



How to count coughs? Counting by ear, the effect of visual data and the evaluation of an automated cough monitor



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KEYWORDS

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Summary

Background: Cough causes morbidity and transmits disease yet has been under-researched. The best method for recognising and counting coughs remains unclear. We tested the accuracy of the human ear and measured the influence of visual data on cough counting. We also evaluated PulmoTrack[®], a potentially fully-automated cough monitor.

Methods: Consistency amongst listeners and the effect of visual data: Three 14–22-min sequences containing 45–79 coughs were played to 15 respiratory physicians on at least two occasions. Only sound was played on the first occasions but on the final occasion a simultaneous display of audio activity was included. Counts of cough sounds across methods and listeners were compared. Evaluation of PulmoTrack[®]: 20-h recordings were made from 10 patients with cough. Automated counts were compared with assessment by one investigator.

Results: Agreement among listeners was high. The intraclass correlation coefficient (ICC) for cough counts by ear alone was 0.89 (95% CI, 0.65–1.00). With a concurrent visual display of sound amplitude it was 0.94 (0.80–1.00). 4.8% (0.6–9.5) fewer coughs were counted using visual data than by listening alone (mean [SD] total coughs: 190.2 [3.4] vs 200.7 [14.6]; $p = 0.04$). Cough frequencies reported by PulmoTrack[®] and the researcher differed substantially (ICC 0.23, –0.51 to 0.34, $p = 0.87$); PulmoTrack[®] had a sensitivity of 26% for detecting coughs identified by ear.

Conclusion: Coughs are well recognised by different listeners. The method used to count coughs should be clearly described as visual information has a significant influence. Non-automated cough counting remains the gold standard method of quantifying cough.

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Introduction

Cough is one of the main symptoms of respiratory disease. Although a defensive mechanism for protecting the airways [1], cough is increased in a range of medical conditions and is a common cause of morbidity [2]. Cough is also important in the transmission of infectious diseases such as measles and tuberculosis [3,4].

The objective measurement of cough is complex but essential if we are to improve our understanding of cough. Fully-automated cough monitors are being developed [5], but counting coughs by ear remains the reference standard [6] against which automated systems should be compared. Individual cough sounds are the basic units of cough [7] but vary among patients and diseases [8]. Although it is assumed the human ear can distinguish coughs from other sounds [9] this has not been adequately tested. Experienced individuals in research groups show good agreement in cough counting within pairs [10–12] but a broader consistency among larger numbers of people naïve to counting coughs has not been examined. Audio editing software can be used to help identify and count coughs by visually representing sound activity at the same time as audio playback [13–16]. The effect of simultaneous visual feedback on cough measurements has not previously been reported.

Automated cough monitors would save time and might offer less variability than human counting yet few automated or semi-automated systems have been tested for clinical use [10,17,18]. PulmoTrack® (iSonea (formerly KarmelSonix), Haifa, Israel) is a fully-automated ambulatory device for measuring respiratory sounds [19]. For cough counting, its use has only been described in a small number of healthy volunteers over short recording times [20].

The aim of the current study was threefold: to investigate observer consistency in counting coughs, to measure the effect of visually representing audio data and to compare human cough counting with the PulmoTrack® cough monitor.

Methods

Patients

Patients with the symptom of cough were recruited as hospital inpatients and from a respiratory clinic after giving written consent. The study was approved by the London Riverside Research Ethics Committee (reference: 12/LO/1923).

Automated cough monitor

Cough monitoring with PulmoTrack® took place in hospital over 16–24 h. Clinic patients were admitted specifically for this purpose. The PulmoTrack® software (Version 6.5.0) uses an algorithm unknown to us to calculate cough counts expressed as *cough events* and *component coughs* per minute. These terms are not clearly defined in the product literature but we presume them to equate to bouts of coughing and individual cough sounds respectively. The system allows playback for non-automated cough counting.

Recordings were analysed by the software twice to test repeatability.

