Long-term Recording and Automatic Analysis of Cough Using Filtered Acoustic Signals and Movements on Static Charge Sensitive Bed*

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Reliable long-term assessment of cough is necessary in many clinical and scientific settings. A new method for long-term recording and automatic analysis of cough is presented. The method is based on simultaneous recording of two independent signals: high-pass filtered cough sounds and cough-induced fast movements of the body. The acoustic signals are recorded with a dynamic microphone in the acoustic focus of a glass fiber paraboloid mirror. Body movements are recorded with a static charge-sensitive bed located under an ordinary plastic foam mattress. The patient can be studied lying or sitting with no transducers or electrodes attached. A microcomputer is used for sampling of signals, detection of cough, statistical analyses, and on-line printing of results. The method was validated in seven adult patients with a total of 809 spontaneous cough events, using clinical observation as a reference. The sensitivity of the method to detect cough was 99.0 percent, and the positive predictivity was 98.1 percent. The system ignored speaking and snoring. The method provides a convenient means of reliable long-term follow-up of cough in clinical work and research. (Chest 1988; 94:970-75)

SCSB = static charge sensitive bed

Quantitative long-term recording of chronic cough is necessary for objective evaluation of the efficacy of different treatments for cough. Thus, over the years, a variety of methods has been developed for assessing the frequency and intensity of cough.

The simplest methods, patient diaries1 or an observer counting the cough events, are still used in clinical drug studies.2 On the other hand, recording of unfiltered cough sounds with a free-field microphone and a cassette recorder was already described by Reece et al3 in the 1960s. In their study the cough frequency was counted off-line by a listener, while Thomas et al4 employed telemetrically recorded acoustic signals and a detector of transient sounds. Rühle et al5 and Matthys et al6 used a pressure transducer attached to the trachea and connected to a single-channel recorder, evaluating the cough frequency and intensity afterward from the analog recordings. Power et al7 developed a system consisting of a directing microphone and auto-editing tape recording. Abdominal EMG recording with surface electrodes8 and the detection of the movement of the thyroid cartilage with a strain gauge9 have also been adapted for efficacy studies of antitussive drugs.

None of these methods has been based on automatic on-line signal processing, which is requisite for convenient long-term recordings in patients. Moreover, methods based on cough sound recording have not been thoroughly validated; their specificity and sensitivity have not been documented.

In view of the large consumption of drugs to relieve cough, studies on the antitussive effects of the drugs are relatively scarce, and few of them are adequately controlled. This may reflect a lack of convenient validated methods. Furthermore, the pathophysiology of chronic cough, either in the waking state or during sleep, is poorly understood. For these reasons we have developed an automatic method for long-term recording and analysis of cough. It is based on simultaneous recording of two independent signals: high-pass filtered cough sounds and cough-induced fast movements of the body.

Material and Methods

The study was performed on seven women with disturbing cough whose ages ranged from 39 to 65 years (mean 53.4 years), height from 152 to 167 cm (mean 162 cm), and weight from 55 to 86 kg (mean 69 kg). Four patients had chronic bronchitis; in two of them the bronchoscopic examination revealed an abnormal tendency to develop tracheobronchial collapse. One patient had acute bronchitis, one fibrosis due to radiation treatment of breast cancer, and one asthma. The ventilatory function of the patients was studied with a flow-volume spirometer (CPI 220). Their FEV1, ranging from 2.20 to 3.62 L BTPS (from 81 to 107 percent of the predicted value10) and their FVC from 2.75 to 3.99 L BTPS (from 81 to 103 percent of the predicted value10). One patient had slight airways obstruction. None of the patients had any other significant disease. During the recordings, antitussive treatment was withdrawn.

The system for recording and analyzing cough consists of two independent pathways: one for detecting and processing cough

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sounds and another for associated body movements. A flow chart of the system is shown in Figure 1. During the recording the patient was lying or sitting on an ordinary bed in an ordinary single hospital room. The patient was instructed not to cough or breathe toward the pillow; but otherwise posture on the bed was not restricted. Ordinary movements and speaking in a low voice were allowed.

**Signal Recording**

The acoustic signals were recorded with a dynamic directing microphone (Beyer Dynamic 23 M 69) with a sensitivity of 2.3 mV/Pa and a frequency range of 50 to 16,000 Hz. The microphone was mounted in the focus of a paraboloid acoustic glass-fiber mirror with a diameter of 60 cm. The distance between the focus and the surface of the mirror was 24 cm. The mirror was located at the foot end of the bed 40 cm above the level of the mattress and directed toward the face of the patient. Signals from the microphone were amplified and high-pass filtered (−3 dB level at 3.6 kHz, −20 dB level at 1.7 kHz) for the elimination of low-frequency noise. The acoustic signal was preprocessed with an analog rectifying integrator (time constant 0.2 s) to enable the discrimination of single cough events.

