

Validation of an Automatic Crackle (Rale) Counter^{1,2}

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Introduction

Since the time of Laennec, clinicians have recognized that crackles heard on chest auscultation commonly indicate a lung disorder. Furthermore, the number of locations on the chest at which crackles are heard often correlates with the severity of the illness. In diffuse interstitial pulmonary fibrosis, crackles are heard initially only at the lung bases; they appear progressively higher over the chest as the disease progresses (1). In the early stages of congestive heart failure, crackles are usually heard only over dependent areas of the lung, whereas in acute cardiogenic pulmonary edema, crackles are invariably present over almost all of the chest, sparing only the apices (2). The common practice of using crackles for clinical decision-making is limited, however, by observer variability, inadequate documentation of findings, and difficulties with nomenclature. We have previously reported that time-expanded waveform analysis, a technique that allows visual demonstration of sounds, provides an objective basis for classification, documentation, and quantification of auscultatory phenomena (3). Quantification of crackles visualized on time-expanded waveforms is tedious and impractical for clinical use. Accordingly, we devised a computer-based system to count these discontinuous sounds. To study the accuracy of this automatic counting system, we compared audible, waveform, and computer crackle counts from subjects with and without cardiopulmonary disorders.

Methods

One hundred samples of lung sounds were recorded from 41 subjects with a variety of conditions, including chronic obstructive lung disease, congestive heart failure, pneumonia, interstitial pulmonary fibrosis, and asbestosis, and patients with no evidence of chest disease. Recordings were made with a Sony Walkman tape recorder using a Sony Electret microphone air-coupled to the chest wall. Time-expanded waveforms were made on each of the sounds as previously described (3). A trained technician examined the waveforms and counted complexes containing be-

SUMMARY Crackles are commonly used in clinical decision-making, and in certain diseases the number of crackles reflects the severity of the illness. Auditory crackle estimations are subjective; crackle counting from time amplitude plots of sound (called time-expanded waveforms) is more objective but is cumbersome. We devised a computer-based system to count crackles automatically. One hundred samples of lung sounds from 41 subjects were recorded using an electret microphone air-coupled to the chest wall. Inter observer agreement in estimating the number of crackles per breath was high ($r = 0.88$, $p < 0.001$), and these counts were significantly correlated with counts made of spike-like deflections seen on time-expanded waveform analysis ($r = 0.78$, $p < 0.001$). The automatic crackle counting correlated with the physician counts ($r = 0.74$, $p < 0.001$). The average number of crackles counted per breath was greater by visual inspection (8.8) and by automatic analysis (7.8) than it was by the physician observers (5.8). Reasons for the discrepancies include the fact that there are no absolute criteria for crackles and that rapidly occurring crackles are difficult to count by ear. Counting crackles by computer-based methods is feasible and can improve noninvasive cardiopulmonary diagnosis. *AM REV RESPIR DIS* 1989; 140:1017-1020

tween three and sixteen baseline crossings that met the following criteria: (1) the amplitude of the largest peak was greater than double the amplitude of the background sound, (2) the beginning of the event had a sharp deflection in either a negative or a positive direction, and (3) crossings of the baseline after the initial deflection were progressively wider (figure 1). A total of 782 such spikes were counted in the 100 lung sound samples from 41 patients. The development of the computer program used in this study was based on analysis of crackles from patients with a wide variety of clinical conditions; the program runs on a standard IBM compatible PC after analog-to-digital conversion of sound input. It counts crackles according to specific criteria relating to their amplitude, duration, frequency, and the amplitude of selected portions of the sonic signal. Two chest physicians experienced in lung auscultation listened independently and without discussion to tape playback of the sound samples in this study and estimated the number of crackles per breath; their counts were averaged. As these physicians had worked together for many years and may have had a hidden source of bias, three other observers also independently counted these crackles. Computer counts were then compared with visual waveform counts and auditory counts. Statistical analyses of the crackle count comparisons were made using Spearman's rank correlation (4).

Results

Automatic crackle counts correlated well with the auditory counts made by the physicians (figure 2). There was close

agreement between the physicians in arriving at the auditory counts used for this comparison (figure 3). The correlation between the mean counts made by these physicians and the three other observers were 0.72, 0.75, and 0.91. The automatic crackle counts correlated well with the visual counts made from the time-expanded waveforms (figure 4). The correlation between the physicians' counts and those made on time-expanded waveforms was 0.78 ($p < 0.001$).

