Lung Function before and after a Large Chlorine Gas Release in Graniteville, South Carolina

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Abstract

Rationale: On January 6, 2005 a train derailment led to an estimated 54,915-kg release of chlorine at a local textile mill in Graniteville, South Carolina.

Objectives: We used the employee health spirometry records of the textile to identify enduring effects of chlorine gas exposure resulting from the incident on the lung function of workers employed at the textile mill.

Methods: Spirometry records from 1,807 mill workers (7,332 observations) were used from 4 years before and 18 months after the disaster. Longitudinal analysis using marginal regression models produced annual population mean estimates for FEV₁, FVC, and FEV₁/FVC ratio. Covariate adjustment was made for sex, age, smoking, height, season tested, technician, obesity, season × year interactions, and smoker × year interactions. The increased prevalence of mill workers having accelerated FEV₁ decline was also evaluated after the chlorine spill.

Measurements and Main Results: In the year of the accident, we observed a significant reduction in mean FEV₁ (−4.2% predicted; $P = 0.019$) when compared with the year before the incident. In the second year, partial recovery in the mean FVC % predicted level was seen, but the cohort's average FEV₁/FVC ratio continued to decrease over time. Severe annual FEV₁ decline was most prevalent in the year of the accident, and independent of mill worker smoking status.

Conclusions: The Graniteville mill worker cohort revealed significant reductions in lung function immediately after the chlorine incident. Improvement was seen in the second year; but the proportion of mill workers experiencing accelerated FEV₁ annual decline significantly increased in the 18 months after the chlorine incident.

Keywords: Graniteville; chlorine gas; lung function; rapid FEV₁ decline; disaster epidemiology, toxic gas exposure

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On January 6, 2005, a freight train traveling through Graniteville, South Carolina was inadvertently diverted off the main track onto an industrial spur leading into the train yard of Avondale Mills. After a 16-tanker derailment, an estimated 54,915 kg of

chlorine was released at the mill, which was located at the center of town (1, 2). For 4 hours, atmospheric conditions, terrain, and chlorine chemical properties caused the gaseous plume to remain at an estimated 900 ppm (1.5 m above ground) within a

2-km radius (3). There were nine fatalities. Hundreds received emergency medical care and dozens were hospitalized. More than 5,000 residents and mill employees were evacuated within 1 mile of the accident (4–6).

Translational and animal studies demonstrate that acute chlorine-induced lung injury can produce precipitous functional decline, and the potential for irreversible epithelial damage (7–11). In humans, chlorine concentrations as low as 10 ppm can overcome upper airway defense mechanisms and penetrate into lower respiratory structures (12, 13). Several studies suggest possible long-term airway hyperresponsiveness, obstructive ventilatory impairment, reactive airway dysfunction syndrome, or reduction in residual volume after acute exposure (14–17). Schwartz and colleagues (18) reported initial airway obstruction for 20 construction workers acutely exposed to chlorine gas. At 12 years' follow-up, 67% showed a significant reduction in residual volume (18). Nevertheless, otherwise healthy individuals are expected to recover, with few experiencing long-term respiratory complications (17, 19–22). Jones and colleagues (22) observed dozens of victims after a Florida train derailment. Within 3 weeks of chlorine exposure, no notable reductions were observed based on distance to the disaster or severity of injury (22).

Graniteville is a traditional mill town. Many residents were current or former mill workers. We believed that employee annual spirometry assessments could be used to assess community lung health before and after the train accident. Mill buildings were located in close proximity to the crash site, and nearly 200 employees were working at the time of the accident (4). Moreover, the accident occurred at 02:40 hours, and many mill worker residents were exposed to chlorine while sleeping in their nearby homes.

In an earlier preliminary analysis, we observed possible “chlorine effects” within this mill worker population immediately after the accident (23). Here, we refined our spirometry selection criteria to improve regression models and reduce some of the inherent bias contained within this secondary data set. We wanted to better define “chlorine effect,” using population-averaged repeated measures analysis. We also wanted to determine whether a significantly greater proportion of mill workers experienced accelerated annual FEV₁ decline after the accident. We hypothesized that immediate and persistent reductions in mill worker lung function would be evident in the years after the chlorine spill.

Methods

The South Carolina Department of Health and Environmental Control (SCDHEC, Columbia, SC) obtained employee health surveillance records from the Avondale Mills facility located at the crash site. As many Graniteville residents were also mill employees, these records were considered part of the SCDHEC public health surveillance program implemented during the disaster recovery.

