Original Article

Cough frequency monitors: can they discriminate patient from environmental coughs?

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Background: Objective cough frequency measurements are increasingly applied in clinical research. Technological advances enable automated detection and counting of cough events from sound recordings of many hours' duration. A possible limitation of sound-based cough frequency measurement is the contamination of recordings by environmental coughs (coughs from persons other than the patient). This study aimed to investigate the accuracy of a sound-based cough monitor for detecting and discriminating patient cough from environmental cough.

Methods: As part of a stroke trial (ISRCTN40298220), patients on a hospital ward underwent 15-minute recordings using the Leicester Cough Monitor (LCM), a sound-based cough monitor ('semi-automated counts'). Participants and other persons in the environment were prompted to cough. An observer present in the room recorded the number of patient and environmental coughs ('live counts'). LCM counts were also compared against a manual cough count, the most commonly used gold standard to determine accuracy ('manual sound counts' from listening to recordings), by a blinded assessor who cross-referenced timed cough events from the respective methods. Data for automated, manual and live cough counts were analyzed using agreement statistics.

Results: On sound recordings from five patients, there were 65 patient coughs and 78 environmental coughs (manual counts). Absolute agreement for patient cough count between all three measurement methods (LCM automated, live, and manual sound counts) was high, with intra-class correlation coefficient of 0.94 [95% confidence intervals (CI): 0.74, 0.99]. The proportion of exact agreements for patient cough between LCM and manual count was 0.92, and kappa was 0.84 (95% CI: 0.75, 0.93). The LCM showed sensitivity of 0.94 (95% CI: 0.84, 0.98), specificity of 0.91 (95% CI: 0.82, 0.96), positive predictive value of 0.90 (95% CI: 0.79, 0.95) and negative predictive value of 0.95 (95% CI: 0.86, 0.98) for detecting patient coughs.

Conclusions: This preliminary study supports the validity of the cough monitor for detecting and discriminating patient from environmental cough. Further validation is recommended, to describe the level of accuracy with greater precision.

Keywords: Cough frequency; measurement; accuracy; validity; Leicester Cough Monitor (LCM)

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Introduction

Cough frequency has long been a parameter of interest in research and clinical practice, for example in studies of excessive coughing and cough suppressants, or where cough is examined as a positive clinical sign of respiratory disease (1-5). Cough frequency measurement could also be of value in the context of neurogenic dysphagia, where the presence of cough might indicate aspiration events and increased pneumonia risk (6).

Objective measurement of cough frequency requires a monitoring system to capture and count cough events. Manual cough counts from sound recordings (cough events counted by a human listener) have been used since the 1950s (7-9). Modern sound-based cough monitors make use of compact digital recording devices that are now available. Automated or semi-automated processes have been developed, which enable a more efficient detection and counting of cough events on sound recordings of many hours' duration (2,10,11). A potential limitation of sound-based cough monitors is compromise of their accuracy by the potential for environmental coughs (coughs from persons other than the patient) to contaminate the recording (2,10,11).

As part of a stroke trial (12), we had an opportunity to validate a sound-based cough monitor (Leicester Cough Monitor, LCM) (13) in an acute stroke unit environment. There is increasing interest in cough frequency measurements in neurologic patient groups, but devices have not been validated in these patient populations. We considered whether the LCM could discriminate stroke patient cough from environmental cough in an inpatient setting, where environmental coughs (for example from patients who share the same room, visitors or staff) could be registered and result in higher measurements. We conducted a preliminary validation study. The aim was to investigate the accuracy of the cough monitor for discriminating patient cough from environmental cough, in this particular clinical environment.

Methods

Design

Sound-based cough monitor recordings were taken from a cohort of five inpatients (consecutive recruits to the stroke trial). The cough frequency outputs generated by the cough monitor system were compared against live observer count and manual sound-file cough counts, a widely used gold standard to determine the accuracy of cough monitoring systems (14). The sample was a convenience sample, and no formal sample size calculation was conducted. The sample size was largely determined by study resources.

Setting and participants

Acute stroke patients who were inpatients at a large metropolitan acute stroke unit were recruited. To be eligible for study participation, patients had to be alert, oriented and able to follow instructions. Participants occupied beds in multi-occupancy open bays, which connected to the main ward corridor. Participants shared the space with three other patients. All participants gave written informed consent to take part in the study. The study had ethical approval from the United Kingdom National Research Ethics Service (Wandsworth Research Ethics Committee, reference 10/H0803/32).

