Pilot Trial of Spirometer Games for Airway Clearance Practice in Cystic Fibrosis

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BACKGROUND: Many children with cystic fibrosis (CF) adhere poorly to airway clearance techniques (ACTs), and would rather play video games that challenge their dexterity and visual tracking skills. We developed gaming technology that encourages forced expiratory maneuvers. OBJECTIVE: Following interviews regarding recreational activities and subjects' practice of ACTs, we conducted a pilot trial of spirometer games in 13 adolescents with CF, to test the hypothesis that games could increase subjects' engagement with forced expiratory breathing maneuvers and improve pulmonary function tests (PFTs). METHODS: After baseline PFTs, subjects were provided with digital spirometers and computers set up as "game only" or "control" devices. After the first of 2 periods (each > 2 weeks), the computer was set-up for the alternate condition for period 2. The *t* test and non-parametric correlation analyses examined use, number of expiratory high flow events (HFEs), and change in PFTs, identifying trends at $P \leq .1$, significance at $P < .05$. RESULTS: Interviews disclosed minimal awareness of ACTs among our pediatric CF patients. Subjects used games and control software a similar percentage of days during the game (26%) and control periods (32%). There was a trend toward more minutes with the game versus control setup ($P = .07$), though HFE count did not differ between the 2 conditions ($P = .71$). Game play showed no overall effect on FEV_1, though correlation analysis showed a modest relation between minutes of play and change in FEV_1 from baseline ($r = 0.50$, $P = .09$). The game period showed a trend to increased vital capacity ($P = .05$). CONCLUSIONS: Spirometer games elicit forced expiratory breath maneuvers in pediatric CF patients. Improvement in PFTs may be due to improved test performance technique, though improved obstructive/restrictive lung function due to game play cannot be excluded. A formal clinical trial of this approach is planned. *Key words: therapeutic games; adherence; motivation; cystic fibrosis; respiratory therapy.* [Respir Care 2012;57(8):1278–1284. © 2012 Daedalus Enterprises]

Introduction

People with cystic fibrosis (CF), like those with other chronic illnesses, must follow intensive, long-term treatment plans. Among other respiratory therapies, active cycle breathing comprises a series of breathing techniques that may prevent exacerbations and optimize pulmonary function.[1] Active cycle breathing features a forced exhalation maneuver termed "huffing," which plays a key role in moving secretions out of airways. As with other chronic pediatric respiratory diseases, adherence to medical therapies is known to be poor in CF.[2] Improving adherence to daily practice of airway clearance techniques (ACTs) such

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as huffing thus constitutes an appropriate goal and outcome measure for studies of behavioral interventions in CF.

It is well known that adolescents (with or without CF) are strongly motivated to engage with digital games.[3] We therefore developed and evaluated a prototype breath biofeedback video game in which pediatric CF patients learned to control their inspiratory and expiratory flow by tracking a moving target. The prototype was tested for acceptability and safety in 10 subjects hospitalized for exacerbations of CF. The prototype target movement was calibrated so that it paced their tidal volume and respiratory rate at a level approximating their minute ventilation requirement. These subjects appeared to enjoy playing the game prototype, and were able to safely learn to improve their tracking accuracy.[4] This experience provided the foundation for further development and evaluation of computer-based breath biofeedback games for home use.

This report describes both the subsequent game development process and the initial evaluation of 2 novel breath biofeedback games aimed to support engagement with forced exhalation maneuvers that approximate those entailed in ACTs. We hypothesized that, compared to non-game based digital spirometer coach software, digital spirometer biofeedback games would increase subjects' engagement with forced breathing maneuvers (high flow events [HFEs]) that include an approximation (because the subject is exhaling through a spirometer) of huffing. Corollary hypotheses predicted that subjects would spend more time with game (experimental) versus coach (control) software, and that the game trial period would lead to improved pulmonary function tests (PFTs), compared to the control period in a randomized crossover study.

QUICK LOOK

Current knowledge

Patients with cystic fibrosis must engage in self-management therapies to enhance secretion removal, improve lung function, and prevent exacerbations. These therapies are time consuming, and patient adherence to airway clearance regimen is difficult to sustain, owing to a host of factors, including fatigue and boredom.