The computer-based methods led to higher crackle counts than those made by the physicians. The average number of crackles per breath was 8.8 by visual inspection of the time-expanded wave form, 7.8 by the automatic analysis, 5.8 by Observer 1, and 5.9 by Observer 2.

Discussion

This study shows that clinically audible crackles can be counted by computer. Assessing the precision of the computer counts, however, is complicated by the fact that there are no absolute criteria for a "crackle." It is clear that when crackles are heard, time-expanded waveforms show intermittent spikes (3, 5, 6). On the

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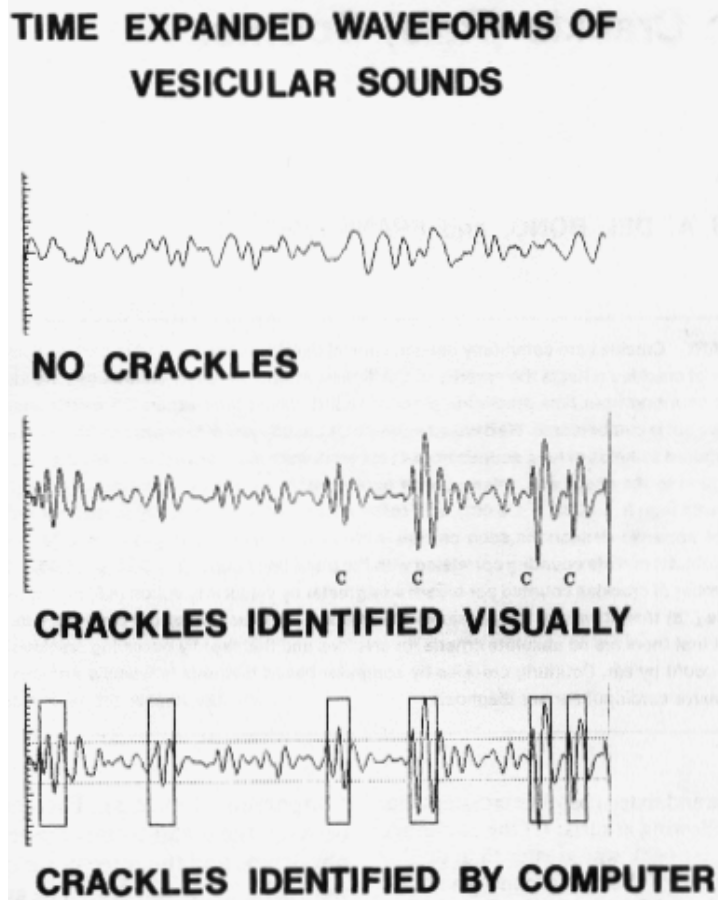


Fig. 1. This figure shows three 100-ms samples of vesicular lung sounds. The typical undulating pattern seen when no crackles are heard is illustrated in the upper tracing. Visually identified spike-like deflections associated with crackles are marked 'C' in the middle tracing. The lower tracing shows the same waveform; the computer drew boxes about the events that met preprogrammed specific criteria (see text).

other hand, it is not clear that all spikes seen on waveforms are associated with audible crackles. When many spikes appear in rapid succession or when the spikes are of low amplitude, some may not be appreciated by the human observer. This raises the question: Is a crackle what is audible, what is visualized on waveform, or what is counted by the computer? Identification of crackles, of course, started with audible perception and, accordingly, audible counts are a useful reference point. When differences in counts occur, however, it is difficult to be sure that the human is correct and the computer-based methods wrong or vice versa. Some artifacts have waveforms that are difficult to distinguish from crackles, and do, in fact, sound like crackles on tape playback. In most clinical situations this is not a problem as long as adequate attention is paid to the quality of the data acquisition. Inspection of waveforms of breath sounds while simultaneously listening to recordings of the same sounds shows that the majority of audible crackles are both visible on wave-

forms and counted by the computer. When crackles occur in rapid succession and the corresponding waveform shows that there are more than 10 perceived crackles in a single inspiration, they are too numerous to be counted easily, and "counts" under these conditions are really only approximations. For this reason we were surprised by the high correlation among our observers. This high correlation is, however, consistent with that seen in a number of other similar studies of crackles under carefully controlled conditions (7). Possible reasons that there are more waveform spikes than audible crackles include masking of low intensity sounds by previously occurring higher intensity sounds, sonic events below the human audible threshold, and mechanisms yet to be identified. It is likely that computer counts are more accurate than counts made by listening when the crackles occur in rapid sequence. As mentioned above, rapidly occurring crackles are difficult for humans to count. This is not a problem for the computer. Such events are readily visualized on waveforms ex-

cept when two crackles appear to be superimposed on each other, but in our experience this is uncommon. The computer counts have the added advantages of being reproducible and not subject to observer variability. Moreover, as mentioned above, crackle counting by humans is tedious.

