Cumulative and Reversible Effects of Lifetime Smoking on Simple Tests of Lung Function in Adults[1-5]

DOUGLAS W. DOCKERY, FRANK E. SPEIZER, BENJAMIN G. FERRIS, JR., JAMES H. WARE, THOMAS A. LOUIS, and AVRON SPIRO III

SUMMARY Data from a random sample of 8,191 men and women from 6 US. cities are used to fit a model describing the effects of cumulative and current cigarette smoking on pulmonary function. The data show that smokers suffer an irreversible loss of FVC and FEV_1, which is described by a linear function of their cumulative cigarette smoking as measured in pack-years. For a typical male 173 cm tall, the estimated loss of FEV_1 is 7.4 ml for each pack-year smoked. For a typical 161 cm tall, the estimated effect is 44 ml per pack-year. Current cigarette smoking adds an acute deficit over and above the cumulative effect of lifetime smoking. For any lifetime pack-years, ex-smokers have higher levels of FEV_1, 123 ml for a typical man, 107 ml for a typical woman, than do current smokers of a pack per day ($p < 0.001$). A man who starts smoking *one* pack of cigarettes per day at 25 yr of age would *at* age 60, after 35 pack-years of exposure, have an expected FEV_1 equal to that of a man 69.4 yr of *age* who had never smoked. If he stopped smoking at 60 yr of age, his expected level would increase to that of a 66.5-yr-old never-smoker. This model therefore estimates how much lung function is irreversibly lost by smoking, estimates how much could be regained with cessation of smoking, and predicts the future loss of lung function in both cases.

AM REV RESPIR DIS 1988; 137:286-292

Introduction

The 1984 Surgeon General's Report on the Health Consequences of Smoking (1) once again documented the association between smoking and chronic obstructive lung disease. The accumulated evidence from many studies leads to the following conclusion with respect to chronic obstructive lung disease morbidity (1, pg 9).

> Within a few pars after beginning to smoke, smokers experience a higher prevalence of abnormal function in the small airways than nonsmokers. The prevalence of abnormal small airways function increases with age and duration of the smoking habit, and is greater in heavy smokers than in light smokers. These abnormalities in function reflect inflammatory changes in the small airways and often reverse with the cessation of smoking.

It is clear from a number of investigations of young smokers that even short periods of smoking can lead to small but significant reductions in forced expiratory volumes (2, 3) and peak flows (4). In adults, there appears to be a direct relationship between number of cigarettes smoked and level of lung function (5, 6) or rate of decline of lung function (7).

This report provides an estimate of the degree of lung function impairment associated with smoking, developed through an analysis of adults participating in a longitudinal study of the health effects of air pollution. The analysis builds on a previous report that described the decline of lung function with age among the never-smoking, asymptomatic adults participating in the study (8).

Methods

Sampling

The sampling plan for this study, often called the Six Cities Study, has been described previously (8, 9). Briefly, historical air pollution data were used in 1974 to select 6 communities representing a range of air pollution levels. The 6 communities are Watertown, MA; Kingston-Harriman, TN; Steubenville, OH; a geographically defined portion of St. Louis, MO; Topeka, KS; and Portage, WI. Two cities were studied each year starting in September 1974.

Adults 25 to 74 yr of age were selected at random in each community and invited to come to a central office to complete a standardized respiratory disease questionnaire and to perform pulmonary function tests on a water-filled 8-L recording spirometer (9). Those not attending the central office were seen in their homes when possible. In all cases, spirometry was performed in the sitting position without a noseclip. Height was measured in stocking feet against a wall with a right angle FEV_1 and FVC were measured in a standard fashion (10, 11) and corrected to BTPS.

The questionnaire was administered by a trained interviewer. A detailed smoking history was recorded for each subject. Separate histories were collected for cigarettes, pipes, and cigars. (Data on hand-rolled tobacco also was collected but has been combined in this analysis with the cigarette data, assuming 1 g of tobacco per cigarette.)

For each individual. total years of smoking was calculated separately for cigarettes, pipes, and cigars, using the age of smoking cessation (or current age for current smokers) minus the reported age of first smoking and the number of years of reported abstention from smoking. Participants estimated weekly smoking amount for each year they had reported being a smoker. These values were then accumulated to produce a total consumption of cigarettes, pipes, and cigars. Total cigarette consumption is represented here as the sum of the packs of cigarettes per day over years of cigarette smoking, i.e., pack-years. Pipe tobacco consumption is represented analogously as ounces of tobacco per day — years smoked, and cigar consumption as ber per day over years smoked. C i smokers were defined as those subjects reporting more than 25 lifetime packs, with current cigarette smokers defined as those reporting

(Received in original form November 18, 1986 and in revised form August 10, 1987)

[1] From the Department of Environmental Science and Physiology and the Department of Biostatistics, Harvard School of Public Health, and Channing Laboratory, Department of Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts.

[2] Supported in part by Grants ES-01108 and ES-00002 from the National Institute of Environmental Health Sciences, Contract No. RP-1001 from the Electric Power Research Institute, and Cooperative Agreement No. CR 811650 from the Environmental Protection Agency.

[3] This report has not been subjected to the Environmental Protection Agency's required peer and policy review and therefore does not necessarily reflect the views of the agency, and no official endorsement should be inferred.