Clinical characteristics

Patient demographic information and stroke characteristics (stroke lesion site and stroke severity) were described from clinical records, CT and/or MRI head reports and admission National Institutes of Health Stroke Scale (NIHSS) scores (15). Respiratory function was assessed by spirometry according to international clinical standards (16) and using a portable spirometer (SpiroUSB; CareFusion, San Diego, CA, USA). Maximum expiratory (PEmax) and inspiratory (PImax) mouth pressures were measured following international clinical guidelines (17) and using a portable device (MicroRPM; CareFusion). Peak cough flow measurements of maximal volitional cough were made using a calibrated Fleisch pneumotachograph with a face mask (18). Respiratory measurements were conducted at the patient bedside. On completion of the study, the treating clinician was asked to give a description of the cough sound quality.

Cough monitor system

Measurements were made using the LCM, a semi-automated cough frequency measurement system (13,19,20). The LCM consists of a portable sound recording device (Digital Voice Tracer LFH0662, Philips Electronics UK Ltd, Guildford, England), which is worn in a pouch or pocket. The small microphone is clipped onto the patient's collar or lapel, as close as possible to the anterior neck. A

continuous sound recording is made for up to 24 hours. The digital recording is then processed through accompanying computer software, which automatically registers sound patterns typical for cough. During data processing, a human operator listens to examples of identified sound patterns that are presented by the software and confirms whether or not the sound is in fact a cough sound. Sounds sometimes misidentified are, for example, short sharp sounds such as the closing of doors or dropping of objects, or snippets of talk or laughter. The cough count is refined through the feedback provided by the human operator. The software output provides the total number of cough events over the entire time period of recording and average hourly cough frequency.

Data collection

Participants wore the LCM for 15 minutes, while a researcher observed the participant from close proximity 'live' for the entire duration of the recording. The researcher conducted a visual live observer count of participant coughs (patient coughs), and of all other coughs which could be heard by the researcher in the environment, including coughs from other patients, staff and visitors within the area (environmental coughs). Recordings were conducted in the late mornings or early afternoons. During all recordings, there were other patients, visitors and/or staff present in the area. To ensure that there were sufficient cough events recorded, the participant and other people in the room were prompted to cough several times during the 15 minutes recording, thereby simulating the conditions that might lead to contamination of cough recordings through environmental coughs.

LCM cough frequency

To obtain the LCM semi-automated cough count, recordings were processed by an operator who was blinded to the visual live observer count. When giving operator input to cough sound recognition, the operator consciously assessed for each sound sample presented by the programme: (I) whether the sound was a cough sound or not (designating sounds that did not resemble cough sounds as 'non-cough'); (II) if the sound was a cough sound, whether it sounded distant or near on the recording (designating distant sounding coughs as 'non-cough'); and (III) if the sound was a cough sound, whether it resembled the participant's cough sound from this input phase (for example, considering whether the participant's cough sound had particular characteristics, such as a wheezing cough quality, which could assist in distinguishing the test subject's coughs from coughs generated by other persons; and considering whether the cough came from a person of the opposite sex to the participant). LCM output consisted of cough frequency for the 15-minute recording, as well as a list of timings to the nearest second for all identified cough events.

Manual cough count

Manual cough counts from sound files (considered the gold standard by some investigators) were conducted by a researcher who was blinded to the visual live observer counts and to LCM counts (14). The researcher listened (without visualisation of sound traces) to the same recordings that were processed with the LCM. Reference samples of participants' typical cough sounds were available to the researcher. Each manually counted cough was identified as either a patient cough or a non-patient cough (environmental cough), based on characteristics of the patient cough reference sample, considering whether the cough came from a person of the opposite sex to the patient, and loudness of the cough (environmental coughs being quieter or sounding 'distant' on the recording). The timing of each manually counted cough was noted (to the nearest second).

Data analysis

Cough frequencies obtained from the visual live observer count, from the manual sound file count, and from the LCM count were compared descriptively and by calculating the intra-class correlation coefficient for absolute agreement between the three measurement methods, using a two-way mixed-effects model for individual agreement in SPSS statistical software (IBM SPSS Statistics v22). Timings of identified cough events from the manual count and the LCM were cross-referenced, and agreement between the two was analyzed calculating Spearman's rho, the proportion of exact agreements, Cohen's kappa, sensitivity, specificity, positive and negative predictive values, and their respective 95% confidence intervals (CI) (21). Exact CIs (22) were calculated for sensitivity, specificity, and positive and negative predictive values using SPSS statistical software.