Systematic clinical correlations between the total number of sites on the chest wall positive for crackles and the number of crackles per breath at a given site have been infrequently done. Nevertheless, there are several reasons why crackle counting is of value. We have demonstrated that auscultation of the chest by an experienced technician can be used to screen for industrial disease (8). In this study, crackle scores based on a technician's estimate of crackle number (i.e., both number per breath and number of sites positive) correlated with other criteria for asbestosis. The automatic system for crackle counting makes such screening more feasible as it can be done rapidly, accurately, and reproducibly. Objective documentation of the results can be provided, and the training time is considerably reduced. We have also documented clinical response to treatment in a variety of illnesses using crackle counts. In animal studies, the magnitude of sound transmission in the lung correlated well with increasing accumulation of intravascular and extravascular fluids and provided a quantitative index of pulmonary congestion (9). Although the relationship between sound transmission, crackle counts, and lung water has yet to be clarified, computerized quantification of sounds using methods similar to those in our study may help translate this experimental observation into a useful clinical method for detecting pulmonary edema non-invasively. Because one of the most accepted mechanisms for the production of crackles is that they are caused by "the sudden equalization of gas pressure between upstream and downstream segments of deflated territories of the lung," assessment of crackles may provide a method for evaluating the degree of atelectasis (10). Preliminary work suggests that the degree of atelectasis is related to the timing of the crackles; the earlier in inspiration the crackles occur, the more severe the atelectasis (11). For similar reasons, crackle quantification may aid in the study of small airways closure. Because crackles can occur in normal persons, and disease can be present in the absence of crackles, clinical studies will

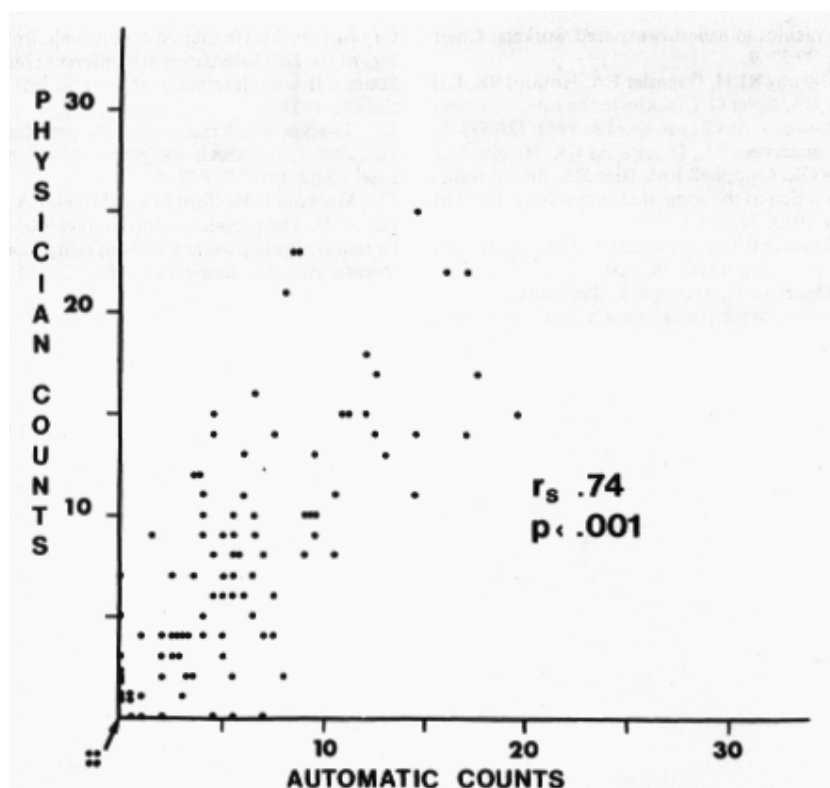


Fig. 2. In this figure, counts made automatically by the computer-based system are compared with those made by two experienced physicians; for a discussion of the discrepancies, see text.

be needed to demonstrate the value of objective crackle measurements and monitoring in noninvasive pulmonary diagnosis such as in the intensive care setting (12, 13).