What this paper contributes to our knowledge

Breath-activated digital games incorporating a digital spirometer have potential to facilitate airway clearance practice and address the need for relatedness in this socially isolated clinical population. Aligning health behaviors with the patient's psychological needs via health-oriented computer games may in principle improve adherence and self-management.

Methods

Game Development Process

To increase the likelihood that the games would be successful and would include themes relevant to our CF patients, we conducted structured interviews of 17 pediatric CF patients (8–16 years old). Interview subjects were recruited from the CF clinic at Fletcher Allen Health Care in Burlington, Vermont, where they had periodic follow-up care, and after they received an introductory mailing prior to their quarterly visit. The interview questions, like the intent of the trial overall, were based upon the principles of self-determination theory, which predicts greater motivation for and engagement with activities that meet subjects' needs for competence, relatedness, and autonomy.[5] The 20 min structured questionnaire focused on how prescribed respiratory therapies related to self-determination, and also identified recreational activities of pediatric CF patients, including engagement with digital media. (See the interview guide in the supplementary material at http://www.rcjournal.com.) Results of these recorded and subsequently transcribed interviews are reported elsewhere,[6] but are briefly described here as they relate to game development, as game design concepts incorporated themes drawn from these interviews.

Games were conceived, programmed, and produced by 2 undergraduate teams (Graphic Art, Game Design, and Computer Science majors at Champlain College) in Adobe Flash software (Adobe, San Jose, California) (Figs. 1 and 2). The game designers incorporated interview results, including preferences of pediatric CF subjects for digital gaming activities and content. Two different games (*Ludicross* and *Creep Frontier*) were intended to resemble games that respondents' were already using, and incorporated interviewees' expressed interests in racing and animals, respectively. In *Ludicross*, the player's forced exhalations drove a race car around a track with spirometer-activated garage activities such as cleaning and fueling the race car. *Creep Frontier* had a more open-ended structure in which the player's forced exhalations enabled their avatar to free wild animals from an enveloping "slime." Both games had colorful, 2-D cartoon-style animated characters and background, and incorporated breath biofeedback such that changes in visual graphics corresponded to exhalation flow and duration (game software available upon request). All procedures were approved by the University of Vermont's institutional review board.

Breath Biofeedback Game Technology

Hardware consisted of a non-clinical spirometer (SPR-BTA, Vernier Software and Technology, Beaverton, Ore-

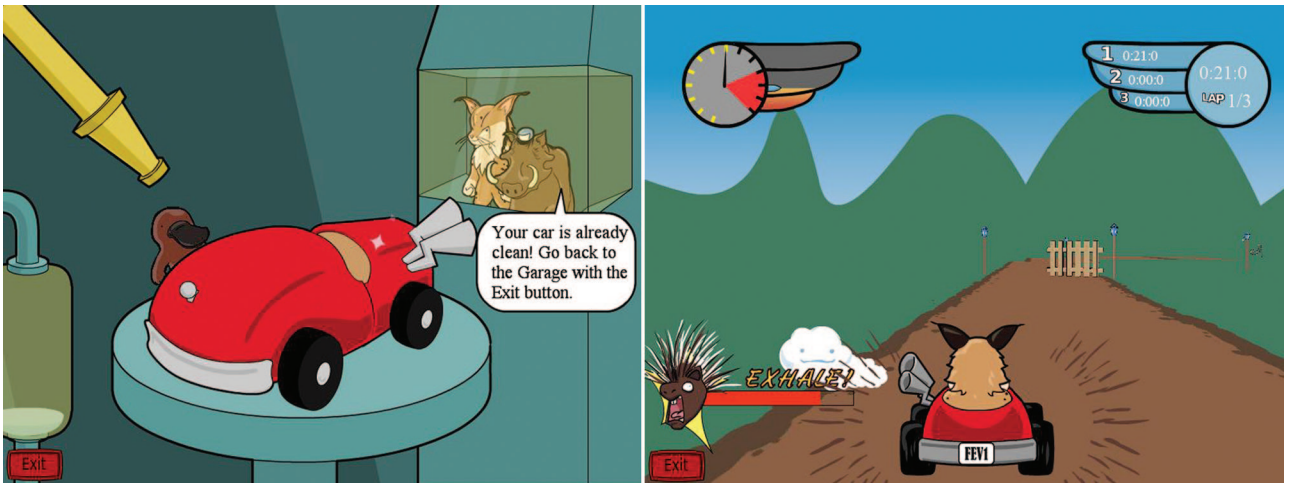

Fig. 1. Screen shots of *Ludicross*. Left: The player is incited to perform a forced exhalation, using the spirometer, to fill a water tank and then direct water at a race car to clean mud off of its surface. Right: The player charges up a race car, sending it zooming around a track, by charging it up with a forced exhalation.