Employee health assessments were performed in accordance with the 1980 U.S. Occupational Safety and Health Administration (OSHA) 29 CFR 1910.1043 Cotton Dust Standard for employees working within the U.S. textile industry and exposed to cotton fibers (24, 25). The U.S. standard requires employers to administer at-hire, for-cause, and annual employee health assessments to monitor for byssinosis. Each annual assessment contains an interviewer-led standardized respiratory questionnaire and spirometry procedure. This study was reviewed and approved by both SCDHEC and University of South Carolina (Columbia, SC) institutional review boards.

Inclusion Criteria

Spirometry assessments performed between January 2001 and June 2006 were used for this analysis. This represented 48 months before and 18 months immediately after the accident. We included at-hire and annual spirometry records; but not spirometry performed because of byssinosis symptoms. We also required a minimum of 240 days between the at-hire and second spirometry assessment (26). Further information regarding sampling strategy can be found in the online supplement (*see EXPANDED METHODS*).

At least two spirometry assessments were required, with one performed before the accident. Records from mill workers hired after January 2005 were not considered. Therefore, 2005 and 2006 spirometry represented mill workers in the workforce before the disaster, who maintained postchlorine employment. Also excluded were records obtained from testing technicians who performed less than 100 spirometry assessments. Decisions regarding data entry errors were made *a priori*, and based on biological plausibility.

Mill worker spirometry assessments were performed throughout the year and categorized into 3-month periods: spring (March, April, and May), summer (June, July, and August), fall (September, October, and November), and winter (December, January, and February). Annual employee assessments were most often performed during the first 3 months of each year (January, February, or March). At-hire and for-cause spirometry occurred throughout the year.

Smokers were identified as those who self-reported as “current” smokers at their most recent prechlorine annual assessment (binomial: yes/no). Pack-year information was also recorded when mill workers reported a history of smoking.

Spirometry Outcome Measures

FVC, FEV₁, and FEV₁/FVC ratio were the outcome measures under investigation. Both absolute volume (ml) and third annual National Health and Nutrition Examination Survey (NHANES III) % predicted estimates (adjustment for age, height, sex, and race) were provided for each outcome variable (27). Accelerated annual FEV₁ decline was defined as “rapid” (>90-ml reduction), or “severe” (>15% reduction, ~420 ml) as measured from the previous year's annual assessment.

Chlorine Exposure

Chlorine exposure status was not contained within employee records. Therefore, we assumed that “all” mill workers had potential chlorine exposure. The train accident occurred on January 6, 2005. Therefore, all 2005 and 2006 spirometry was performed after the accident.

Statistical Analysis

Analysis of variance and χ^2 tests compared demographic, smoking, and seasonal differences. Longitudinal trends were evaluated using marginal models containing a repeated statement and a heterogeneous autoregressive (1) covariance structure for the *R* matrix (28). Akaike information criteria identified the “best fit” for correlation matrices and regression models (28, 29). Covariate adjustment was made for age, height, sex, race (African American vs. white; there were no Hispanic whites within this cohort), prechlorine smoking status (smoker vs. nonsmoker), obesity

(>30 kg/m²), testing technician, and season (spring, summer, fall, winter).

We also included a season × year of assessment interaction term and a smoking status × year of assessment interaction term to investigate the potential variation of season and smoking effects over the years. Least-squares means with Tukey HSD (honestly significant difference) identified significant spirometry differences between years. Log-binomial models provided prevalence ratio (PR) estimates for annual accelerated FEV₁ reduction comparisons between pre- and postchlorine periods. Analyses were performed with SAS 9.3 (SAS Institute, Cary, NC).

Results

Between 2001 and 2006, the employee health surveillance program performed 12,863 spirometry screenings for 4,396 mill workers (Figure 1). First-year employee attrition was high, as we eliminated 2,355 (53.3%) mill workers employed less than 240 days or with only one at-hire spirometry record. Eliminated mill workers were significantly younger; more likely to be male; less likely to smoke, with a shorter

pack-year smoking history; and with a more equitable seasonal distribution of spirometry testing when compared with mill workers included in this analysis (see Table E1 in the online supplement). Also removed were 163 mill workers whose first spirometry was performed after the 2005 chlorine disaster (Figure 1).