[4] Presented in part at the Annual Meeting of the American Thoracic Society, Anaheim, CA, May 12-15, 1985.

[5] Requests for reprints should be addressed to Dr. Douglas W. Dockery, Assistant Professor, Department of Environmental Science and Physiology, Harvard School of Public Health. 665 Huntington Ave., Boston, MA 02115.

more than one cigarette per day for the last month. Pipe smokers were similarly defined as those subjects reporting more than 25 lifetime ounces of tobacco, and cigar smokers as more than 25 lifetime cigars.

Smokers were asked "Do/did you inhale the cigarette smoke?" The response was graded in 4 categories: Not at all, Slightly, Moderately, and Deeply. A similar question was asked for pipes and cigars.

Smokers were also asked "Do you smoke filter-tip cigarettes currently?" The response was graded in 4 categories: Never, Less than half the time, More than half the time, and Always. Brands of tobacco products were not recorded.

TABLE 1

PREVALENCE OF CIGARETTE SMOKING AMONG WHITE ADULTS IN THE SAMPLE

	Men						Women					
	Never		Former		Current		Never		Former		Current	
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)
Total	1,001	27.0	1,277	34.4	1,436	38.7	2,302	51.4	680	15.2	1.495	33.4
Age, yr												
25–34	257	34.5	146	19.6	343	46.0	405	47.2	112	13.0	342	39.8
35-44	187	29.3	169	26.4	282	44.2	329	44.4	106	14.3	306	41.3
45–54	216	22.6	341	35.7	398	41.7	575	48.3	193	16.2	422	35.5
55–64	194	23.6	355	43.2	272	33.1	523	51.7	178	17.6	311	30.7
65–74	147	26.5	266	48.0	141	25.5	470	69.6	91	13.5	114	16.9

Statistical Methods

Previously reported analyses of pulmonary function among the 2,454 healthy, white, never-smokers participating in this study (8) showed that when FEV, and FVC measurements are standardized for height (HT) by dividing by HT^2, the decline of lung function with age among never-smokers is described by a simple linear function of AGE and AGE'. More importantly, these analyses showed that this method of standardization and only this method eliminated the relationship between FEV_1 or FVC and height. This report uses the same method of standardization for height and assesses its validity.

To make the results presented in this report more interpretable, FEV_1/HT^2 and FVC/HT^2 values are all adjusted to the height of a typical subject. FEV_1/HT^2 and FVC/HT^2 were multiplied by a sex-specific standard squared height – (173 cm)² or 3.0 m² for men and (161 cm)² or 2.6 m² for women. Thus, a man of 178 cm tall with an FEV, of 3.00 L would have a height-adjusted FEV, of 3.00 L x (173 cm)²/(178 cm)² = 2.83 L. In the remainder of this report, all references to FEV, and FVC are to these height-adjusted values. Age is centered at 50 yr so that the estimated regression coefficients are interpretable as values for a 50-yr-old subject.

The impact of cigarette smoking on FEV_1 ([illegible] FVC), as distinct from the effects of age, was estimated as the difference between the measured FEV_1 (or FVC) and the expected value for a healthy never-smoker. Tabular and graphic presentations of these residuals are presented to characterize the effects of smoking. Multiple linear regression techniques were used to fit the models suggested by these exploratory techniques. Potential confounders, such as years of smoking, inhalation patterns, filter tip usage, and pipe and cigar smoking also were investigated.

Results

The initial population-based sample consisted of 8,842 adults between 25 and 74 years of age in 6 U.S. cities. Of these, 8,508 were white, 8,191 (96.3%) of whom had acceptable FVC measurements that met criteria for acceptable pulmonary performance maneuvers (11). The proportion of white subjects and the frequency of acceptable pulmonary function examinations was evenly distributed across age decades and cities (8).

The age-specific prevalences of smoking of cigarettes, cigars, or pipes were very close to estimated prevalences for the 1974 U.S. population (12). Among the men, 38.7% were currently smoking cigarettes; of the women, 33.4% (table 1). More men had stopped smoking cigarettes (34.4%) than women (15.2%). The frequency of current cigarette smoking was highest for men between 25 and 34 yr of age, and for women between 35 and 44 yr of age, and lowest in the oldest age group, 65 to 74 yr. The frequency of former smokers increased dramatically with age in men, from 19.6% in the youngest men to 48.0% in the oldest. Among women, there was no apparent trend in frequency of former smokers with age. Among the men, 7.2% also reported that they currently smoked cigars, and 7.4% that they formerly smoked cigars. Current pipe smoking was reported by 7.8%, and former pipe smoking by 6.5%. Thus, for combined smoking of cigarettes, cigars, and pipes, 21.1% of the men were never smokers, 30.9% were former smokers, and 48.0% were current smokers. Among the women, only 3 subjects reported ever smoking cigars or pipes.

The mean age was higher for the former cigarette smokers than for the current cigarette smokers (table 2). Years of cigarette smoking and total pack-years were higher among the current cigarette smokers. For those currently smoking cigarettes, the mean daily consumption was 1.3 pack for men and 1.1 pack for women; 54% of the male smokers and 36% of the female smokers reported that they currently smoked 1 pack per day. As expected, respiratory symptoms were reported more frequently among the current cigarette smokers than among the former or never-smokers: 51.7, 27.3, and 18.3%, respectively, among men and 41.7, 19.3, and 18.7% among women.