Fig. 2. Screen shot of *Creep Frontier*. The player's avatar, in this case a character in a gothic-tech helicopter, could free animals from slime by forced exhalations that enveloped them with "emulsifying" bubbles.

gon) with USB (universal serial bus) output, which is commonly used for science education. The setup included bacterial filters (VBMAX33, A-M Systems, Sequim, Washington). The spirometer connected via USB to a laptop computer (Windows XP Pro operating system, Microsoft, Redmond, Washington). Dedicated device driver software was developed so that the digitized signal from the Vernier spirometer could be introduced into the Adobe Flash game programming software environment. Although the spirometer used was a relatively inexpensive device that was not designed for formal clinical assessment of flows, there was an interest in deducing approximate flows generated by subjects in the course of the study. We therefore analyzed 4 files generated using a fixed volume of air delivered to the game spirometer via a calibration cylinder used for clinical calibration of PFT spirometers. The results allowed us to infer flows from the amplitude of displacements in the digital flow versus time files that subjects generated during the trial in both game and control conditions.

To avoid inducing hyperventilation, the frequency of high flow maneuvers within the game context was set so as not to occur more often than once every 30 seconds. Control software that was used as a comparison for the breath biofeedback games presented the subject with relatively featureless graphics and background and instructed them to iteratively perform forced respiratory maneuvers (inhalations and exhalations), with no feedback as to flow or volume. Use (minutes) and number (of HFEs) (see definition below) were logged digitally in both control and game modes. A "shell" or host software environment, as well as data-logging functions (Tag New Media, Burlington, Vermont) featured a log-on screen that introduced either game or control software, and prompted the subject to enter his or her name, so that if friends or family wanted to use the technology, their activity could be distinguished by the log-on name. In preliminary acceptability and safety tests of these 2 games, 5 pediatric CF patients showed interest in the games' narrative and graphic scenarios, and did not experience dyspnea, or show signs of hyperventilation or exercise intolerance.

Pilot Clinical Trial Procedures

A 2-period, within-subject, crossover design was implemented to examine subjects' spontaneous engagement with the breath biofeedback games, compared to the control software. Subjects were randomized to receive either the

game treatment condition or the control treatment condition, and were then crossed over after the first trial period. Travel logistics precluded incorporation of a washout period between study conditions. Nineteen pediatric CF patients (7–14 years old) were recruited using approved institutional review board methods from the same CF clinic that served as the source of patient interviews. The primary outcome measure was the number of HFEs, as identified by blinded review of data files generated by engagement with software (game or control) during each study period.

Respiratory therapists associated with our CF clinic instructed patients, in company with their parent(s), on the use of the digital spirometers and the computers, which were set up in kiosk format to restrict use to only the assigned software implementations. Participants were asked to use the assigned software (game or control) for 15 min daily, and to return the equipment at a subsequent clinic visit (ie, in 2–3 weeks). Parents were asked to remind subjects about the spirometer once a day but otherwise not to prompt engagement: use of the technology was thus essentially ad lib. Thirteen participants completed both phases of the 2-period crossover study with evaluable data.

PFTs of vital capacity and FEV_1 were obtained at a baseline visit, after completion of the first trial period, and, following the completion of trial period 2, by a pulmonary clinician who was blinded to experimental condition assignments.

Analysis

Basic descriptive statistics (mean ± SD and percentages) were used to characterize the study population. Our initial power calculation called for 20 subjects; however, accrual of 19 subjects ultimately required us to extend the original study period from 6 to 18 months. Six of those 19 recruited subjects did not complete the study, due to difficulty making study appointments. Analysis was therefore completed on 13 available completed subjects. Because of unexpected logistical challenges in carrying out the study, the durations of the experimental and control periods varied considerably among subjects, and a measure of player engagement (minutes used) was corrected for the number of days of software use during each period.