Table 1 Clinical characteristics of study participants

Patient	Sex	Age (years)	Stroke lesion site	Stroke severity (NIHSS score)	Time from stroke (days)	Smoking status	FVC (L)	FVC % predicted (%)	PCF (L/min)	Cough sound quality	PEmax (cmH_2O)	PImax (cmH_2O)
1	F	83	Right cortical	17	13	Never smoked	1.1	54	217	Weak	40	31
2	F	70	Right cortical	9	4	Never smoked	0.9	45	232	Weak	31	30
3	M	41	Right cortical	7	29	Never smoked	2.1	48	632	Explosive	77	62
4	M	54	Right subcortical	4	18	Never smoked	2.3	70	641	Explosive	134	81
5	M	53	Left brainstem/ cerebellum	6	3	Never smoked	2.7	68	676	Bovine	74	36

F, female; M, male; NIHSS, National Institutes of Health Stroke Scale: score range 0–34, higher score indicates more severe stroke, score <5 predicts favourable clinical outcome; FVC, forced vital capacity; PCF, peak cough flow of volitional cough; PEmax, maximal expiratory mouth pressure; PImax, maximal inspiratory mouth pressure.

Table 2 Cough frequencies according to live observer count, manual sound file count and LCM output

Patient	Cough classification	Live observer count	Manual sound file count	LCM count
1	Patient coughs	9	10	9
	Environmental coughs	12	11	–
2	Patient coughs	27	25	23
	Environmental coughs	24	24	–
3	Patient coughs	5	5	5
	Environmental coughs	12	11	–
4	Patient coughs	11	11	10
	Environmental coughs	13	12	–
5	Patient coughs	15	14	21
	Environmental coughs	20	20	–

LCM, Leicester Cough Monitor.

Results

Sample

The sample consisted of two women and three men within the first month following acute stroke. Clinical characteristics of the five study participants are given in *Table 1*. Participants' cough sound qualities included 'normal' explosive cough sounds (patients 3 and 4), as well as weak (patients 1 and 2) and 'bovine' (patient 5) cough sound qualities.

Cough frequency according to live observer count, manual sound-file count and LCM count

Table 2 presents cough frequencies according to visual live observer count, manual sound file count and LCM count. Live observer counts corroborate manual cough counts of patient and environmental coughs. Discrepancies between observer and manual count ranged from 0–2 coughs (≤8% of manual count).

Cough frequencies obtained from manual count and

Table 3 Agreement between manual sound file count and LCM count (verified by listening to individual events) for each patient

Patient	Cough classification	Manual count patient coughs	Manual count environmental coughs
1	LCM-classified patient coughs	9	0
	LCM-classified non-patient coughs	1	11
2	LCM-classified patient coughs	23	0
	LCM-classified non-patient coughs	2	24
3	LCM-classified patient coughs	5	0
	LCM-classified non-patient coughs	0	11
4	LCM-classified patient coughs	10	0
	LCM-classified non-patient coughs	1	12
5	LCM-classified patient coughs	14	7
	LCM-classified non-patient coughs	0	13

LCM, Leicester Cough Monitor.

Table 4 Agreement between manual sound file count and LCM count (verified by listening to individual events) for the entire sample

Cough classification	Manual count patient coughs	Manual count environmental coughs	Total
LCM-classified patient coughs	61	7	68
LCM-classified non-patient coughs	4	71	75
Total	65	78	143

LCM, Leicester Cough Monitor.

LCM output correspond well for patients 1–4, with discrepancies ranging from 0–2 coughs (≤10% of manual count). For patient 5 (bovine cough sound), there was a discrepancy of 7 coughs between manual count and LCM output. From the data in *Table 2*, the intra-class correlation coefficient (95% CI) was 0.94 (0.74, 0.99) for all patients, and 0.98 (0.92, >0.99) only including patients 1–4.

For patient 5, we also processed a 24-hour recording (recorded on the same day as the 15-minute validation recording) using the same operator input as described in our methods. LCM 24-hour cough frequency was 280 coughs, or 11.7 coughs per hour. We verified each sound event that was designated by the LCM as a cough by listening to the corresponding section of the sound recording. Out of 280 designated cough events, only 3 (1%) were coughs likely to be from persons other than the patient.

Agreement between manual sound file count and LCM count

Agreement between the manual sound file count and the LCM count according to the timings of identified cough events is presented in *Table 3* (individual patients) and *Table 4* (entire sample). For individual patients, manual sound file count and LCM count were highly correlated, with Spearman's rho of 1.0 (P<0.01) for coughs classified as patient coughs, and 0.95 (P=0.014) for coughs classified as non-patient (environmental) coughs. For the entire sample, the proportion of exact agreements was 0.92, and kappa was 0.84 (95% CI: 0.75, 0.93). LCM sensitivity was 0.94 (95% CI: 0.84, 0.98), specificity was 0.91 (95% CI: 0.82, 0.96), positive predictive value was 0.90 (95% CI: 0.79, 0.95) and negative predictive value was 0.95 (95% CI: 0.86, 0.98).

Discussion

This preliminary validation study of the LCM system has shown good agreement between LCM semi-automated cough counts and the gold-standard manual cough count, both for the detection of patient cough events and for the discrimination of patient and environmental coughs.