For each person in the sample, the predicted height-adjusted lung function values, FEV, and FVC, were calculated from a model fitted to the pulmonary function values of asymptomatic never-smokers (8) and subtracted from the observed height-adjusted values to produce pulmonary function residuals. Mean values of these residuals were significantly less than zero, indicating lung function lower than predicted, as would be expected given the effect of smokers and symptomatic subjects in the sample (table 3). Subjects with a history of cigarette smoking had lower mean residuals than did those who had never smoked; current smokers had lower mean residuals than did ex-smokers (table 3). Mean lung function residual was lower among men than among women, but this should be expected since 73% of the men were current or former cigarette smokers versus 49% of the women.

Plots of mean lung function residuals against lifetime cumulative cigarette pack-years show a linear relationship be-

TABLE 2

MEAN (STANDARD DEVIATION) OF CIGARETTE SMOKING CHARACTERISTICS AMONG CURRENT AND FORMER CIGARETTE SMOKERS

	Current	Former
Age, yr		
Men	46.5 (12.9)	52.8 (12.7)
Women	46.3 (12.4)	49.9 (12.7)
Years smoked		
Men	28.4 (13.1)	21.7 (13.3)
Women	24.7 (11.8)	16.2 (12.3)
Pack-years		
Men	31.8 (21.8)	25.3 (23.7)
Women	20.8 (15.3)	12.8 (16.7)
Current pack/day		
Men	1.3 (0.7)	*0*
Women	1.1 (0.6)	*0*

TABLE 3

MEAN RESIDUAL HEIGHT-ADJUSTED LUNG FUNCTION IN MILLILITERS AND (STANDARD ERRORS) COMPARED WITH EXPECTED VALUES FOR HEALTHY, NEVER-SMOKERS

	Men			Women		
	Number	Residual FEV_1	Residual FVC	Number	Residual FEV_1	Residual FVC
Total	3,714	−293 (10)	−231 (11)	4,477	−98 (6)	−62 (7)
Cigarette Smoking						
Never	1,001	−34 (16)	−27 (19)	2,302	−24 (8)	−19 (6)
Ex	1,277	−257 (18)	−219 (19)	680	−54 (16)	−23 (17)
Current	1,436	−506 (16)	−384 (17)	1,495	−234 (11)	−146 (12)
Respiratory Symptoms						
No	2,440	−165 (11)	−128 (12)	3,291	−51 (6)	−24 (7)
Yes	1,274	−538 (19)	−428 (20)	1.186	−230 (13)	−165 (14)
Age, yr						
25–34	746	−128 (20)	−68 (22)	859	−38 (13)	−13 (15)
35–44	638	−222 (22)	−174 (25)	741	−94 (15)	−47 (17)
45–54	955	−304 (19)	−251 (20)	1,190	−122 (12)	−70 (13)
55–64	821	−416 (24)	−354 (24)	1,012	−120 (13)	−86 (14)
65–74	554	−397 (29)	−298 (29)	675	−107 (16)	−89 (17)

tween mean residual and pack-years of smoking (figure 1), suggesting a cumulative and irreversible effect of cigarette smoking that was directly related to the number of cigarettes smoked.

Among never-smokers, the distribution of pulmonary function residuals (figure2) was very close to Gaussian (that is, the normal distribution). As the cumulative pack-years of cigarette smoking increased, the mean of the distribution of residuals became more negative. In addition, the variability of pulmonary function measurements, measured by the interquartilerange, increased with cumulative pack-years of smoking. The distributions of pulmonary function residuals, however, remained close to Gaussian for all cumulative exposure groups, as has been shown previously by Burrows and coworkers (5).

The subjects in the sample who reported having ever smoked cigarettes (n = 4,888) were divided into current cigarette smokers (n = 2,931) and former cigarette smokers (n = 1,957). Comparison of sex-specificresidual FEV, for the current cigarette smokers versus ex-smokers (figure 3) showed a linear relationship between pulmonary function residual and pack-years. For each cumulative smoking group, however, the mean residual was lower for current cigarette smokers than for ex-smokers. This implies an additional deficit in lung function associated with active smoking which apparently is recovered over some time period after the subject stopped smoking. These data were fit by parallel straight lines (figure 3), with no significant difference between the regression coefficientson cumulative pack-years for current and ex-smokers ($p > 0.10$). The irreversible effect of cumulative pack-years was estimated to be a loss of 8.9 ml/pack-years for men and 6.3 ml/pack-years for women. The additional, reversible effect of active smoking was estimated to be 200 and 128 ml for men and women of typical size, respectively.

A multiple regression model of the full dataset of height-adjusted FEV, and FVC measurements (n = 8,191) was used to develop a unified model for normal aging and the effects of cigarette smoking. The model included AGE and AGE^2, the previously identified aging model for healthy never-smokers, plus 2 measures of smoking exposure, cumulative pack-years and current cigarette smoking in packs/day as regression variables (table 4). Because of apparent difference in the effect of cigarette smoking between the sexes, separate models were fitted for men and women.