The primary outcome measure (HFEs/d) was derived for each study subject and for each of the 2 study periods by reviewers who were blind to study condition. Trial spirometer data collected at home was accumulated as a series of extensible markup language (XML) files, each representing approximately 10–30 seconds of digitized flows (exhalation or inhalation). Logged data could be displayed as a graph showing flow (Y axis) over time (X axis). Criteria for identifying (counting) expiratory and inspiratory HFEs were established through a series of iterative, cross-validation trials among 3 observers, and were defined as upwards (expiratory) deflections with a sharp contour (ie, having steep upward and downward slopes), since these deflections reflected abrupt flow changes associated with the subject's effort to register high flow. To ensure reliability of HFE counts, counts of samples were repeated until each independent observer's total HFE counts for each of 5 files matched: for any 2 scorers, the total scores for each file (HFEs) were within 5%.

To validate that identified HFE events from the data log did in fact represent forced breathing maneuvers, we compared HFE counts with counts derived from observation of videotaped game play. The scorer identified and counted instances on the videotape when the test subject was performing a forced respiratory maneuver. Agreement of this visual count with the analysis of data files from the same sessions (5 different videotaped sequences), with the test subject playing both games as well as control, was 100%.

Using the calibration data (see above), flows associated with expiratory HFEs were calculated for the numerous flow versus time digital events that subjects generated in the course of the study. This analysis allowed us to compare flows to reported values for huffing maneuvers in subjects with CF,[7] and also to compare amplitudes of HFEs (peak flows) during control versus experimental conditions.

Secondary outcome measures included percentage of days used compared to number of days the software was available, number of minutes using the software per day of use, and percent relative change in pulmonary function (FEV_1, vital capacity) during game versus control study period. Here, the baseline value was subtracted from the post-game or post-control period value and then divided by the baseline value. These values were then multiplied by 100 to form percentages.

Paired *t* tests were performed to compare game and control periods for HFE counts (total, expiratory, corrected for usage) and for the relative percentage PFT changes. Non-parametric Pearson correlation coefficients were used to examine the association between software usage measures and study outcomes. A $P \leq .05$ was considered statistically significant, while a $P \leq .10$ was considered of marginal significance for this pilot study.

Results

Six of the original 19 recruits withdrew from the study and did not have complete data for analysis: one did not want to carry out PFTs, and 5 withdrew because of time requirements/difficulty making study appointments. The average age of the remaining, evaluable 13 subjects (study population) was 9.3 ± 2.1 years. Thirteen percent of the subjects were male. Disease severity was classified by

Table 1. Subject Demographics for Trial (n = 13)

Subject Number	Age, y	Sex	Ethnicity	% Predicted FEV_1	CF Status*
1	10	F	White	53	Moderate
2	12	F	White	71	Mild
3	10	F	White	77	Mild
4	8	M	White/Black	114	Normal/minimally affected
5	8	F	White	114	Normal/minimally affected
6	9	F	White	68	Mild
7	12	F	White	95	Normal/minimally affected
8	12	F	White/American Indian	74	Mild
9	7	F	White	98	Normal/minimally affected
10	7	F	White	99	Normal/minimally affected
11	8	M	White	91	Normal/minimally affected
12	12	F	White	88	Mild
13	7	M	White	69	Mild

* Subjects categorized as having normal/minimally affected, mild, moderate, or severe degree of cystic fibrosis (CF) pulmonary involvement according to percent predicted FEV_1.

Table 2. Pulmonary Function Test Results Organized by Study Period

	Baseline	Control Period	Game Period
FEV_1, mean ± SD L	1.77 ± 0.38	1.77 ± 0.37	1.84 ± 0.38
% predicted FEV_1	85.5 ± 18.6	84.2 ± 13.9	87.2 ± 15.1
Vital capacity, mean ± SD L	2.12 ± 0.46	2.08 ± 0.45	2.20 ± 0.39
% predicted vital capacity	96.5 ± 19.5	91.8 ± 11.6	98.5 ± 16.2

