Regional lung clearance during cough and forced expiration technique (FET): effects of flow and viscoelasticity

A Hasani, D Pavia*, J E Agnew, S W Clarke

Abstract

Background – In vitro studies have suggested that both the viscoelastic properties of lung secretions and the peak flow attained during simulated cough influence clearance. This study examines the possible association of the viscoelastic properties of sputum and maximum expiratory flow with measured effectiveness of mucus clearance induced by instructed cough and by forced expiration technique (FET) in patients with airways obstruction.

Methods – Nineteen patients (11 men and eight women) of mean (SE) age, % predicted FEV₁, and daily sputum wet weight of 64 (2) years, 52 (6)% and 37.5 (7.9) g respectively participated in the study. Mucus movement from proximal and peripheral lung regions was measured by an objective non-invasive radioaerosol technique. Each patient underwent three assessments: control, cough, and FET. During cough and FET, maximum expiratory flow was measured at the mouth level. Apparent viscosity and elasticity of the expectorated sputum samples were measured with a viscometer.

Results – Compared with the control run (mean (SE) clearance: 16 (3)% there was an increase in clearance from the whole lung during cough (44 (5)% and FET (42 (5)%), and also an enhanced clearance of inhaled, deposited radioaerosol from the trachea, inner and intermediate regions of the lungs, but not from the outer region. There were, however, no differences in regional clearance between cough and FET. Neither regional nor total clearance correlated with maximum expiratory flow, apparent viscosity, elasticity, or daily sputum wet weight.

Conclusions – These results confirm that cough and FET both promote effective clearance but suggest that, unlike in vitro studies, sputum production and viscoelasticity, as well as maximum expiratory flow, provide no guide to clearance efficiency in humans.

Cough is a reserve defence mechanism for removal of lung secretions.¹ It is particularly important as a back-up mechanism in airway diseases where mucociliary transport – the primary host defence mechanism for mucus clearance – is often compromised.² In health, cough comes into action during emergency situations such as following the inhalation of a foreign body.

Several studies have addressed the question of the efficacy of cough in clearing inhaled, deposited radioaerosols from the lungs of healthy non-smokers,³⁶ asymptomatic smokers,⁷ and patients with lung disease.⁴⁷⁵–⁶¹ Only four of these studies examined the effectiveness of cough in clearing lung secretions on a regional basis from the lungs.⁴⁷⁵–⁶¹ The other studies considered effectiveness only for mucus clearance from the lungs as a whole. The regional clearance studies have given conflicting evidence as to the effectiveness of cough in peripheral regions of the lungs.

The forced expiratory technique (FET) or “huffing” was introduced by physiotherapists as an alternative to coughing for the removal of excess lung secretions.¹² Its introduction was based on the claim that it reduces transluminal pressure compared with cough, thereby resulting in less airway compression and closure.¹⁰ Its effect on mucus clearance from the lungs as a whole using radioaerosols has been studied in patients with hypersecretion.¹³

We now report a study on the effect of cough and FET on regional mucus clearance in a group of patients with airways disease and varying amounts of daily sputum production. This study also examined the possible association between cough/FET and the maximum expiratory flow attained during these manoeuvres, the viscoelasticity of the expectorated secretions, and a measure of hypersecretion in these patients.

Methods

PATIENTS

Nineteen patients (11 men, eight women) with a mean (SE) age of 64 (2) years participated in the study. Twelve patients (six women) had chronic obstructive pulmonary disease (COPD) and seven (two women) had bronchiectasis. Fifteen patients were on inhaled bronchodilators of whom eight were also taking oral bronchodilator therapy, and 12 were maintained with inhaled corticosteroid therapy (one of them was also taking oral corticosteroids). One patient was on home nebuliser bronchodilator therapy and four patients (two
COPD and two bronchiectasis) were on no medication. The mean (range) increase in 
FEV₁ (following the administration of two 
puffs (100 μg each) of salbutamol was 9 (0– 
40)%). The group comprised four non-smokers 
with bronchiectasis, two current smokers with 
COPD (46 and 68 pack-years), and 13 ex- 
smokers with a mean (SE) of 31 (4) pack-years. 
The mean (SE) daily sputum weight wet pro-
duction for the group was 37.5 (7.9) g.

STUDY DESIGN
The study was designed in a randomised, three 
way, crossover (within patients) manner. Each 
patient attended our laboratories on three 
occasions separated by at least three days. 
During each visit the patient underwent an 
identical experimental procedure but per-
formed one of three treatment manoeuvres. 
These manoeuvres were cough, FET, and 
control which were all carried out with the 
patient sitting in the upright position. During 
the cough manoeuvre the patient was 
instructed to perform six coughs (each cough 
after full inspiration) per minute, repeated five 
times, with a rest period of one minute 
between each series of six coughs. During the 
FET manoeuvre the patient was instructed to 
perform six forced expirations per minute with 
the glottis open, starting from approximately 
mid lung volume and ending the exhalation 
close to residual volume, for five minutes with 
one minute rest period after every six forced 
expirations. During the control manoeuvre the 
patient just rested with no coughs or forced 
expirations.