The estimated effect of each pack-year of cigarette smoking on height-adjusted FEV, for men was 7.4 ml/pack-years (table 4). Current smoking of 1 pack/day was estimated to contribute an additional deficit of 123 ml. For women, the estimated effect of cumulative smoking on height-adjusted FEV, was 4.4 ml/pack-years. Current smoking of 1 pack/day would produce an acute loss of 107 ml. Thus, the estimated effect of cumulative smoking in women was about 60% of that for men, and the estimated effect of current smoking was slightly less for women. For both sexes, the effects of cumulative smoking (pack-years) and current smoking (packs/day) were smaller on FVC than on FEV, (table 4).

Among the subjects in this sample, 533 reported smoking more than 25 ounces of pipe tobacco during their life. Two of these were women. The mean cumulative burden was 6.7 ounce-years. Of those

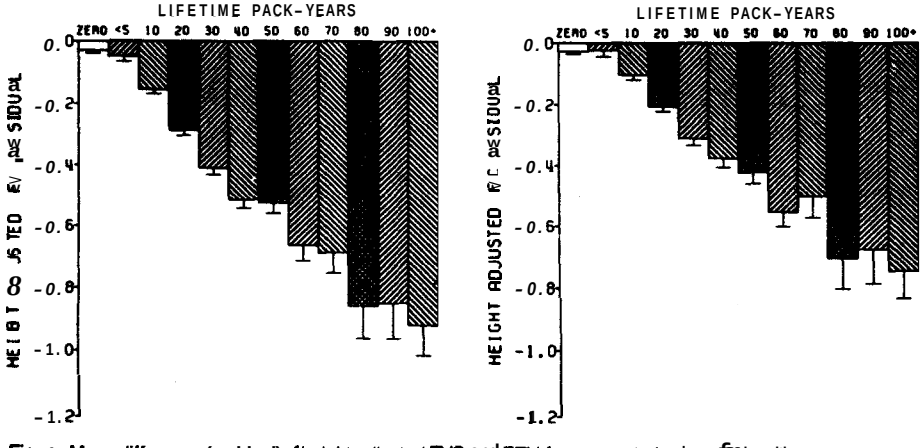

Fig. 1. Mean difference (residual) of height-adjusted FVC and FEV_1 from expected values for healthy never smokers versus lifetime pack-years.

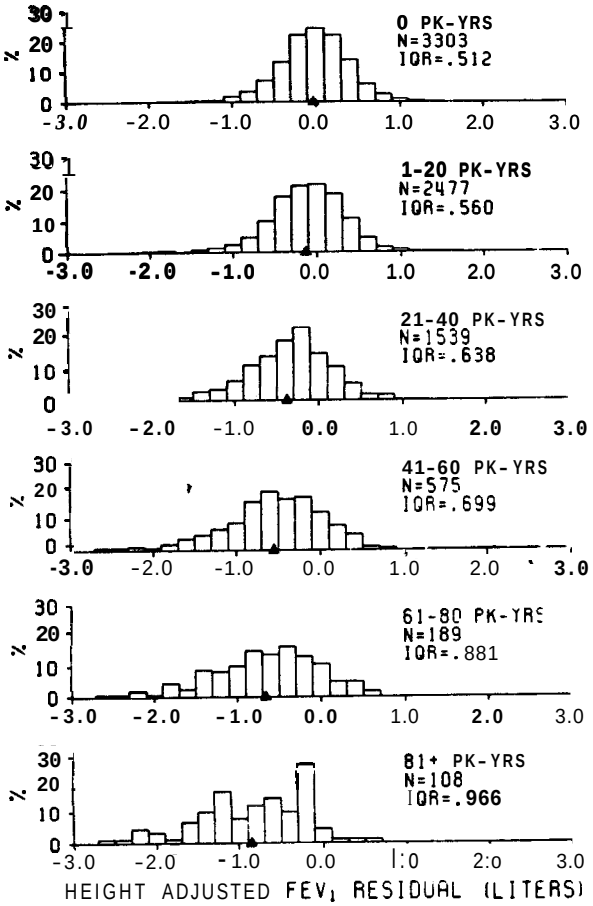

Fig. 2. Distribution of height-adjusted FEV_1 residuals from normal model for both sexes combined as a function of pack-years. Triangle indicates mean; IQR is interquartile range.

with a history of pipe smoking, **290 (54.4%)** reported pipe smoking at the time of their examination. Their mean consumption was 0.5 ounces/day. Similarly, **561** subjects reported smoking more than **25** cigars during their life. One was a Wman. The mean cumulative burden was **40.7** cigar-years. Of these, **275 (49.1%)** reported cigar smoking at the time of their examination. Their mean consumption was **2.7** cigars/day.

Regression analysis of the men's height-adjusted FEV, and FVC showed that after adjusting for age, age², pack-years of cigarette smoking, and daily cigarette smoking, there was no association with cumulative burden of either pipes or cigars ($p > 0.20$) nor with daily smoking of either pipes or cigars ($p > 0.20$). Equivalent results were found when the effects of cumulative and current pipe or cigar smoking were estimated separately for never, former, and current cigarette smokers.