Table 3. Software Usage and Relative Percent Pulmonary Function Test Changes

	Game, mean ± SD	Control, mean ± SD	P*
Days available	38.6 ± 20.2	26.4 ± 11.3	.02
Days used	10.0 ± 11.2	8.5 ± 7.2	.59
Days used/days available	27.9 ± 24.2	32.0 ± 24.3	.55
Total minutes used	169.1 ± 231.3	44.8 ± 60.7	.07
Total minutes used/days used	4.8 ± 4.4	1.6 ± 1.8	.02
Expiratory HFEs	88.8 ± 149.5	73.5 ± 95.6	.71
Expiratory HFEs/days used	7.5 ± 4.0	8.6 ± 5.2	.59
Total HFEs†	122.6 ± 223.3	89.8 ± 116.5	.52
Total HFEs†/days used	11.4 ± 8.3	8.1 ± 5.6	.61
% FEV_1 change	4.1 ± 16.1	0.8 ± 17.3	.16
% FEV_1 change/days used	0.3 ± 2.4	−2.5 ± 5.2	.01
% VC change	4.3 ± 10.6	−2.1 ± 12.6	.05
% VC change/days used	0.4 ± 1.7	−2.6 ± 5.3	.03

* Paired t test.
† Total high flow events (HFEs) includes both inspiratory and expiratory HFEs.
VC = vital capacity

percent of predicted FEV_1 at baseline. Six subjects were considered normal/minimally affected (% of predicted FEV_1 > 90%), 6 were mildly affected (% of predicted FEV_1 65–90%), and 1 was moderately affected (% of predicted FEV_1 40–65%) (Table 1). Interviews disclosed that 12 of the 13 subjects with available information were not involved in any kind of daily breathing or airway clearance practice as of the time they entered the study.

Table 2 shows the mean measured as well as percent of predicted FEV_1 and vital capacity at baseline, and at the end of the control and experimental periods. Both FEV_1 and vital capacity showed small improvements following the game versus control periods, relative to baseline. The context of these relative changes in terms of usage and breathing activity is shown more fully in Table 3 (see below).

The total number of days for game period exceeded the control periods (P = .02) (see Table 3). However, the percentage of days for which game (26%) versus control software (32%) was used, did not differ (P = .59). Although the total number of minutes spent during the game period was marginally greater, compared to the control period (P = .07), the total HFEs and HFEs per day of use did not differ (P = .71 and .59, respectively). The Pearson correlation coefficients between the 3 software use measures (minutes used, days used, days available) were all significant (r > 0.80, P < .001) during both trial periods. Analysis of flows generated by study subjects showed that the flows associated with the HFEs during the game and control sessions were similar (1.55 L/min vs 1.63 L/min, respectively, no significant difference), though lower than the reported flow values for huffing maneuvers in older patients with CF (2.9 L/min).[7]

The relative percentage change from baseline for FEV_1 did not show a difference between the 2 trial periods (P = .16), although the control period change (0.8 ± 17.3%) was smaller than the game period effect (4.1 ± 16.1%, see

Table 3). Correction of the FEV_1% change for number of days the software was used showed a significant improvement in FEV_1 during the game period ($P = .01$). A separate, exploratory analysis showed a correlation between minutes of game time and improvement in FEV_1 relative to baseline ($r = 0.50$, $P = .09$), whereas there was no relationship between minutes of control time and change in FEV_1 (data not shown). Percent change in vital capacity improved ($4.3 \pm 10.6\%$ vs $-2.1 \pm 12.6\%$ after control period) following the game period, either with ($P = .05$) or without ($P = .03$) correction for number of days the software was used.

Discussion

Consistent with our clinical experience, our interviews with pediatric CF patients showed that most have received, but do not adhere to, airway clearance practice recommendations. No respondent gave any indication that airway clearance practices improve their breathing or support their sense of competence, autonomy, or relatedness.[6] Like many children and adolescents, our interview respondents do commonly engage with digital gaming at home, and as a coping strategy for stressful scenarios such as hospitalization. The observation, borne out in our interviews, that digital gaming supports our CF patients' needs for self-determination stimulated us to carry out the current pilot/feasibility trial of digital spirometer games incorporating respiratory maneuvers for airway clearance practice in pediatric CF patients.

