computer power can greatly simplify and accelerate this process. As early as 1989, it was reported that computer-based crackle counts were correlated with the physician counts ($r = 0.74$, $p < 0.001$, number of subjects = 41) [20]. Since then, the algorithm was improved, and a 16-channel automatic sounds analyzer (STG) was developed. This system consists of electronic stethoscopes, a signal-conditioning box, an analog to digital converter and a standard PC running dedicated software. This electronic stethoscopes are imbedded in a soft foam pad for application to the patient, Figure 2. The lung sound information is provided in three principle ways.

First, the recorded lung sounds are displayed in a TEWA, which allows visual examination and audio playback of the data. The display of the traces, similar to an electrocardiograph,

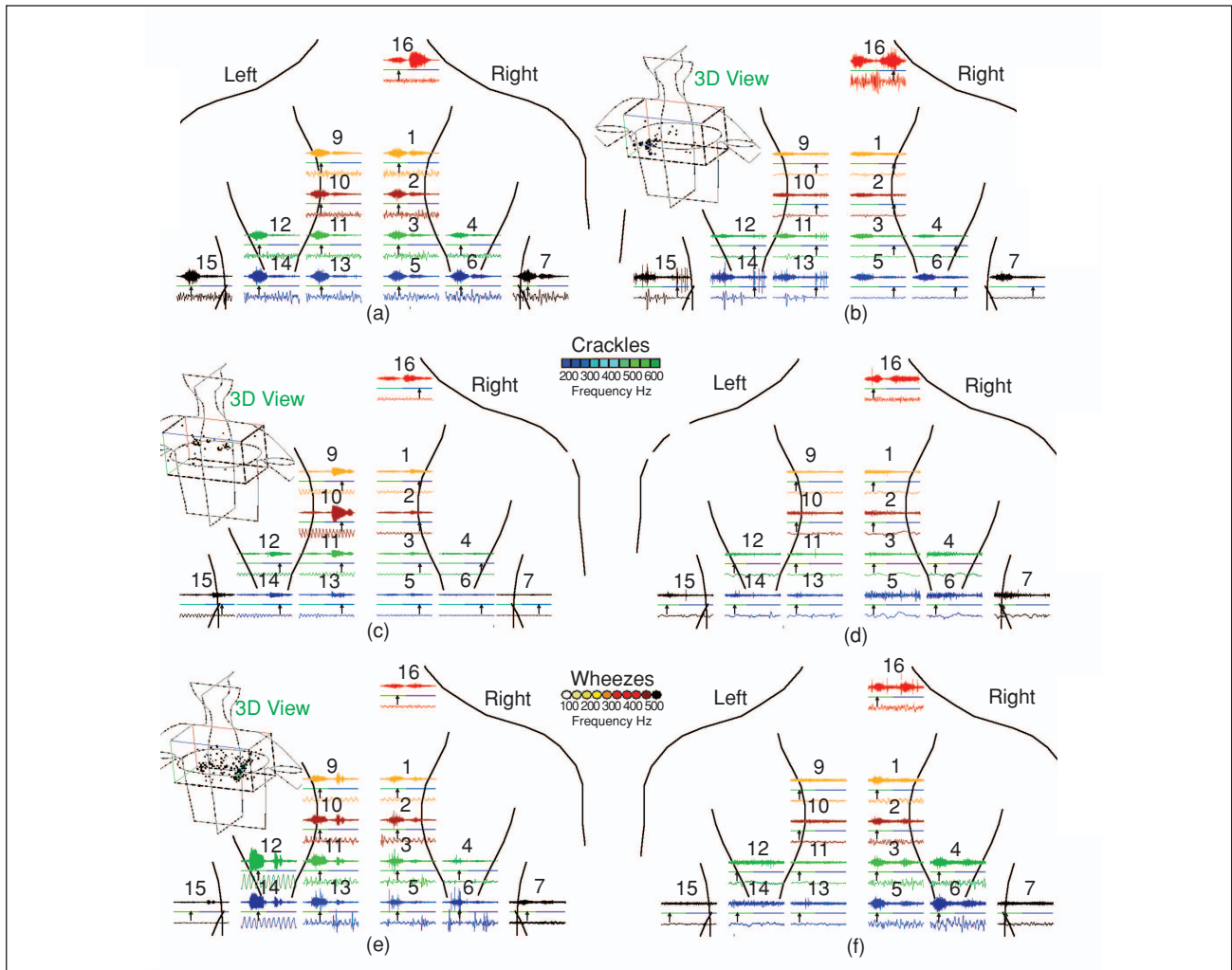


Fig. 3. Time amplitude plots of a single breath are displayed as they were detected by the microphones arrayed over the posterior chest. Twelve microphones are placed on the back; numbers 1 through 6 are on the right side, 9 through 14 are on the left. There is one on each lateral base—microphone numbers 7 and 15 respectively. One microphone is over the trachea—number 16. Waveforms are presented in both the unexpanded (top) and expanded (bottom) modes. The unexpanded waveform shows one full breath. The unexpanded and expanded waves corresponding to the same channel are shown in the same color. The choice of colors is arbitrary. The solid bars under the unexpanded waves mark respiratory cycle—green bars indicate inspiration and blue bars indicate expiration. The arrow indicates the location of the expanded interval. The duration of the expanded interval is 100 milliseconds. (a) Normal lung sounds. The time amplitude pattern seen over the chest is relatively uniform from site to site. (b) Pneumonia crackles are concentrated at the left base where opacification was detected on X-ray. Both inspiratory and expiratory crackles are present. The insert shows 3-D localization of abnormal lung sounds. Crackles are indicated by cubes. Wheezes and ronchi are indicated by spheres. Color indicates the frequency of the sound. Size of markers is proportional to crackle and wheeze rate. (c) Acute bronchial asthma; significant expiratory wheezing is present. (d) Chronic bronchitis and emphysema. The overall intensity of the breath sounds is decreased. The expiratory phase is relatively prolonged. A few basilar crackles are present. (e) Congestive heart failure; inspiratory crackles are present at both bases. Inspiratory ronchi are detected on the left. (f) Pneumothorax; breath sounds are diminished in the collapsed (left) lung.

allows direct visual detection of the abnormalities. Each channel can be examined for the patterns of crackles and wheezes. In addition, the patterns of the inspiratory and expiratory phases can be examined to see if they are relatively smooth and regular as is the case in normals or if they are irregular as is found in many disease states (see Figure 3). The inspiratory phase is usually easily separated from the expiratory phase by the marked difference in the pattern of the expiratory phase over the trachea as compared to the pattern of the expiratory phase over the chest. Contrasts between abnormal data and data recorded for healthy individuals are often pronounced.

Second, the computer algorithm automatically analyzes acoustic energy versus time and detects crackles, wheezes, and ronchi. Derived measures of the sound characteristics are displayed on an anatomical diagram to allow visualization of the spatial distribution of lung function and abnormalities. Further information on the overall amplitude of breath sounds, timing of the abnormalities, and crackle and wheeze counts is included in this display. Differences in abnormal patterns among different diseases become apparent in this context.

Technology for the automatic localization of intrathoracic sounds has also been developed [21]. This is used to integrate