Of the male smokers, **14%,** and of the female smokers, **30%,** reported that they inhaled slightly or not at all. These subjects had lower mean residual FEV, than did those who inhaled moderately or deeply (difference, -39 ± 18 ml). Similar results were found for FVC (difference, -63 ± 9 ml). Almost all of the smokers reported that they smoked filtered cigarettes: **91%** of the women and **84%** of the men. No association was found between lung function residual and use of filtered cigarettes.

Discussion

Many epidemiologic studies have found a progressive relative loss of pulmonary function with cumulative smoking. For example, Anderson and Ferris **(6)** found a progressive decrease of FEV_1/FVC with increasing pack-years of smoking in a random sample of **1,167** adults in Berlin, NH. In a study of a random sample of **2,369** whites **14** yr of age and older from Tucson, AZ, Burrows and coworkers **(5)** reported that the most important predictor of percent predicted FEV, was pack-years of smoking. Beck and colleagues **(13)** studied pulmonary function in a random sample of **4,609** whites 7 **yr** of age and older from **3** communities in the eastern United States. The most important predictors of loss of FEV, compared with healthy never-smokers were duration of smoking and pack-years.

Changes in pulmonary function have been observed even among smokers with very short durations of smoking. Seeley

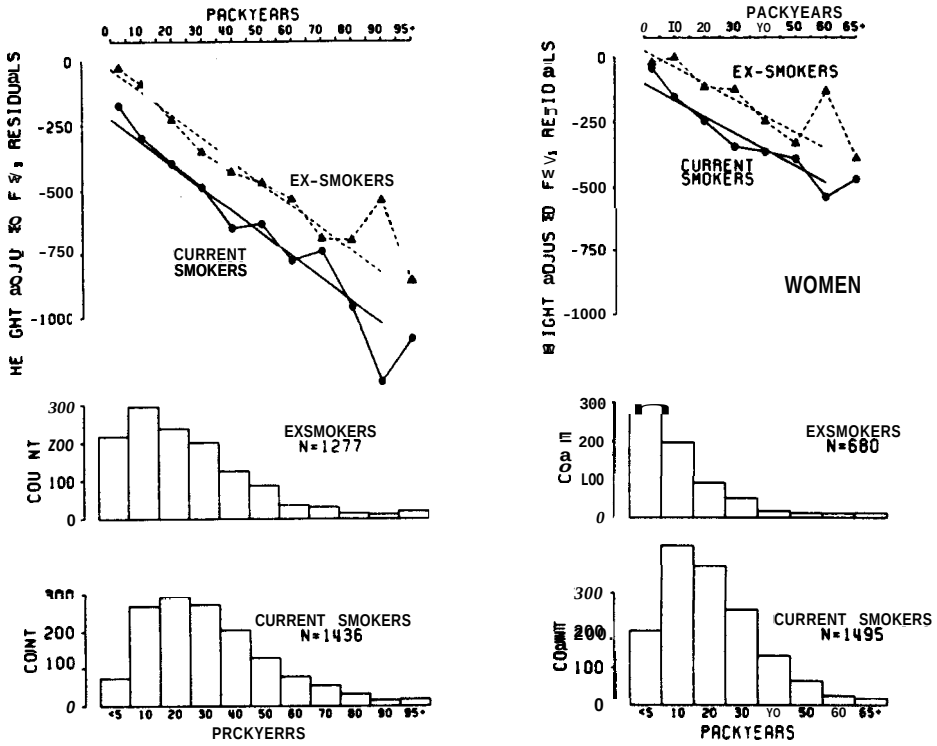

Fig. 3. Sex-specific mean height-adjusted FEV, residuals versus pack-years for current and ex-smokers. Distributions of number of subjects by pack-years are also presented.

TABLE 4

SIMPLIFIED MULTIPLE REGRESSION ESTIMATES (STANDARD ERRORS) FOR THE ENTIRE SAMPLE (3,714 MEN AND 4,477 WOMEN). AGE IS CENTERED AT 50 YR.

	Height-Adjusted FEV,*		Height-Adjusted FVC	
	Men	Women	Men	Women
Constant	3,477.6 (16.9)	2,506.2 (9.4)	4,393.2 (18.7)	3.123.3 (10.7)
[AGE-50] (yr)	−34.7 (0.8)	−28.3 (0.5)	−34.6 (0.9)	−28.7 (0.5)
[AGE-50]² (yr²)	−0.204 (0.053)	−0.121 (0.033)	−0.234 (0.058)	−0.270 (0.037)
Lifetime pack-years	−7.4 (0.5)	−4.4 (0.6)	−5.6 (0.6)	−2.9 (0.6)
Current packs/day	−123.3 (14.2)	−107.1 (13.1)	−96.7 (15.8)	−81.3 (14.9)
R²†	0.576	0.548	0.548	0.584
RMSE, ml‡	568	381	629	437

* Height-adjusted FEV_1 (ml) equals observed FEV_1 divided by height squared t i i (1.73m)² for men and (1.61 m)² for women. Height-adjusted FVC is defined equivalently.

† R^2 is squared correlation between predicted and observed FEV_1 or FVC.

‡ RMSE is root mean squared difference between predicted and observed FEV_1 or FVC.

and associates (2) examined teen-agers in high school, and reported that flow at 50% of vital capacity was lower in smokers than in nonsmokers. Peters and Ferris (3) found reduced flow rates among college seniors who smoked. Part of this reduction in function may be a reversible effect of active smoking. Beck and colleagues (13) found that current smoked-ad lower pulmonary functions than did those who had stopped, after adjusting for cumulative smoking, whereas Burrows and coworkers (5) did not.