Maximum expiratory flow during the cough 
and FET manoeuvres was measured at the 
mouth using a Vitalograph Compact spiromo-
eter which employed a Fleisch type pneumo-
tachograph. The mean value of the maximum 
expiratory flows measured for the 30 coughs or 
FET's was calculated for each patient. 
The patients were asked to refrain from 
taking any inhaled bronchodilators for at least 
two hours before each visit to the laboratories. 
Informed written consent was obtained 
from all the patients and the study was 
approved by the hospital's Ethical Practices 
Subcommittee.

RADIOAEROSOL TECHNIQUE
An objective radioaerosol technique, which 
has previously been described in detail, was 
used to assess movement of mucus within the 
patients' lungs. Polystyrene particles (5 μm in 
diameter) labelled with technetium-99m 
were inhaled under controlled conditions 
through the mouth. Each patient, while seated 
and wearing a nose clip, inhaled discrete 
breaths (0-45 litre) from the resting level of the 
lungs followed by a three second breath hold 
pause in order to enhance deposition of the 
radioaerosol in the peripheral airways of the 
lungs. The patient gargled and drank some 
water after inhaling the radioaerosol to clear 
any deposited particles from the oropharynx 
and oesophagus. Two axially opposed, collimi-
ated scintillation detectors located antero-
posteriorly to the chest were used to ascertain 
the radioactivity present in the lungs immedi-
ately after inhaling the radioaerosol and 24 
hours later. The 24 hour particle retention was 
expressed as a percentage of the initial value 
after being corrected for background radiation 
and physical decay of the radionuclide and was 
taken to represent "alveolar deposition" 
within the lungs. 

REGIONAL CLEARANCE
A large field-of-view gamma camera (Ohio 
Nuclear-110) linked to a computer (Nuclear 
Diagnostics) was used to assess the initial 
topographical distribution and subsequent 
clearance of the radioaerosol particles from the 
lungs. The initial distribution of the particles 
was expressed quantitatively as a penetration 
index which is the ratio of the amount of 
radioaerosol in an outer to inner region of the 
lungs divided by the same ratio for krypton-
81m gas. The measurement of the radioaero-
sol clearance was based on dividing the gamma 
camera images (64 × 64 format) of the lung into 
four arbitrary regions (fig 1). The four regions 
were a tracheal region which comprised mainly 
the trachea, an inner region which comprised 
mainly large airways, and intermediate and 
outer regions which comprised mainly small 
airways. A posterior 81mKr ventilation image 
was taken for each patient to assess the outer 
edges of the lungs (15% and 30% contours), 
and was adjusted to align with the aerosol 
images. A 5 × 8 matrix was fitted as closely as 
possible to the outer contours of the 81mKr 
image to define the four regions of the lung. 
The regional clearance of the radioaerosol par-
ticles was corrected for alveolar deposition and 
inter-regional movement.

Images of the distribution of the radioaero-
sol particles within the lungs were taken im-
mediately before and after each of the three 
treatment manoeuvres which were com-
menced within 10–15 minutes after the 
radioaerosol inhalation.

RHEOLOGICAL PROPERTIES OF SPUTUM
The patients were provided with containers 
and instructed to collect all sputum produced 
over a 24 hour period before each visit. The 
daily sputum production for each patient was 
described by the mean wet weight for the three 
sputum collections. All sputum samples 
expectorated during the cough and FET ma-
 noeuvres were collected and the wet weight 
was ascertained.

The viscoelastic properties — that is, appar-
ent viscosity (η) in mPa s and elasticity (G') in 
mPa — were measured only in sputum samples 
collected during the cough and FET man-
 oeuvres. A Contraves Low Shear 30 Sinus 
viscometer was used and measurements were 
taken at a frequency of 0.325 Hz and a tempera-
ture of 37°C. Whenever possible, three 
samples of 1 ml in volume were tested within 
one hour of production for each patient and 
the results were expressed as the mean.
ventilation image.

**Effect of flow rate**

Figure 1 Definition of four regions relative to contours (15% and 30%) of $^{99m}$Kr ventilation image.

**PULMONARY FUNCTION**

Forced expiratory volume in one second (FEV$_1$), forced vital capacity (FVC), and maximum mid expiratory flow rate (MMF$_{25-75}$) were measured with a Vitalograph spirometer for each patient. A Wright peak flow meter was used to measure peak expiratory flow rate (PEF). Flow rates at 25% and 50% of vital capacity (Vmax$_{25}$, Vmax$_{50}$) were measured with an Ohio 840 spirometer. For each of the pulmonary function indices the best of three technically acceptable measurements was recorded and expressed as % predicted value based on the subject’s sex, age, and height. The pulmonary function tests were carried out on each of the three visits after the radioaerosol assessments were completed in order not to disturb the lung secretions.