information from multiple channels to generate a three-dimensional (3-D) view of the human thorax with crackles and wheezes localized to specific lung regions. Advanced visualization software also allows 360-degree rotation, extraction of sectional views, and comparative views. The 3-D feature of the STG can help minimize radiation exposure in neonatal patients by providing sound lung mapping potentially reducing the number of X rays.

Recently, a paper was published showing that an acoustic score generated by computer utilizing the variations in breath sounds separated patients with pneumonia from normal patients with a sensitivity of 0.84, a specificity of 0.94, and a positive predictive power of 0.93 [22]. When that paper was published, it was accompanied by an editorial. The author commented on the efficiencies of computerized auscultation as compared to a well-executed lung exam with an acoustic stethoscope, pointing out that this could take up to 10 min. He titled the editorial "Is the Stethoscope on the Verge of Becoming Obsolete" [23]. The principal investigator replied to the editorial with a letter to the editor expressing the opinion that the stethoscope is not becoming obsolete but is getting married to the computer [24]. Indeed, stethoscopes that are connected to personal digital assistants (PDAs) have been developed and are on the market [25]–[27]. Automated analysis of sounds is now available at the bedside.

The advances in computer technology in the past decades now allow more precise quantification of sound, improved documentation, and archiving and can aid in the diagnosis of many cardiopulmonary conditions. Indeed, pneumonia has been detected by computerized lung sound analyses that were missed by chest X ray and even by CT scan. The diagnostic utility of chest X rays in the intensive care unit setting is notoriously poor because of a variety of factors, including a patient's ability to cooperate with the examination when they are very sick or sedated. The use of CT scans in the intensive care setting is extremely difficult. Computerized acoustic technology can be used in this setting, even in severely ill patients on ventilators [22].

In summary, computerized analysis of lung sounds can play a very important role in management of patients with a variety of medical conditions, particularly those who are seriously ill. While single-channel devices can play an important role in making auscultation more objective, multi-channel instruments greatly improve the efficiency of data collection. This has a particular advantage in the rapid assessments of patients who are in acute distress from cardiopulmonary conditions. As noted, it has the distinct advantage of being noninvasive. This is a particular advantage in the case of children and pregnant women. A number of other groups are currently working with multichannel devices, but have not yet reported their findings. The future will likely see improved acoustic instruments useful in diagnosis and management of medical conditions.



Raymond Murphy has been a practicing physician since 1966. He holds degrees in public health and occupational medicine. He was serving as chief of pulmonary medicine at the Faulkner and Lemuel Shattuck Hospitals, Boston, Massachusetts, for more than 25 years. He is professor of Medicine at the Tufts University School of Medicine.

In 1975, he cofounded the International Lung Sounds

Association. He has published more than 50 articles and papers. He holds a B.S. degree from Holy Cross College, an M.D. from New York University, and both an M.P.H. and Sc.D. from Harvard University. He has retired from Harvard's School of Public Health after serving on the faculty for 25 years. In 1998, he founded Stethographics, Inc., and serves as a company chief medical officer.

Address for Correspondence: Raymond Murphy, MD, MPH, DSc, Dept. of Pulmonary Medicine, Brigham & Women at Faulkner Hospital, 1153 Centre St, Boston, MA 02130 USA. Phone: 617 983 4436. Fax: 617 522 4156. E-mail: Rlhm@stethographics.com.

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