Clinicians routinely listen for crackles and use their presence (or absence) to make important decisions such as ordering tests, administering medication and fluid, and following the course of a variety of illnesses. It is now feasible to quantify and document this common clinical finding.

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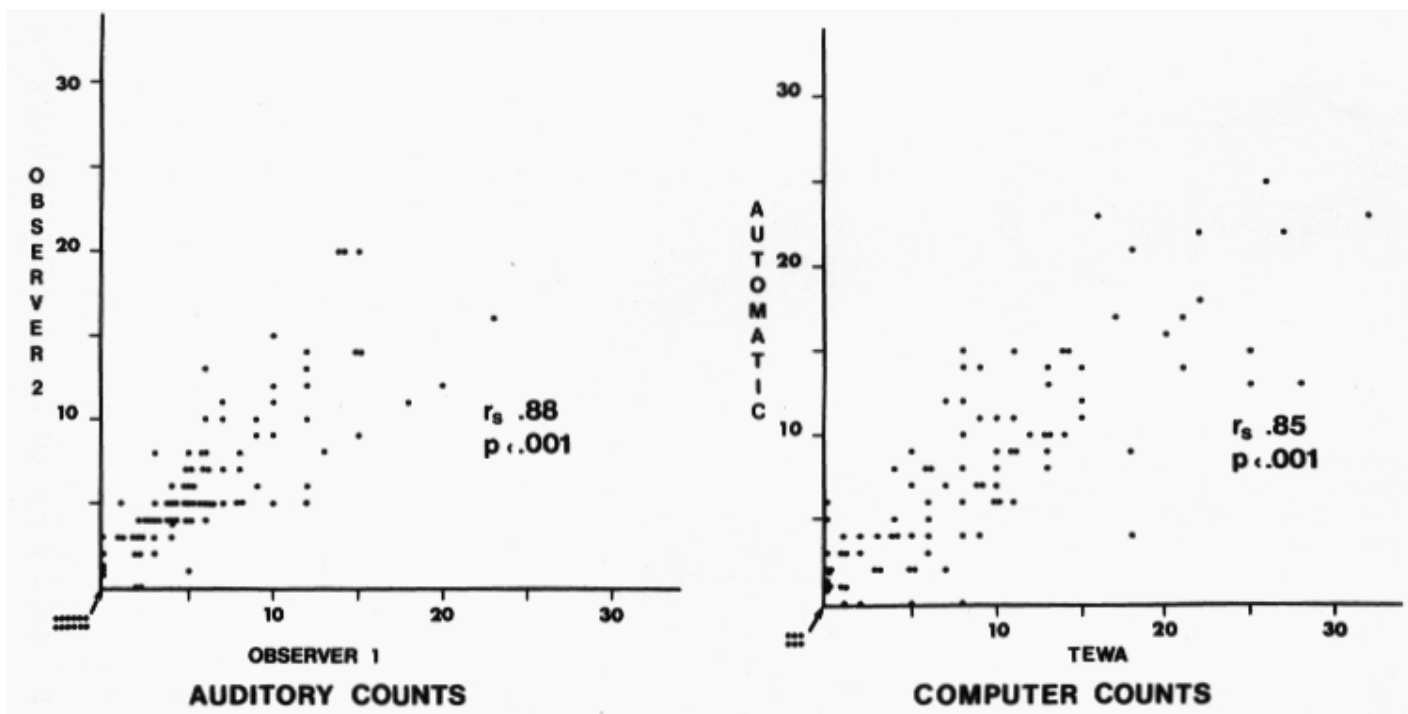


Fig. 3 (left). This figure shows the comparison of the results of crackle counts made by two physicians. A third independent observer agreed closely with the counts ($r = 0.90$ with Observer 1; $r = 0.89$ with Observer 2).

Fig. 4 (right). Crackle counts made by the computer-based system (automatic counts) are compared with those made by visual inspection of the time-expanded waveform (TEWA).

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