Listeners

One of us (RT) counted cough sounds in a 4-h section from each of the recordings where PulmoTrack® indicated the greatest number of coughs. 15 respiratory physicians counted cough sounds in 3 sequences lasting from 14 to 22 min on 3 occasions in the same order at intervals of ≥ 4 weeks. The sequences were selected by the investigator for the high density of coughs and differing underlying pathologies. Listeners were asked about known hearing problems and, in order to estimate experience of listening to closely spaced sounds, frequency of playing a musical instrument and confidence in detecting fixed splitting of the second heart sound on auscultation of the praecordium (minimum duration 0.02 s [21]). No specific training of how to count coughs was given; listeners were instructed only to count cough sounds whether occurring in isolation or as part of a bout of prolonged coughing. Playback could be paused and repeated as desired. Participants were unaware of the cough counts of other auditors and the interpretation of the machine.

Visual data were not shown on the first two occasions, but on the final occasion a simultaneous visual representation of sound amplitude was provided using Audacity® open source audio editing software (version 2.0.2; see Fig. 1 and online supplementary audio file) [22]. The study protocol is summarised in Fig. 2.

Supplementary audio related to this article can be found at <http://dx.doi.org/10.1016/j.rmed.2014.10.003>.

Data analysis

Statistical analyses were performed using Stata (version 13.0) and PASW Statistics 18. Two-group comparisons were made with Student's *t*-tests for continuous variables and Fisher's exact test for categorical variables. Tests were two-sided unless stated otherwise. Intraclass correlation coefficients were used to describe agreement between observers and to evaluate PulmoTrack®. Mixed effects regression models and a likelihood ratio test were used to explore the variation associated with each non-automated counting method (using sound alone or sound with visual data). The two methods were also compared with a Bland–Altman plot. We aimed to enlist 15 observers. From initial data this number would give 80% power at a significance level of 0.05 to detect a difference in total cough counts of 7% when comparing listening alone to listening with the addition of visual data, or 50% power to detect a difference of 5%.

Results

We recruited 13 patients with sarcoidosis ($n = 1$), exacerbations of asthma ($n = 2$) and chronic obstructive pulmonary disease (COPD; $n = 2$), stable COPD ($n = 1$), tuberculosis ($n = 2$), non-tuberculous mycobacterial infection ($n = 1$), idiopathic pulmonary fibrosis (IPF;

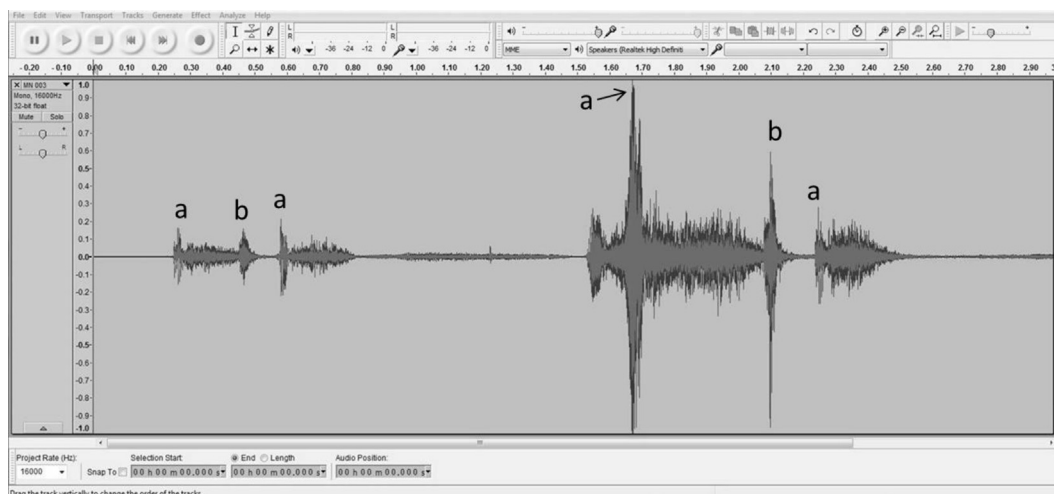


Figure 1 Audacity® audio editing software representing four cough sounds from patient with unexplained chronic cough. Initial explosive phases (a) and final, voiced, phases (b) of each cough sound indicated where present [23]. See also online supplementary audio file. [Reproduced with permission. Audacity® software is copyright (c) 1999–2014 Audacity Team. The name Audacity® is a registered trademark of Dominic Mazzoni.]