Several studies have shown that smoking a single cigarette causes an immediate increase in airway resistance and a decrease in expiratory flow. Sobol and associates (14) found significant acute changes in FEV_1 with smoking. Tockrnan and coworkers (15) suggested that small airways dysfunction occurs relatively soon after the onset of smoking and is not affected by duration of smoking. Buist and colleagues (16) and Manfreda and coworkers (17) suggested that smoking itself and not the quantity of cigarettes smoked is the crucial factor in the development of early lung function impairment.

Pathologic studies have found smoking to produce both structural changes in the airways that indicate irreversible effects and inflammatory responses that are likely to be reversible. In a classic report on the pathologic abnormalities of chronic bronchitis, Reid (18) reported that inflammatory responses were found in the large central airways in mild cases of chronic bronchitis, and were found in small airways in advanced disease. She suggested that excessive mucus in the airways may cause impairment of breathing, especially if peripheral bronchioles are involved.

Berend and coworkers (19) did pulmonary function tests before lung resection and correlated the function tests with morphologic abnormalities. They found that structural changes in the peripheral airways were associated with abnormalities of both special tests of small airways function and spirometry, including FEV_1. Inflammation was the most important cause of obstruction to flow in the small airways. A reanalysis and expansion of this study (20) reported that the degree of inflammation correlated well with level of FEV_1.

Several studies have reported that performance on tests of small airways function returned toward normal in cigarette smokers without significant chronic airflow obstruction who quit smoking (16, 21–25). Thus, the observation that there are both cumulative irreversible, and acute, reversible effects of smoking on FEV_1 and FVC is consistent with epidemiologic, physiologic, and pathologic studies of small airways dysfunction.

To illustrate the magnitude of the combined acute and cumulative effects of cigarette smoking, consider a white man, 173 cm tall, with FEV_1 equal to the expected value for his height at age 25 (4.218 L). If he begins smoking 1 pack of cigarettes per day at age 25 (figure 4, curve B), the model predicts that his FEV_1 will drop by 123 ml. With each year, his cumulative smoking burden will increase by 1 pack-year. This leads to an increasing deficit with respect to the ex... value for a never-smoker (figure 4, A). By 60 yr of age, he will have ... of 35 pack-years of cumulative sm... exposure, and have an expected FEV... of 2.728 L, 382 ml (13%) lower than ex... pected for a never-smoker. This is equ... to his expected FEV_1 at age 69.4 if he had never smoked. His expected FEV_1 would have dropped 1.490 L from his starting value at age 25. Most of this change, 1.1... L (74%), is associated with aging ... 0.382 L (26%) is associated with ... rette smoking. If he continued sm... 1 pack per day until age 75, his exp... FEV, would be 1.989 L (figure 4, curve B). Even smoking 2 packs per day be... tween 25 and 75 yr of age (figure 4, curve D) would only give an expected value at age 75 of 1.496 L. If after smoking ... per day for 35 yr the subject ... smoking at 60 yr (figure 4, curv... model predicts that he would re... 123 ml associated with active c... smoking, but not the 259 ml de... sociated with his lifetime smok... den. This would bring his expect... back to the expected value at a... for a never-smoker. The time requ... this recovery cannot be determine... cross-sectional analyses, altho... studies of small airways dysfun... dicate a time scale of less than a y... 24).

Clinically, only a small fracti... smokers (approximately 10 to 15... velop serious respiratory impai... that is, very low pulmonary fu... values (26). This suggests that a ... within the population of smokers is ...

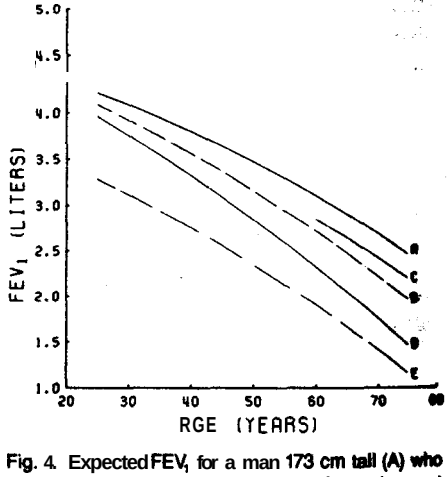

Fig. 4. Expected FEV_1 for a man 173 cm tall (A) who is at 50th percentile at 25 yr of age and who does not smoke, (B) who smokes 1 pack per day starting at 25 yr of age, (C) who stops smoking at 60 yr of age, (D) who smokes 2 packs per day starting at 25 yr of age, and (E) who is at the 5th percentile at 25 yr of age and smokes 1 pack per day.

susceptible to the effects of cigarette smoking.

Buist and Ducic (27) have described 3 possible ways that persons can come to have low values. First, their lung growth and development may have placed them at the lower end of the age-specific distribution curve for the maximum obtained lung function. Second, they may have started out with normal function, but had a faster than normal decline in function with age. Finally, they may have had a normal rate of decline with age plus a discrete loss of function caused by some insult, such as necrotizing pneumonia.