Body movements were recorded with a sensitive kinesthetic transducer, a static charge-sensitive bed (Biorec, Biorec Inc), connected to an amplifier and a filter unit (Biorec Inc). High-pass filtering (≥3 Hz) was used to record only fast body movements, typical for cough, and to suppress ordinary slow respiratory movements. The SCSB mattress was placed under an ordinary 7-cm thick plastic foam mattress. An example of recorded analog signals is presented in Figure 2.

The signals were recorded with a four-channel FM recorder (Teac HR-10 J) and simultaneously fed after analog-to-digital conversion (12 bit resolution, Tecmar Labmaster) to a portable microcomputer (IBM PC) for automatic on-line analysis.

**Computer Analysis**

The sampling rate of the high-pass filtered and integrated acoustic signals and the body movement signals was 30 Hz. The digitized signals were rectified and integrated in epochs. The duration of an epoch and the time resolution of the analysis was 0.3 s for the acoustic and 1.2 s for the body movement signal. The program first calculated the mean noise levels of the signals. For acoustic signals the detection level was four times and for body movement signals three times the mean noise level. The program accepted an event as cough if the spikes in both acoustic and body movement signals simultaneously exceeded the detection threshold. The duration of a single cough was measured at the detection level, the time resolution being 0.3 s. The algorithm used in the analysis of transients has been found to be useful in studies of sleep and sleep-related apneas. Figure 2 shows computer graphs of sound and movement signals.

The following statistics were calculated and printed: the number of cough events at desired intervals; the total duration of accepted acoustic cough signals; classification of the detected cough signals.

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**Figure 2 (A)** Recorded and preprocessed analog sound and movement signals (25 s) and **(B)** the computer output graphs (60 min) in asthmatic patient with severe cough.
according to the duration: shorter than 1 s, 1.0 to 1.9 s, 2.0 to 2.9 s, and 3.0 s or longer; the number of one-minute epochs containing at least one cough, and the total number of one-minute epochs in bed without any cough events. The duration of a single cough was indicated by the height of the vertical bar on the graph. Further, the software compiled a frequency histogram of cough events over the whole recording period and graphs of the integrated sound and movement signals in addition to the accepted cough events (Figs 3 to 5).

The duration of an uninterrupted recording and analysis varied from one to ten h; it is limited only by the memory capacity of the computer. The printed report with graphs was automatically given by the computer at the end of each recording.

Validation Procedure

For the validation of the method a trained observer (laboratory assistant) was present in the recording room outside the acoustic field of the system. The observer did not see the graphs on the computer screen during the recording. Every time she observed a cough, she pushed a button to give a 1-V rectangular pulse, which was fed to the computer and to the tape recorder. The sequence of the pulses was processed in the same way as the acoustic signals: rectified and integrated with the time resolution of 0.3 s. For validation, four graphs were printed using a time base of 210 mm/15 min of recording: (1) acoustic signal, (2) movement signal, (3) observer's push button signal, and (4) cough events accepted by the computer (Fig 4).

The data for the validation consisted of 809 automatically accepted cough events recorded in seven patients. The total recording time was 12 h. False positive and false negative events were counted manually from the graphs by comparing the timing of the push button and accepted cough event signals. The same comparison was made between the acoustic spikes exceeding the detection level and the push button signals to evaluate the additional benefit of the use of the movement signal.

The Effect of Body Position, Speaking, and Snoring

In one patient with chronic bronchitis the recording was carried out by varying her position systematically. The patient was asked to lie supine, on the left as well as the right side, and to sit on the bed. She was also asked to talk and to move on the bed. Further, one recording was made with a patient who snored heavily.

Statistical Methods

The sensitivity and the positive predictivity of the present method were calculated by using the formulas:

\[
\text{sensitivity} (\%) = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}} \times 100
\]

FIGURE 4. Computer graph (15 min) used in the validation of the method showing acoustic spikes (channel I), body movement spikes (III), push button impulses (III) by the human observer, and automatically accepted coughs (IV) classified according to the duration. One false positive event was included (arrow).

FIGURE 3. Computer graphic output (140 min) of simultaneous integrated sound and body movement signals and automatically accepted cough events in patient with chronic cough due to chronic bronchitis. Effect of codeine is demonstrated. DL1 and DL2, detection levels.
positive predictivity (%) = \frac{\text{true positives}}{\text{true positives} + \text{false positives}} \times 100

Positive predictivity describes the specificity of the algorithm.

RESULTS

Detailed data from the validation study are given in Table 1. The automatic cough counting based on the combination of sound and movement signals produced a total of 809 cough events, of which 794 were true positives. The system missed eight cough events (false negatives) and detected erroneously 15 false positive events. Thus, the method had a sensitivity of 99.0 percent and a positive predictivity of 98.1 percent.