$n = 1$), community acquired pneumonia ($n = 1$) and chronic cough of uncertain cause ($n = 2$). All had a cough noted as part of their medical history.

sensors ($n = 3$). One patient with chronic cough agreed to undergo repeat monitoring. The median duration of the 10 successful recordings was 19.6 h (range 9.3–24.5 h).

Cough monitoring

PulmoTrack WHolter™ setup took an average of 9 min. Recordings were inadequate on four occasions owing to battery failure ($n = 1$) and disconnection of recording

Intra- and inter-listener consistency

Cough counts of the three sequences using only auditory information are as shown (Fig. 3). The selected sequences were from patients with COPD, sarcoidosis and asthma and

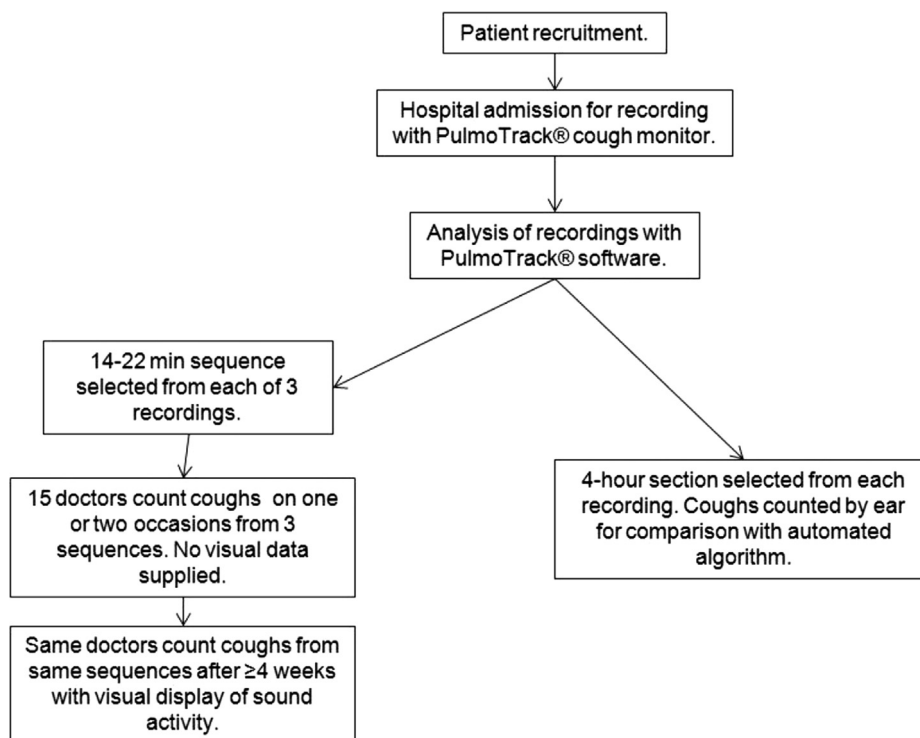


Figure 2 Study overview. See text for further explanation.