The model presented here assumes that all smokers lose pulmonary function at a rate determined by their sex, age, and smoking habits. Differences between subjects are assumed to be due to measurement error and random individual variation. The model therefore implies that those subjects who entered adulthood with lung function on the low end of the distribution of pulmonary function are at the highest risk of disability associated with respiratory impairment from cigarette smoking. We showed earlier that a 25-yr-old male, 173 cm tall, who has never smoked and has an FEV, equal to the expected mean value for a never-smoker, would, if he smoked 1 pack of cigarettes per day until 75 yr of age, have an expected FEV_1 of 1.989 L. Even smoking twice as much, his expected FEV, at age 75, 1.496 L, would not be low enough to be considered clinically impaired (28). However, a similar person at 25 yr of age was on the low end of the normal range, for example, the 5th percentile for asymptomatic never-smokers, based on our previously published distributions for asymptomatic never-smokers (8) (FEV_1 = 3.411 L), then after smoking 1 pack/day until 75 yr of age, his expected FEV_1 would drop to 1.182 L. At this level of FEV_1, he would probably be complaining of shortness of breath and would be Classified as severely impaired by the ATS schema (28). Because the additional loss of FEV, associated with smoking is small compared with that in normal aging, the risk of developing respiratory impairment based on this model is determined primarily by level of FEV_1 at maturity.

Thus, this simple model is sufficient to show that only a small fraction of Smokers will actually develop pulmonary function low enough to be impaired. It may be true that some proportion of smokers have faster rates of pulmonary function loss than the population mean for their sex, height, age, and smoking habits. That is a hypothesis that can only be addressed with longitudinal, not with cross-sectional, observations.

Burrows and coworkers (5) have reported that subjects with chronic productive cough have steeper rates of decline of FEV,, and therefore may represent a susceptible subgroup. In this analysis, a history of chronic productive cough (chronic cough with chronic phlegm) was associated with lower levels of pulmonary function after adjusting for age and smoking, for both men (−283 ± 30 ml for FEV, and −214 ± 33 ml for FVC) and women (−124 ± 26 ml for FEV, and −98 ± 30 ml for FVC), but there was no significant difference in the loss of pulmonary function between those subjects reporting and those not reporting chronic productive cough. Smoking is associated with both chronic productive cough and steeper decline of pulmonary function. Chronic productive cough, or any respiratory symptom associated with smoking, should not be considered as a risk factor, but rather as an intermediate variable. The risk factor producing both symptoms and more rapid loss of pulmonary function is smoking.

Clinically, this description of the effect of smoking implies that, on average, there is a modest additional loss of FEV, or FVC associated with cigarette smoking. The expected annual decline of height-adjusted FEV, caused by aging alone for a 50-yr-old man is 34.7 ml/yr and for a 50-yr-old woman is 28.3 ml/yr (table 4). The expected annual effect of smoking 1 pack of cigarettes per day is an additional annual loss of 7.4 ml/yr for men and 4.4 ml/yr for women. Thus, smoking a pack of cigarettes per day increases the annual decline of FEV_1 by approximately one-fifth that of the effect of normal aging for a 50-yr-old man, and one-sixth for a 50-yr-old woman. However, because this additional loss is cumulative, and irreversible, the net loss of lung function becomes substantial after 10 or 20 yr of smoking. If a patient stops smoking cigarettes, his annual rate of pulmonary function decline will return to that of a never-smoker. For the example we have been considering of a man who smokes 1 pack per day who stops smoking at 60 yr of age, the annual FEV, loss would be reduced by 17%, from 44.1 to 36.7 ml/yr. There should also be some improvement in level of FEV, over a period of approximately 1 yr. The size of this improvement is small in men, only about 123 ml for each pack/day previously smoked. The recovery of the acute loss is equal to 3.2 yr of aging for our male example. It would take this patient approximately 11 yr to lose an additional 500 ml of FEV, if he continued to smoke 1 pack/day. If he stopped at age 60, he would take approximately 17 years to reach that same level.

One class of patients at higher risk of disability from respiratory impairment are those on the low end of the distribution of pulmonary function for their age. While it is obvious that those with low lung functions compared with predicted are at risk, the model presented allows the physician to plot the predicted track of lung function decline for his or her patient given an initial observed value and assuming continued cigarette smoking.

For the epidemiologist, this analysis provides guidance in efficiently controlling for the effects of cigarette smoking when evaluating the effect of environmental agents or other risk factors on lung function. Most such studies do not have the luxury of many thousands of subjects randomly chosen from the community. While it may not be appropriate to use the prediction equations presented here for comparison to other samples, it is appropriate to use the functional form presented to remove the effects of sex, age, and smoking from the analysis.

This analysis describes the mean cross-sectional effect of smoking, but the behavior of an individual subject may not follow the cross-sectional model. These results do suggest that there should be some initial improvement of lung function among subjects who stop smoking, and that their subsequent annual loss of lung function should be equal to that of never smokers. The public health implications of these findings are obvious. Stopping smoking at any age reduces the progression of lung function loss, and also provides an immediate improvement in lung function that may amount to a significant fraction of the overall loss caused by smoking.