**DATA ANALYSIS**

The data were analysed using the non-parametric paired Wilcoxon and Spearman rank correlation tests. The level of significance was taken at $p < 0.05$.

**Results**

The mean (SE) pulmonary function indices for the patients during the three visits are given in Table 1. Pulmonary function remained unchanged between the visits.

The initial topographical distribution of the radioaerosol within the lungs was similar between the three runs. Mean (SE) alveolar deposition was 24 (2)%, 25 (2)%, and 24 (2)%, and penetration index was 0.38 (0.05), 0.39 (0.05), and 0.39 (0.04) for the control, cough, and FET runs respectively. Figure 2 shows the percentage of initial tracheobronchial deposition of the radioaerosol in the four regions of interest of the lungs for the three runs. The distribution for any one region between the three runs was similar.

Tracheobronchial clearance from the lungs as a whole measured with the scintillation detectors showed that clearance was significantly enhanced ($p < 0.01$) following cough (44 (5)% and FET (42 (5)% compared with control during which the patients did not cough (16 (3)%). Following the pulmonary function tests (which themselves involved nine forceful expiratory manoeuvres) tracheobronchial clearance was significantly faster ($p < 0.05$) for the control run (22 (4)% compared with both cough (10 (1)% and FET (9 (2)%).

Figure 3 illustrates the regional tracheobronchial clearance for the manoeuvres. Cough and FET significantly enhanced clearance of radioaerosol from the trachea, inner, and middle regions of interest of the lungs, but not from the outer region. There were, how-

---

**Table 1** Mean (SE) % predicted pulmonary function indices for the patients during the three study visits

<table>
<thead>
<tr>
<th>Pulmonary function indices</th>
<th>Control</th>
<th>Cough</th>
<th>FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEV$_1$</td>
<td>50 (5)</td>
<td>53 (5)</td>
<td>52 (6)</td>
</tr>
<tr>
<td>FVC</td>
<td>69 (5)</td>
<td>73 (4)</td>
<td>71 (5)</td>
</tr>
<tr>
<td>PEF</td>
<td>50 (5)</td>
<td>53 (5)</td>
<td>52 (5)</td>
</tr>
<tr>
<td>MMF$_{25-75}$</td>
<td>28 (5)</td>
<td>29 (6)</td>
<td>28 (5)</td>
</tr>
<tr>
<td>Vmax$_{25}$</td>
<td>22 (4)</td>
<td>21 (4)</td>
<td>23 (4)</td>
</tr>
<tr>
<td>Vmax$_{50}$</td>
<td>24 (5)</td>
<td>24 (5)</td>
<td>25 (4)</td>
</tr>
</tbody>
</table>

FEV$_1$ = forced expiratory volume in one second; FVC = forced vital capacity; PEF = peak expiratory flow rate; MMF$_{25-75}$ = maximum mid expiratory flow rate; Vmax$_{25}$ and Vmax$_{50}$ = flow rates at 50% and 25% of vital capacity.

**Figure 2** Mean (SE) initial tracheobronchial deposition of the radioaerosol within the four regions of the lungs for the three study days.

**Figure 3** Mean (SE) tracheobronchial clearance of the radioaerosol from the four regions of the lungs during the three manoeuvres.
ever, no differences in regional clearance between cough and FET.

The mean (SE) maximum expiratory flow recorded during cough (288 (29) l/min) was significantly (p < 0.01) higher than that during FET (203 (25) l/min). The higher flows measured during cough may be attributed to the higher lung volumes from which this manoeuvre commenced compared with the FET manoeuvre. The amount of sputum produced under instruction was identical between the cough and FET (3.4 (0.5) g) runs. Four of the 19 patients produced small amounts of sputum during the cough and FET manoeuvres which were insufficient for assessment of their viscoelastic properties. The apparent viscosity values for the sputum samples produced during the cough (693 (78) mPa s) compared with FET (684 (106) mPa s) runs were similar, as were the elasticity values (2979 (503) mPa or 3054 (560) mPa respectively).

There was no correlation between regional clearance and any of the following: maximum expiratory flow attained during the manoeuvres, the apparent viscosity and elasticity of sputum (fig 4), the amount of sputum expectorated during the manoeuvres, and the daily sputum production of the patients before the study. Table 2 gives the correlation coefficients for the comparison between clearance from the four regions of interest of the lungs and apparent viscosity and elasticity of sputum and maximum expiratory flow.