When the body movement signals were omitted and the analysis was based on the acoustic signals only, the total number of automatically detected cough events was 876, with 82 false positive events (Table 1). This simplified method yielded the sensitivity (99.0 percent), but the positive predictivity was lower, 90.6 percent.

Speaking while lying or sitting on the bed did not induce false positive events, provided no transient body movements occurred, as shown in Figure 6. Snoring was also ignored by the method, as seen in the same figure.

DISCUSSION

The high sensitivity (99.0 percent) and positive predictivity (98.1 percent) of the present method are due to adequate selection and processing of the two signals associated with cough events, sound and movement. It has been shown recently that cough sounds are transients containing frequency components from 80 Hz to at least 4,000 Hz. Thus, by using a relatively high frequency level for high-pass filtering, it was possible to cut off low-frequency noise, odd sounds, speech, and snoring. Further, the acoustic field of the system was concentrated and delimited by the parabolic mirror (as used in ornithology) collecting sounds only from the site of the patient on the bed. As the time constant used for the integration of rectified acoustic signals was short (0.2 s), possible

Table 1—Individual Results of the Validation Study

<table>
<thead>
<tr>
<th>Patient Age, yr/sex</th>
<th>Diagnosis</th>
<th>Duration of Recording, min</th>
<th>Duration of Coughs, s</th>
<th>No. of Cough Events*</th>
<th>False Positives</th>
<th>False Negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acute bronchitis</td>
<td>100</td>
<td>38</td>
<td>106</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Chronic bronchitis</td>
<td>120</td>
<td>90</td>
<td>183</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Chronic bronchitis</td>
<td>120</td>
<td>62</td>
<td>89</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Chronic bronchitis</td>
<td>120</td>
<td>62</td>
<td>89</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
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<td>39</td>
<td>45</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Chronic bronchitis</td>
<td>120</td>
<td>95</td>
<td>181</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Chronic bronchitis</td>
<td>120</td>
<td>98</td>
<td>108</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Asthma</td>
<td>120</td>
<td>79</td>
<td>97</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>720</td>
<td>501</td>
<td>809</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

*Calculated by the automatic method.
high-frequency tonal sounds could not cause any long-lasting disturbing effect on the recording. On the other hand, the time constant was short enough to allow the discrimination of a single cough event. The automatic analysis of the acoustic spikes alone also showed a high specificity (positive predictivity 91 percent) and very high sensitivity (99 percent). The additional utilization of fast body movements in conjunction with transient high-pitched sounds decreased the number of false positive events, i.e., sounds unaccompanied by movement.

With the present method it is not possible to discriminate transient sounds with high-frequency components combined with fast body movements, e.g., sneezing and hiccup from cough. The problem is, however, of minor importance.

The SCSB mattress used in this study is a sensitive device to detect body movements. The baseline noise of the body movement signal is mostly caused by the heartbeats (ballistocardiogram). Fast and slow body movements of patients with sleep-related disorders (e.g., apneas and periodic myoclonus of feet) have been recorded with the SCSB.

The patients included in the validation study had different types of cough, producing variable patterns of sound frequency and transients. As there were no clear interpatient differences in the number of false positive or negative counts, the type of cough produced by a patient does not seem to have an essential influence on the sensitivity and specificity of the method.

The recording of cough-induced signals with a microphone in a free field and a SCSB mattress is a totally noninvasive method; no electrodes or transducers are attached to the patient. In this respect the present method differs from those based on recording of transient sounds with a microphone attached to the patient, tracheal pressure, EMG transients, or movement of the thyroid cartilage. Moreover, in some of these methods movements of the head or speaking cause artifacts, which must be characterized before the analysis. By our method the patient is free to move on the bed and to speak; thus, recording can take place without the patient's being aware of it. The only restrictions are that the patient stays on the bed and does not make any noises with high-frequency transients simultaneously with fast body movement. Acoustic shielding of the patient room is not required.

There are no previous reports on automatic long-term analysis of cough, to our knowledge. The present method of automatic detection of two simultaneous cough-induced signals is convenient and gives more reliable data than do methods in which subjective counting of coughs is performed. Errors caused by subjective bias or fatigue are absent, and the recording and analysis of cough can be continued for long periods, e.g., for a whole day or night. After the session, the essential statistics and graphs are immediately available.

The results suggest that the present method for long-term recording and automatic analysis of cough has several advantages over earlier methods, including high sensitivity and specificity. The method seems well suited for quantitative assessment of cough both in clinical work and for research.

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REFERENCES

6 Matthys H, Bleicher B, Bleicher U. Dextromethorphan and

Figure 6. Recorded and preprocessed analog sound and movement signals (A) and computer outputs (B) during speaking (I) and sneezing (II) in a patient with chronic bronchitis. No false positive events detected. Owing to high-pass filtering, sound signals during low voice speaking (IA) and sneezing (IIA) are of low amplitude. Sound and movement signals during loud speaking (IB) do not exceed detection levels (DL1 and DL2).

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