Acknowledgment

The writers are grateful to all those who have assisted in the examination of the adults, especially those who have directed the data collection in the 6 communities: George Allen, Eric Bjsmstad, Steve Hancock, Charles Humble, Marcia Lyndon, Lynn McClelland. and Vicki Senape. Many others have worked to prepare these data for analysis, including Hermia Chen, Renee Croxen, Martha Fay, Stefana Ferris, David Glicksberg, Dean Harris, Ellie Root (deceased), and Janice Weener.

Most importantly, we wish to acknowledge the continuing voluntary participation of the adults in our sample and the cooperation of the local public health professionals in each of our 6 communities.

References

1. U.S. Department of Health and Human Services. The health consequences of smoking: chronic obstructive lung disease Washington, DC: USGPO, 1984. DHHS (PHS) 84-50205.

2. Seeley JE, Zuskin E, Bouhuys A. Cigarette smoking: objective evidence for lung damage in teen-agers. Science 1971; 17241-3.

3. Peters JM, Ferris BG Jr. Smoking, pulmonary function, and respiratory symptoms in a college-age group. Am Rev Respir Dis 1967; 95:774-82.

4. Barkhouse CI. Peak expiratory flow in youths with varying cigarette smoking habits. Br J Med 1975; 1:360-2.

5. Burrows B, Knudson RJ. Cline MG, Lebowitz MD. Quantitative relationships between cigarette smoking and ventilatory function. Am Rev Respir Dis 19777; 115:195-205.

6. Anderson DO, Ferris BG Jr. Role of tobacco smoking in the causation of chronic respiratory disease N Engl J Med 1962; 267:787-94.

7. Fletcher C. Peto R. Tinker C, Speizer FE. The natural history of chronic bronchitis and emphysema. London: Oxford University Press, 1976.

8. Dockery DW, Ware JH, Ferris BG Jr, et al. Distribution of FEV_1 and FVC in healthy. white adult never-smokers in six U.S. cities. Am Rev Respir Dis 1985; 131:511-20.

9. Ferris BG Jr, Speizer FE, Spengler JD, et al. Effects of sulfur oxides and respirable particles on human health: methodology and demography of population in study. Am Rev Respir Dis 1979; 120:767-79.

10. Ferris BG Jr (principal investigator). Epidemiology standardization project. Am Rev Respir Dis 1978; 118(Part 2):55-88.

11. Ferris BG Jr, Speizer FE, Bishop Y, Prang G, Weener J. Spirometry for an epidemiologic study: deriving optimum summary statistics for each subject. Bull Eur Physiopathol Respir 1978; 14:145-66.

12. Harris JE. Cigarette smoking among successive birth cohorts of men and women in the United States during 1900-80. J Natl Cancer Inst 1983; 71:473-9.

13. Beck GJ, Doyle CA, Schachter EN. Smoking and lung function. Am Rev Respir Dis 1981; 123:149-55.

14. Sobol BJ, Van Voorhies L, Emirgil C. Detection of acute effects of cigarette smoking on airway dynamics: a critical and comparative study of pulmonary function tests. Thorax 19777;32:312-6.

15. Tockman M, Menkes H, Cohen B, et al. A comparison of pulmonary function in male smokers and nonsmokers. Am Rev Respir Dis 1976; 114: 711-20.

16. Buist AS, Ghezzo H, Anthonisen NR, et al. Relationship between the single-breath N, test and age, sa, and smoking habit in three North American cities. Am Rev Respir Dis 1979; 120:305-18.

17. Manfreda J, Nelson N, Cherniack RM. Prevalence of respiratory abnormalities in a rural and an urban community. Am Rev Respir Dis 1978; 117:215-26.

18. Reid LM. Pathology of chronic bronchitis. Lancet 1954; 1:275-8.

19. Berend N, Woolcock AJ, Marlin GE. Correlation between the function and structure of the lung in smokers. Am Rev Respir Dis 1979; 119:695-705.

20. Berend N. The correlation of lung structure with function. Lung, 1982; 160:115-30.

21. Ingram RH, O'Cain CF. Frequency dependence of compliance in apparently healthy smokers vs. non-smokers. Bull Eur Physiopathol Respir 1971; 7:195-210.

22. Bode FR, Dosman J, Martin RR, Macklem PT. Reversibility of pulmonary function abnormalities in smokers. A prospective study of early diagnostic tests of small airways disease. Am J Med 1975; 5943-52.

23. McCarthy DS, Craig DB, Cherniack RM. Effect of modification of the smoking habit on lung function. Am Rev Respir Dis 1976; 114:105-11.

24. Buist AS, Sexton GJ, Nagy JM, Ross BB. The effect of smoking cessation and modification on lung function. Am Rev Respir Dis 1976; 114:11[illegible]

25. Bake B, Oxhol H, Sixt R, Wilhelmsen. Ventilatory lung function following two weeks tobacco abstinence. Scand J Respir Dis 1978; 59: 311-8.

26. American Thoracic Society. Cigarette smoking and health. Am Rev Respir Dis 1985; 132:[illegible]

27. Buist AS, Ducic S. Smoking: evaluation studies which have demonstrated pulmonary function changes. In: Macklem PT, Permutt S, eds. The lung in transition between health and disease. New York: Marcel Dekker, 1979; 271-86.

28. American Thoracic Society. Evaluation of impairment/disability secondary to respiratory disease. Am Rev Respir Dis 1982; 126:945-[illegible]