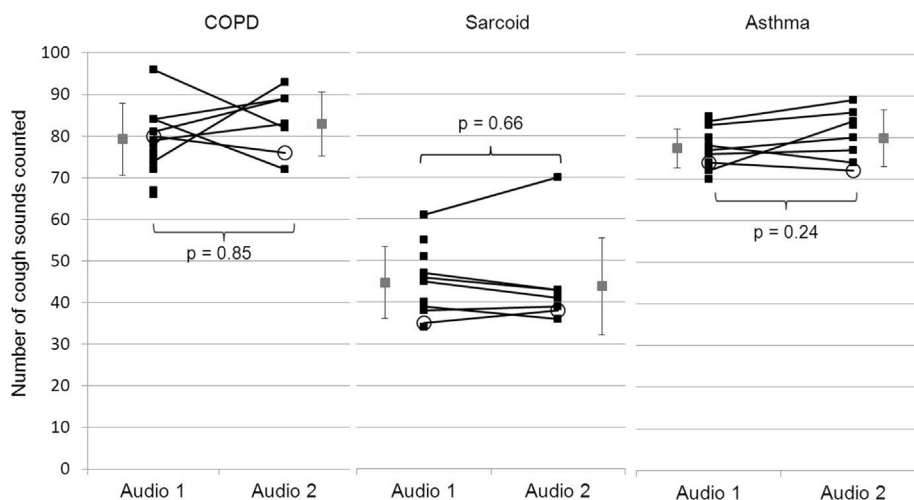


Figure 3 Intra- and inter-observer variation in cough counting with auditory information alone. Sequences from 3 patients were played to 15 doctors, to 7 of them on two occasions. O = counts by investigator RT. Error bars: means and SD. *p*-values are for paired 2-tailed *t*-tests for differences between listening attempts.

lasted exactly 19, 14 and 22 min respectively. On the first attempt mean (SD) cough counts were 78.7 (8.1), 44.6 (7.5) and 77.3 (4.7) respectively (total count for all sequences: 200.7 [14.6]).

7 of the 15 doctors listened to the sequences on a second occasion without visual data. Intraclass correlation coefficients (ICCs) between individuals were 0.89 (95% confidence interval [CI], 0.65–1.00) on the first attempt and 0.86 (0.53–1.00) on the second. Within-individual ICCs were in the range of 0.96–0.99 between 1st and 2nd attempts with a mean of 0.7% more coughs counted on the second attempt (95% CI, –4.7 to 6.1).

Sequences were analysed as 1 min segments. Those segments in which coughs were counted by any observer were compared as two equal-sized groups: periods with lower variation in counts against those with higher variation (SD of mean < 1.15 or > 1.15). The only factor strongly associated with higher variation was a higher count of cough sounds (mean 7.3/minute in high variation periods, 3.2/min in low variation periods, *p* = 0.03). 8 and 5 segments contained speech in the higher and lower variation groups respectively (*p* = 0.12). Sounds which we considered to represent throat clearing did not affect count variation although they were only present in 8 segments. There were even fewer background noises to test their influence on cough counting.

All doctors stated having normal hearing. Gender, doctor seniority, musical ability and ability to detect fixed splitting of the second heart sound did not affect the total numbers of coughs counted (online [supplementary table 1](#)).

Audio vs. audio-visual counting

13 of the 15 original listeners reanalysed the sequences with simultaneous visual data. Mean counts of cough sounds were lower than the corresponding average values from the two attempts without visual information, significantly so for the sarcoidosis and asthma sequences (Fig. 4; mean [SD] total cough count 190.2 [3.4]). A mean of 3.1

(4.8%) [95% CI: 0.3–9.2, (0.6–9.5%)] fewer coughs were counted in each sequence with the visual display than when listening without it (*p* = 0.04). For all but two of the counts the differences between methods were within two standard deviations of the mean (Fig. 5).

The agreement between the 13 doctors counting by ear and eye together was excellent (ICC = 0.94, 95% CI 0.80–1.00). The apparent decrease in inter-observer variation between methods, as assessed by the regression analysis and likelihood ratio test, was not statistically significant (*p* = 0.80).

The majority of participants stated that cough counting was quicker with the addition of the visual display.

Automated cough counting

PulmoTrack[®] took approximately 7 h to process a 24 h recording. Automatically detected numbers and timings of coughs were identical the second time all sequences were analysed. A comparison of the number of sounds counted as coughs by the machine and the human observer in the 4-h recording segments is shown in Fig. 6. Almost 2000 coughs were counted by the researcher. Even ignoring agreement over individual sounds, overall crude counts of cough sounds between auditory and automated methods substantially differed (ICC = –0.23, 95% CI, –0.51 to 0.34, *p* = 0.87). On non-automated counting mean cough rates in these sequences ranged from 19 to 119 cough sounds/h. A median of 100 (range –29 to 465) fewer cough sounds were counted by PulmoTrack[®] than by the non-automated method in each 4-h sequence.

A total of 39% of the cough sounds across sequences counted by PulmoTrack[®] were identified as such only by the machine (Fig. 6). We recognised these most commonly as speech, swallowing, microphone interference, breath sounds and background noise (online [supplementary table 2](#)). With non-automated cough counting as the reference standard the overall positive predictive value of PulmoTrack[®] was 60% and sensitivity 32%.