Discussion

Our observations of an enhancement of whole lung radioaerosol clearance following instructed cough confirm previous observations reported by other workers on smaller numbers of patients. Furthermore, the enhancement of whole lung radioaerosol clearance following FET is in keeping with the observations of Sutton and coworkers.

On theoretical grounds and using Weibel’s model of the human lung Leith postulated that cough may be effective in clearing secretions from the trachea down to the seventh or eighth airway generation. Scherer, however, using an in vitro model, suggested that cough in the presence of hypersecretion may be effective in clearing secretions from airways as far as the respiratory bronchioles. Our data on regional clearance show that cough is effective in clearing secretions from the inner and intermediate regions, in keeping with observations from other published data. However, clearance of secretions from the outer region due to cough failed to attain statistical significance.

This is in agreement with a much earlier cough study from our laboratory, but contrasts with those reported by Oldenburg et al and Rossman et al. The apparent discrepancy may have arisen because of differences in the selection of regions of interest between those studies, and because more of the radiotracer (20% approximately) was deposited in the outer region in the studies from our laboratory than in the other two studies (12.5% approximately).

The present study shows that FET on its own is effective in clearing secretions from the inner and intermediate regions of the lungs compared with control runs. As such its role in physiotherapy for the clearance of lung secretions with reduced peak flows must be advocated as an alternative to cough.

Early studies have indicated that, for cough to be effective in clearing inhaled radioaerosol from the lungs, the presence of hypersecretion is essential. More recently Bennett et al have shown a small improvement in whole lung clearance following 60 controlled coughs over a one hour period in healthy subjects, but not in a group of asymptomatic smokers. The number of coughs used by Bennett et al were far in excess of those used by other investig-

---

Table 2  Spearman correlation coefficients (r_s) for comparison between clearance (% from the four regions of the lungs and apparent viscosity and elasticity of sputum and maximum expiratory flow during cough and FET.

<table>
<thead>
<tr>
<th></th>
<th>Tracheal (Cough/FET)</th>
<th>Inner (Cough/FET)</th>
<th>Intermediate (Cough/FET)</th>
<th>Outer (Cough/FET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (mPas)</td>
<td>-0.24/-0.34</td>
<td>-0.05/-0.19</td>
<td>-0.27/-0.11</td>
<td>-0.01/-0.14</td>
</tr>
<tr>
<td>Elasticity (G')</td>
<td>-0.09/-0.31</td>
<td>0.004/-0.25</td>
<td>0.40/-0.01</td>
<td>0.10/-0.25</td>
</tr>
<tr>
<td>Maximum flow</td>
<td>-0.18/0.01</td>
<td>-0.01/0.07</td>
<td>-0.26/0.21</td>
<td>-0.28/0.18</td>
</tr>
</tbody>
</table>

p not significant for all regions.
Effect and viscoelasticity on production of the barry These predictable. The enhanced clearance during the pulmonary function testing (which required nine forceful expiratory manoeuvres) in the control run compared with the other two runs was predictable. These expiratory manoeuvres enhanced the clearance of the excess secretions which were still present in the airways during the control run, whereas in the other two runs instructed cough and FET had already helped to expel the excess secretions.

It is acknowledged that sputum may not be representative of the quality and quantity of mucus in the airways. Nevertheless, it serves as an acceptable surrogate. Alternative means of accessing secretions from the airways are invasive and, as such, may in themselves alter the properties of the secretions.

In vitro studies using simulated mucus with apparent viscosity in the range of 1–77 Pa·s have suggested that cough is more effective in less viscous mucus. The lack of a correlation between mucus clearance by cough or FET and viscoelasticity of expectorated secretions in our study may possibly be explained by the fact that the viscosity of the sputum samples ranged over a much narrower “window” (0.3–1.7 Pa·s). The in vitro studies may therefore wrongly predict what actually happens in vivo. The lack of a correlation between mucus clearance by cough or FET and elasticity of expectorated secretions in this study also contrasts with published in vitro studies which suggest that elastic forces in the mucus gel impede cough clearance. Clearance stimulated by cough has been reported to be impaired by increases in spinnability and adhesivity of mucus simulants.

Again in vitro studies using mucus simulants have indicated that cough clearance is significantly enhanced with increases in peak flow rate. Our studies in patients do not confirm this and, indeed, show that FET and cough result in similar radioaerosol clearances from the lungs despite a statistically significant reduction (mean 30%) in maximum expiratory flow during the former manoeuvre. A possible explanation for this might be that although the maximum flow rates during FET are lower than those attained during cough, their duration could be substantially longer than those for cough and thus make them equally effective in clearing lung secretions.

In conclusion, our study confirms in a substantial number of patients that cough and FET are equally effective in clearing lung secretions, although the latter can be achieved with less effort on the part of the patient. Furthermore, our study indicates the possible risks in extrapolating data from in vitro studies to what actually happens in clinical practice.