Sensitivity of ≥0.90 has been recommended for cough monitoring to be clinically useful (2). With a sensitivity of 0.94 in our study, LCM performance is consistent with other cough monitor systems (2,23-26). However, it has to be acknowledged that the performance of systems may vary according to patient population and the specific circumstances of application, for example the duration of recording and the environment. Our data also lend support to the validity of the LCM system for application in patient groups with neurological impairment, where the cough sound might present with a weak or bovine sound quality as opposed to the normal characteristic explosive cough sound. Our analysis highlights that even the weak cough sounds of patients 1 and 2 were accurately assessed by the system.

We describe a validation method through cross-referencing of cough events according to their timings on the sound recording. This allows a one-to-one comparison of each sound event that is designated and counted as a patient cough by the LCM system against the coughs identified by manual sound file count. We conducted manual counts from sound as opposed to video recordings. Using video (capturing the patient's face) may provide an additional layer of visual verification of manual counts, although both methods are considered equally valid (14,27). In our study we used the visual live observer count to corroborate manual sound file counts, in particular with respect to the ratio of patient to environmental coughs. The small discrepancies between these two methods are best explained by the difficulty of maintaining attention to the entire environment throughout the period of live observation.

In our study, LCM cough counts from patient 5 differed considerably from the manual count, over-counting by seven coughs. Cross-referenced timings of cough events showed that this was due to non-patient coughs, which were counted as patient coughs by the LCM during a sequence when a number of interchanging patient and non-patient coughs occurred very closely together and partly overlapped; and also distinct non-patient coughs, which occurred in isolation, which were counted as patient coughs by the LCM. This patient's cough sound had a bovine quality, in accord with their clinical presentation with brainstem and cerebellar stroke. 'Bovine' cough describes a non-explosive or hollow sound quality of cough related to vocal cord weakness or dysfunction, typically caused by peripheral damage to the vagus nerve or the relevant central nervous pathways (28,29). We considered that the LCM software algorithm may require learning from a longer sound recording to fine-tune the automated detection algorithm for this particular cough sound quality. To investigate this possibility, we processed a 24-hour recording from the same patient (recorded on the same day as the 15-minute validation recording) using the same operator input as described in our methods. LCM incorrectly classified only 1% of environmental coughs as patient coughs.

Alternative to sound-based cough monitor systems, some devices record cough signals directly from the chest wall, for example using a contact microphone, accelerometer or electromyography (14,30). Cough frequency may be obtained from these signals directly; or these signals may be used in conjunction with sound recordings, one serving to verify the other. The addition of a throat-mounted accelerometer, for example, has been shown to improve the performance of a sound-based cough detection system (31). A disadvantage of these methods for application in an acute stroke unit setting may be that sensors applied to the chest wall under clothing can become displaced, in particular during the frequent moving and handling of patients by staff that takes place during nursing and rehabilitation activities on a stroke unit. When recording over many hours, a system such as the LCM may be of advantage, as the position of the microphone is evident to members of staff and also easily adjusted or corrected, whereas displaced sensors under clothing may go unnoticed for a long time, leading to loss of signal, and may also require specific knowledge for correct re-positioning (for example when using electromyography over a particular muscle).

The possibility of objective cough frequency measurement in neurologic patient groups and in acute ward settings may lead to new insights about cough frequency in dysphagia and aspiration, an aspect that has attracted some interest in the past, but has been restricted by the limitations of data collection through subjective reporting of coughing episodes (6,32). Potential areas for future research could be the correlation between dysphagia severity, reflex cough sensitivity and cough frequency; or the temporary distribution of coughs in relation to the time of ingestion of food and drink.

We acknowledge that the present study is limited by the small number of patients and the relatively short duration of recordings. Taking into consideration that manual cough analysis is a very labour intensive method, our data make a relevant contribution to validating the cough monitor. Nevertheless, we view our results as preliminary, and studies with larger samples are required to yield greater statistical precision.

Conclusions

The semi-automated cough monitor examined in this study demonstrated good ability to detect and discriminate patient cough from environmental cough. The device may provide an appropriate method for measuring cough frequency in an acute stroke unit environment. Further validation studies using recordings of longer duration are recommended to describe the level of accuracy with greater precision and inform interpretation of cough frequency measurements in this clinical setting.

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Footnote

Conflicts of Interest: SS Birring is developer of the LCM system. The other authors have no conflicts of interest to declare.

Disclaimer: The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health.

Ethical Statement: The study had ethical approval from the United Kingdom National Research Ethics Service (Wandsworth Research Ethics Committee, reference 10/H0803/32). All participants gave written informed consent to take part in the study.

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