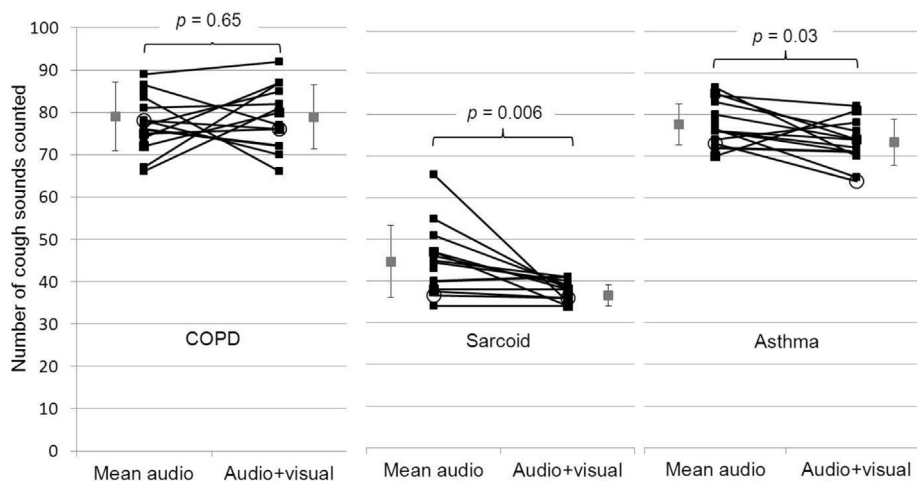


Figure 4 Comparison of auditory with visual and auditory cough counting. Sequences from three patients played to 15 doctors on two or three occasions. Mean cough counts from attempts using only auditory information compared to counts when visualising a display of sound amplitude simultaneous to audio playback. O = counts by investigator RT. *p*-values from paired sample *t*-tests between means.

Discussion

This study has shown that untrained listeners are consistent in counting cough sounds, that simultaneously visualising audio sequences led to lower counts and that the automated cough monitor we used disagreed with human cough counting.

To our knowledge this is the first work to test consistency in cough counting among more than two individuals. The overall relative standard deviation in our study of 7.3% (14.6/200.7) when listening alone and 6.4% (12.1/190.2) with both visual and auditory representation is of the same order of magnitude as studies comparing two listeners. Key

et al. noted a 9.5% difference in cough counts between two individuals experienced in cough counting when coughs from 30 min sequences in 19 patients with IPF occurred at 9.4/h [12]. The same group also report a difference between two people of about 2.6% when analysing 24 h recordings from 10 patients with chronic cough due to a variety of conditions [11]. The intraclass correlation coefficient for 11 listeners of 0.94 concurs well with the 0.98 reported for studies comparing just two listeners [10].

Intra-observer consistency was high (ICC 0.96–0.99). Birring et al. report an ICC of 0.99 when one cough researcher counted cough sounds in 2-h recordings from 9