Our interest in an objective measure of behavior change that would be relevant to daily ACT practice (ie, instances of forced respiratory maneuvers at home) precluded a trial comparing spirometer games to a "usual practice" scenario. The control condition for this trial—equipping subjects with a digital spirometer and laptop computer on which they could register forced exhalations that were prompted by a "bland" digital coach—therefore constituted an important intervention. Judging from their negligible involvement with ACTs at baseline, both the control and experimental study conditions apparently increased daily breathing practice for our subjects. Therefore, while this pilot trial did not identify an impact of the game versus control periods on recommended breathing practice, we believe that both of these novel interventions increased breathing maneuvers, including maneuvers that approximate huffing. Also, the breath activated games did draw more of the subjects' attention (measured as minutes logged in), compared to the control condition. The CF patients' input to game content and design (via interview) likely contributed to this effect.

Strategies used to validate that the HFEs approximated what pulmonary clinicians refer to as huffing suggest that the expiratory flows attained during the game and control period were similar to published estimates for the huff maneuver (peak flows of 2.9 ± 0.5 L/s and volumes of 1.08 ± 0.35 L). The relative decrease in flows for expiratory HFEs, compared to reported flow values associated with huffing,[7] may relate to differences in age (our subjects were younger), instrumentation (the spirometers we used were not rated for clinical diagnostic accuracy), or lack of the motivational effect of having an actual versus a "virtual" coach. Still, the correspondence between the flows measured by the study software and the reported huffing flows suggests that home-based spirometry games have strong potential to increase adherence to recommended huffing breath maneuvers.

Considering flows of HFEs during the game versus control periods, exploratory analyses of flows showed no difference in the game versus control periods. This finding suggests that the PFT changes associated with the game versus control period were not due to different effort or motivation during the game versus control condition. Therefore it is not clear that gaming software incites more vigorous flows, compared to the relatively unstimulating control software.

In this crossover trial, the game period was associated with improvement in the relative percentage change from baseline for vital capacity and a trend to improvement in FEV_1, compared to the control trial period. The small number of subjects precludes analysis for an order affect. Although number of HFEs was similar during both periods, it is possible that subjects performed HFEs differently, or that other breathing maneuvers during the game period may have contributed to an improvement in pulmonary function after the game exposure. Interest or emotional salience of the games may have contributed to improvement in PFT *technique* (eg, lip seal, effort, coordination of respiratory and oral muscles). Further studies will be needed to elucidate the possibility that playing breath activated spirometer games may lead to improvement in PFTs, and whether, if it is reproducible, such improvement may be mediated by differences in technique, play-related improvement in lung mechanics, or a combination of the two.

Generalizability is limited by the considerations that the subjects were largely white and recruited from a single CF center with a catchment including a largely rural population. Failure of completion of 6 study subjects may have further biased study results. In addition to the small sample size, our study is also potentially limited by short duration. While the provision of a spirometer for home use *with or without* gaming software led to increased engagement with airway clearance maneuvers, the relatively short period of this study leaves open the question as to whether subjects would continue to engage with a digital spirometer as a feedback tool for inciting airway clearance practice over longer periods.

The potential for negative effects of video games, including possible social isolation, sedentism, and competition for better educational opportunities, also needs to be considered. Some authors even consider a form of addiction among potential ill effects of video games,[8] though the concept of video game addiction in chronically ill children has not been explored or discussed in this literature. Despite social stigma and concerns regarding ill effects of video games, an emerging academic focus emphasizes their potential for educational and health applications, including opportunities for exercise, physical therapy, and enhanced mental well-being.[9] As with other treatments for CF that increase quality as well as length of life, the success of respiratory therapies depends upon patient effort and adherence.[10] Video games, to which our subjects have a strong affinity, facilitate communication and relationships among children and adolescents with CF.[11] To the extent that a CF-oriented digital game could support a patient's sense of competence, relatedness, and autonomy, this approach has potential to foster self-management and adherence in this clinical population.[12]

Conclusions

This feasibility study indicates that breath-activated digital games incorporating a digital spirometer have potential to facilitate airway clearance practice, and to address needs for relatedness in this socially isolated clinical population. Considering that "Only a small proportion of the variance in adherence has been accounted for in the literature,"[13] self-determination theory, on which this project was based, offers a viable foundation for assessing determinants of adherence, and for developing health behavior interventions in CF. Aligning health behaviors with patients' psychological needs—for example via health-oriented computer games—will in principle increase their adherence and self-management. In that ACT behaviors can be passively logged in the context of a computer game, this approach can also facilitate validation of efficacy/dose-response of forced exhalations in patients with CF.

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