Performance of a digital signal processing algorithm for the accurate quantification of cough frequency

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To the Editor:

The ability to measure cough frequency from sound recordings has changed the standards by which new cough treatments are evaluated and is providing insights into the mechanisms underlying cough in respiratory disease [1–5]. Objective measures of the number of coughs over extended time periods can be made using off-the-shelf sound recording devices, with aural counting of cough sounds captured. Although excellent inter-observer agreement can be achieved, this process is extremely laborious and limits the size and scope of possible studies [6, 7]; thus, there is a need for more efficient cough quantification methods. Accurate cough detection is, however, complicated by the substantial variability in cough acoustics both within and between individuals. There is also the challenge of distinguishing cough from large amounts of speech and an infinite array of environmental noises that may be captured during ambulatory sound recordings. Indeed, fully automated cough detection systems have failed to achieve sufficient accuracy to be useful, despite apparent success in preliminary tests [8, 9]. A semi-automated algorithm is in use in clinical studies but has only undergone preliminary validation, reporting modest sensitivity in small numbers of individuals (82.3–86%) in recordings made by a now obsolete mp3 player/recorder [10, 11]. The influence of user input, and the robustness of this algorithm to detect cough in different respiratory diseases and in recordings made using different recording devices with different acoustic encoding have not been assessed.

The VitaloJAK cough monitoring system has been developed as a collaboration between clinical academic and industrial partners and is currently the only system with the regulatory approvals necessary for use in clinical trials of investigational medicinal products (CE marked, FDA 510k approved). It comprises a digital sound recording device, a web-based portal for data transfer, tracking and storage, and a digital signal processing algorithm (WH03_V1.12) to remove most non-cough sounds and silence from 24 h sound recordings, prior to manual counting of cough sounds by trained analysts. The aim of this evaluation was to assess two key indicators of the performance of the algorithm in patients with a range of different respiratory diseases and in a larger group of patients with refractory chronic cough. These were the efficiency of the algorithm in reducing the length of the recordings to be listened to (an indicator of specificity) and secondly the retention of cough sounds from the original 24 h recording after filtering (sensitivity).

We assessed the algorithm performance in recordings from 143 randomly selected subjects participating in clinical studies who had additionally consented to use of their recordings for the development and testing of cough analysis software; these were academic studies in Manchester, Newcastle, London and Cardiff, and a single commercial study. First, we evaluated different diagnostic groups compromising refractory/unexplained chronic cough (n=21), asthma (n=10), COPD (n=14), idiopathic pulmonary fibrosis (IPF; n=12), bronchiectasis (n=6), children with a range of chronic respiratory diseases (asthma, cystic fibrosis and primary ciliary dyskinesia; n=10) and healthy volunteers (n=10) (ethics number 18/NW/0254). Subject age, gender, diagnosis and lung function data were available in all adult subjects and the associated recordings were 24 h in length. Some paediatric subjects wore the device for <24 h, median duration 23.1 h (interquartile range (IQR) 15.3–24 h). In 11 subjects, repeat recordings on a second occasion were

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The VitaloJAK filtering algorithm has undergone the most extensive testing of any cough monitoring software and is sensitive/efficient across a range of diagnoses and age groups, and in recordings containing a wide range of cough counts https://bit.ly/3rF9vp1

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TABLE 1 Subject demographics and performance of filtering software by diagnosis