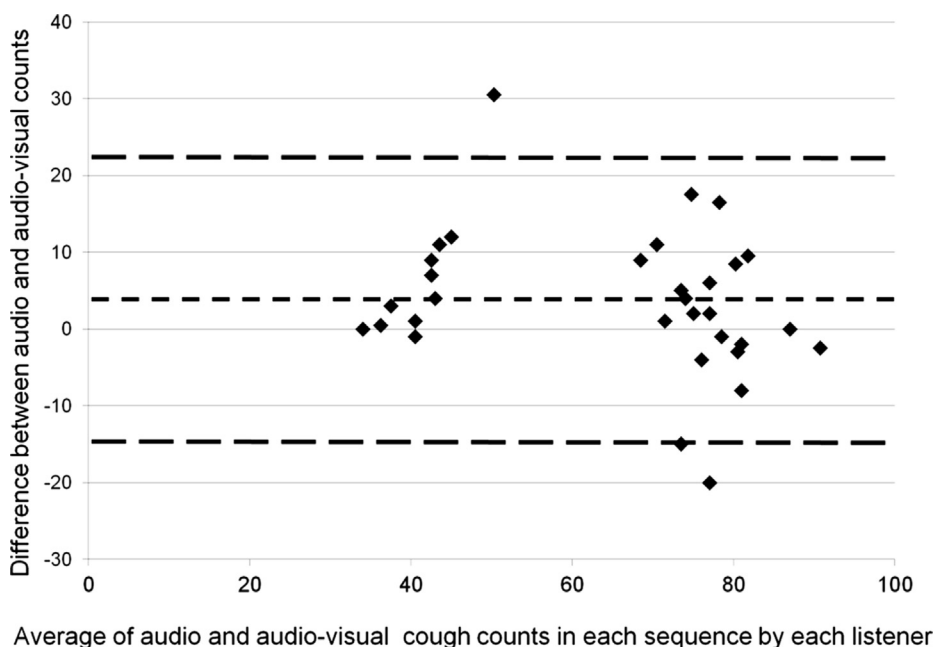


Figure 5 Bland–Altman plot comparing methods of non-automated cough counting. Mean count from listening alone minus count with additional visual data plotted against the average cough count from between methods for each listener for each sequence. Dotted lines: mean difference (3.1) ± 2SD (–15.3 to 21.5).

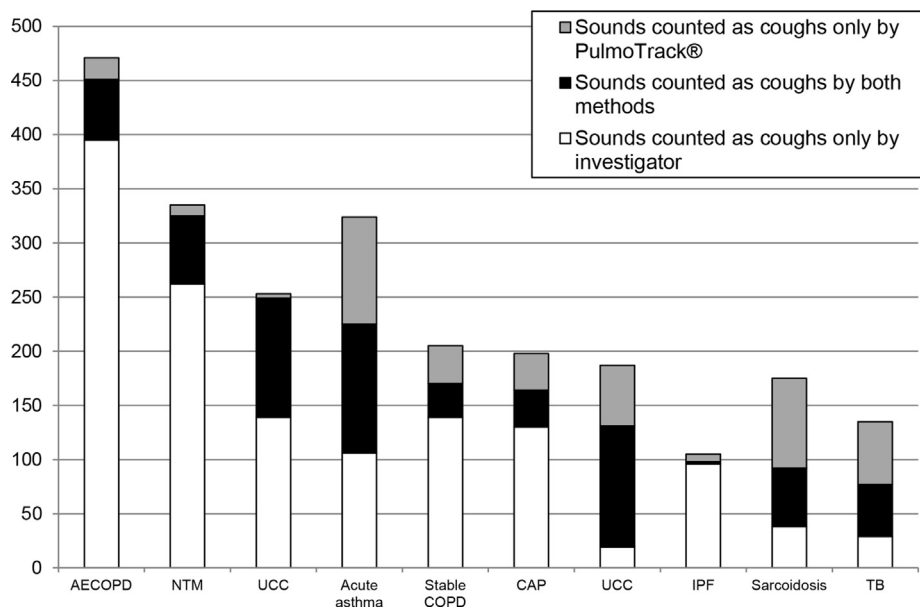


Figure 6 Comparison of PulmoTrack® and non-automated cough counting. Number of sounds counted as coughs by PulmoTrack® and a human observer in 4-h sequences from 10 patients. Data presented in descending order of numbers of coughs counted by the investigator. AECOPD – acute exacerbation of COPD; NTM – non-tuberculous pulmonary mycobacterial infection; UCC – unexplained chronic cough; COPD – chronic obstructive pulmonary disease; CAP – community-acquired pneumonia; IPF – idiopathic pulmonary fibrosis; TB – pulmonary tuberculosis.

patients twice but the time interval between counting attempts is not stated [10].

We found no listener factors which affected cough counting. Disagreement was associated with higher cough frequencies and possibly the presence of speech but not the rarer presence of throat clearing or background noise. Further comment on causes of inter-observer variation is limited as it was so low. The fact that untrained listeners demonstrated good agreement, and that there was no evidence for an effect of doctor seniority, suggests that experience and specific training in counting coughs might not be required. Not including listeners with experience of cough counting here allowed us to test more easily the previously untested assumption that the ‘characteristic sound’ [7,9] of cough is universally distinguishable from other noises.