Diagnosis	Subjects n	Age years	Sex F/M	FEV_1 % predicted	FVC % predicted	Coughs in 24-h file n	Coughs in filtered file n	Sensitivity %	Length of filtered file min	Filter efficiency
Chronic cough	21	64.0 (54.5–68.5)	16/5	102 (92.0–109.6)	101 (96.0–117.6)	509 (249–1046.5)	509 (249–1025.5)	99.9 (99.2–100.0)	106.9 (83.0–144.0)	7.4 (5.8–10.0)
IPF	12	67.0 (66.3–78.5)	1/11	73.5 (66.3–82.5)	68.0 (61.0–79.0)	193.5 (110.5–666.8)	192.5 (110.5–651.8)	100 (99.4–100.0)	92.6 (48.7–147.2)	6.4 (3.4–10.2)
COPD[#]	14	73.5 (69.5–76.5)	6/8	61.1 (43.0–72.4)	95.9 (75.9–110.5)	165.5 (27.5–857.0)	164.5 (26.8–833.6)	97.8 (96.1–99.7)	72.6 (58.5–119.1)	5.0 (4.1–8.3)
Asthma	10	26.5 (21.8–32.0)	6/4	100.0 (95.8–107.5)	106.5 (101.8–117.3)	35.0 (13.5–144.0)	35.0 (13.5–143.8)	100.0 (100.0–100.0)	100.2 (70.2–136.2)	7.0 (4.9–9.5)
Bronchiectasis	6	72.0 (68.8–73.5)	2/4	59.3 (38.3–71.4)	71.9 (59.1–94.1)	500.5 (250.0–551.5)	492.5 (249.3–523.5)	99.3 (93.6–100.0)	55.3 (50.6–68.9)	3.8 (2.9–7.8)
Paediatric subjects	10	4.5 (3.5–7.5)	4/6			86.0 (30.5–423.0)	83.5 (30.5–423.0)	100.0 (100.0–100.0)	130.3 (92.4–248.6)	11.9 (6.6–19.0)
Healthy volunteers	10	38.5 (24.0–65.5)	3/7	107.0 (101.0–120.3)	113.5 (96.8–123.5)	13.5 (2.5–23.3)	13.5 (2.5–22.5)	100 (100–100.0)	148.9 (77.7–196.3)	10.3 (5.4–13.6)
Severe chronic cough	60					327.0 (157.5–643.8)	327.0 (157.5–641.3)	100.0 (99.7–100)	126.6 (82.2–199.8)	8.8 (5.7–13.9)
Overall	143					256.0 (80.0–587.0)	254.0 (77.0–587.0)	100.0 (99.5–100.0)	108.6 (73.1–168.7)	7.6 (5.1–12.1)

All data are median and interquartile ranges, unless stated otherwise. F: female; M: male; FEV_1: forced expiratory volume in 1 s; FVC: forced vital capacity; IPF: idiopathic pulmonary fibrosis. [#]n=10 recordings in stable COPD patients, plus n=4 recordings during COPD exacerbations.

available allowing an assessment of repeatability of the algorithm performance (COPD n=1, bronchiectasis n=6, chronic cough n=2, IPF n=2). Secondly, we evaluated performance in a larger set of patients with refractory/unexplained chronic cough, recruited to a multicentre clinical trial with a cough severity of >40 mm on a visual analogue scale (with permission from Vitalograph Ltd); demographic data was not available for these subjects.

The VitaloJAK cough monitoring system consists of a recording device with two microphones; a free field microphone attached to the lapel and a contact microphone attached to the chest wall over the manubrium. Two versions of the recording device have been produced (mark 1 and mark 2), developed to make recordings to the same digital recording standards. The device records continuously for 24 h (8 Hz sampling rate, 16-bit). Recordings were transferred to a PC and the explosive part of the cough sounds identified and marked with an electronic tag by trained cough analysts, listening to the sound recordings whilst visualising the sound waveforms using audio editing software (Adobe Audition version 3.0, Adobe Systems Incorporated) [12]. The algorithm was applied to each sound file to remove silence and the bulk of non-cough sounds. Cough sounds are highly variable both within and between subjects. The philosophy behind the filtering algorithm is to recognise these differences and fit the analysis technique to the nature of individual cough sounds. The initial processing identifies the start and end time of all sounds within the 24-h recording, with a particular focus on typical cough sound patterns. All sounds identified are categorised as a potential cough sound or not; potential cough sounds must be confirmed from both microphone recordings to be retained by the filtering. All potential cough sounds are merged and sorted by time position, to produce a reduced length sound file. The performance of the software was assessed by the percentage of original tagged cough sounds retained after filtering (sensitivity) and the efficiency of the filtering by the length of the filtered sound file, as a percentage of the unfiltered file length.

Subjects in the different diagnostic categories exhibited a wide range of cough frequencies, with significant differences between groups ($p<0.001$) (table 1); all patient groups coughed significantly more than healthy volunteers (all $p\leqslant0.004$) and chronic cough patients coughed significantly more than other groups (all $p\leqslant0.038$), except for those in the bronchiectasis group. The sensitivity of the algorithm was remarkably high for all subject groups (median 100%, IQR 99.5–100%) and >90% for all individuals, apart from one healthy volunteer with a sensitivity of 81% (four coughs missed of a total of 22). Sensitivity was different between diagnostic groups ($p=0.001$), being lower in COPD patients, but as can been seen from table 1, the absolute difference was small. Equally, the filtering algorithm substantially reduced recording length from a median of 24 h to a median of 1 h 48.6 min, *i.e.* 7.6% of the original recording. Efficiency of the algorithm was slightly less in paediatric patients and healthy volunteers. In the 11 patients with repeat recordings, the performance of the algorithm was highly consistent: the median difference between recordings in sensitivity was 0.2% (IQR −4.2% to +2.8%) and in efficiency was −0.9% (−10% to +0.0%).

In the subjects where demographic data was available, regression analysis suggested sensitivity and efficiency of the algorithm were not influenced by age, gender or lung function. The reduction in length of the recording and sensitivity were not correlated with the number of coughs present.

In conclusion, this is the largest and most comprehensive evaluation of an algorithm to facilitate cough monitoring reported to date. The data suggests the VitaloJAK filtering algorithm is sensitive and efficient across a range of diagnoses, age groups, and in recordings containing a wide range of cough counts. Performance was also high in a large group of patients with refractory/unexplained chronic cough recruited to a clinical trial of a novel therapy, the group currently most studied in the development of novel anti-tussive treatments.

Jaclyn A. Smith [1,2], Kimberley Holt [1,2], Rachel Dockry [1,2], Shilpi Sen[2], Kitty Sheppard[2], Philip Turner[2], Paul Czyzyk[2] and Kevin McGuinness[2]

[1]Division of Infection, Immunity and Respiratory Medicine, University of Manchester, Manchester, UK. [2]Manchester University NHS Foundation Trust, Manchester, UK.

Corresponding author: Jaclyn A. Smith (jacky.smith@manchester.ac.uk)

Author contributions: J.A. Smith drafted the manuscript and analysed the data; K. McGuinness developed the algorithm; K. Holt and R. Dockry were involved in data collection and cough counting; S. Sen, K. Sheppard, P. Turner and P. Czyzyk performed cough counting. All authors reviewed and contributed to the final manuscript.

Data availability: De-identified cough recording data from this study will be shared, following publication, with researchers following review by the steering committee of the research database. Proposals for access should be directed to kimberley.holt@manchester.ac.uk

Conflict of interest: J.A. Smith reports non-financial support (provision of equipment) from Vitalograph Ltd, during the conduct of the study; grants and personal fees for consultancy from Merck, Bayer, Bellus, Shionogi, Nerre, Nocion and Axalbion, personal fees for consultancy from Attenua, Menlo, Boehringer Ingelheim and Algernon, grants from GSK, outside the submitted work; and has a patent Cough detection with royalties paid to her hospital. K. Holt has nothing to disclose. R. Dockry has nothing to disclose. S. Sen has nothing to disclose. K. Sheppard has nothing to disclose. P. Turner has nothing to disclose. P. Czyzyk has nothing to disclose. K. McGuinness reports non-financial support (provision of equipment) from Vitalograph Ltd, during the conduct of the study; has a patent Cough detection with royalties paid; and invented the VitaloJAK filtering algorithm which has been licensed by Manchester University Foundation Trust and the University of Manchester to Vitalograph Ltd and Vitalograph Ireland (Ltd); Manchester University Foundation Trust receives royalties which may be shared with K. McGuinness as the inventor and the clinical division in which J.A. Smith works.

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