Audio editing software simplifies cough counting by eliminating the need to listen to periods of silence which are evident from visual inspection. Fewer coughs were counted with a visual display of sound amplitude simultaneous to audio playback. The appearance of the sound amplitude trace presumably leads to dismissal of certain sounds which would have been counted by listening alone. This is suggested most clearly by the difference in cough counts between methods in the sequence from the patient with sarcoidosis (Fig. 4). The finding that recognition of coughs depends partly on the appearance of the amplitude waveform has implications for the definition of a cough, about which there has been debate [24,25].

It is not clear why there was only a significant difference in cough counts between methods of non-automated counting for two of the sequences (from the patients with asthma and sarcoidosis); there may be certain types of cough that are more consistently recognised by listening alone. The cause of the two outlying results in the

comparison between methods (Fig. 5) is uncertain. Distraction leading to missing coughs, double-counting or errors in transcribing results to the data sheet are possibilities. There was no other evidence that attention span or fatigue were significant problems but these factors may become important with longer recordings.

Although the addition of visual data to audio sequences appeared to improve inter-observer agreement in cough counts we did not show this to be a statistically significant. A type 2 error is possible as the study was not powered to detect relatively small differences in variation between counting methods.

Our data are limited by the inclusion of only three short sequences for testing consistency between observers in cough counting. We have therefore not examined the role of auditory fatigue or inattention in longer recordings. However, the sequences were selected for their very high number of coughs, aiming to amplify any differences between counting methods or observers that might only have become evident by using longer sequences with lower cough frequencies. We deliberately used short sequences to make involvement in the study more acceptable to the volunteering listeners.

We cannot comment on the recognition of coughs by non-clinicians, although the absence of an effect of doctor seniority suggests that clinical experience is not important for distinguishing coughs from other respiratory sounds and counting them. Neither do we have enough data to describe the effects of types of cough as possibly influenced by pathology, gender, age and anatomy, or the effects of background recording conditions. Nevertheless, this study has examined consistency in cough counting between and within observers more thoroughly than any other of which we are aware.

PulmoTrack[®] provided useful ambulatory recording and playback of patient data and showed perfect consistency on repeated analysis of the same sequences. However, there were technical problems and agreement between PulmoTrack[®] and non-automated cough counting was unsatisfactory. Neither the nature of respiratory pathology nor the rate of coughing appeared to affect agreement. One study to evaluate PulmoTrack[®] showed high agreement with non-automated cough counting, but recruited 12 healthy volunteers who were asked to make voluntary coughs and other noises during 25-min recordings [20]. Our evaluation was more representative of the circumstances in which such a system might be normally employed.

All of our recordings were made on hospital inpatients due to our limited access to the cough monitoring equipment. A more rigorous assessment of PulmoTrack[®] would also include recordings in the ambulatory setting to test the effect of background noise and the acceptability of wearing the device during routine activities. We only counted cough in 4-h sections of recordings from ten patients but the very poor agreement between the non-automated counts and those of the machine strongly suggests that a more extensive assessment is unlikely to have altered our conclusions. No other work of which we are aware has contradicted this.

The development of a completely automated system for counting coughs has been slow [5]. The brain appears to identify a cough from both a complex distribution and pattern of sounds with ease (Fig. 1), suggesting there may be an evolutionary advantage to the recognition of cough. The currently best tested automated or semi-automated cough monitors require human input either to help calibrate the system [10,26] or to actively count coughs in sequences that have been condensed to remove silences and non-cough sounds [17,27]. High cough rates, speech, background noise and the ability to perform across a range of types of patient and cough are particular challenges for automated cough monitors.

Conclusion

Cough counting is consistent among and within doctors without specific training. Audio-editing software simplifies the process and leads to lower counts, which may be more accurate than counting by ear alone. The fully automated PulmoTrack[®] cough monitor agreed poorly with non-automated counting. The optimum method for objectively quantifying cough is yet to be defined but any technique should be clearly described and non-automated methods remain the reference standard.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.rmed.2014.10.003>.

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