In total, we analyzed 5,343 observations in the 4 years preceding the accident (n = 1,807), and 1,989 screenings (n = 1,104) after the chlorine incident (Figure 1). This represented 41% of the 2001–2006 employee spirometry records. Annual attrition remained substantial in the remaining mill worker cohort; 16.2% for the 4 years preceding the accident and 26.2% in the 18 months after (data not shown). On average, each mill worker performed four annual spirometry screenings during the 6 years under investigation. Shortly after the accident, the mill filed for bankruptcy and closed in July 2006. No employee spirometry was performed after this time. Thus, the mill closure limited our after-exposure spirometry assessment period to 18 months.

Demographic characteristics remained relatively stable, although in the time period after the accident, significantly more obesity

was seen compared with the 4 years before the accident (Table 1). Nearly 94% (n = 6,891) of spirometries were performed within the first 3 months of each year (January, 24.6%; February, 27.8%; March, 41.7%; data not shown).

Spirometry

Between 2001 and 2006, all spirometry mean percent predicted estimates were within normal limits (Table 2, left-hand side). However, mill workers suffered significantly greater than average decline in 2005 (year of the disaster) when compared with prechlorine years. In 2006, partial recovery was seen for FVC and FEV₁, but FEV₁/FVC ratio continued to decline in the second year (2006, –2.5% annual decline; Tukey $P > 0.05$) (Table 2 [right-hand side] and Figure 2). Significant fixed effects were also seen for sex, age, race, height, obesity, smoking, testing technician, season, seasonal period × year of assessment interactions, and smoking × year of assessment interactions (see Tables E2 and E3).

In 2005, mean FEV₁ was reduced by 129 ml (Tukey $P = 0.020$) (Table 2 [right-hand side] and Figure 2). This represented a 4.2% predicted decrease from the 2004 average (Tukey $P = 0.019$). The 68-ml decrease seen in FVC volume was not significant (Tukey $P = 0.68$), but this reduction was more than double the annual grand mean of –29 ml (Table 2 [right-hand side] and Figure 2). In 2006, there was a slight, but not statistically significant, improvement in FVC volume (+33 ml; $P > 0.05$), as well as a small corresponding increase in FEV₁ (+41 ml; $P > 0.05$).

Between 2002 and 2003 there was a significant increase in mean FEV₁ volume (+159 ml; Tukey $P = 0.040$). However, this volume increase was not reflected in a corresponding FEV₁ % predicted increase (Table 2). Recall that, between 2001 and 2004, individual mill workers were allowed to enter the cohort as long as they met inclusion criteria. Therefore, 2002–2003 volume changes most likely reflected one theory of the “healthy worker effect” known as the “healthy hire effect” rather than true functional changes (30, 31). Between 2002 and 2004, those entering the workforce had significantly larger FEV₁ and FVC mean volumes than mill workers leaving the workforce (see Tables E4–E6). In addition, newly hired mill workers were generally younger (see the online supplement).

Figure 1. Selection of the Graniteville mill-worker cohort analytical data set, based on the study inclusion criteria. Obs = observations; PFT = pulmonary function testing.

Table 1. Characteristics of Graniteville mill worker health surveillance cohort in the years before and after the chlorine disaster

	Prechlorine (2001–2004)	Postchlorine (2005–2006)	P Value (Student t test or χ^2)
Sample size, n	1,807	1,190	
Observations	5,343	1,989	
Age (yr), mean (SD)	40.6 (12.4)	42.4 (12.5)	<0.001*
Smoking (pack-years), mean (SD)	11.9 (13.1)	13.0 (12.6)	0.077
Height (cm), mean (SD)	171.9 (9.8)	171.6 (10.3)	0.317
BMI (kg/m ²), mean (SD)	28.5 (5.6)	28.6 (5.5)	0.367
Sex, n (%)			
Male (0)	1,117 (61.8)	712 (59.8)	0.196
Female (1)	690 (38.3)	478 (40.2)	
Obese (>30 kg/m ²), n (%)			
Yes	571 (31.6)	409 (34.4)	0.037*
No	1,236 (68.4)	781 (65.6)	
Race, n (%)			
White	739 (40.9)	462 (38.8)	0.153
African American	1,068 (59.1)	728 (61.2)	
Smoker, n (%)			
Yes	844 (46.7)	524 (44.0)	0.069
No	963 (53.3)	666 (56.0)	
Season, obs (%)			
Spring (Mar, Apr, May)	3,168 (59.3)	445 (22.4)	<0.001*
Summer (Jun, Jul, Aug)	192 (3.6)	48 (2.4)	0.030*
Fall (Sep, Oct, Nov)	102 (1.9)	4 (0.2)	<0.001*
Winter (Dec, Jan, Feb)	1,881 (35.2)	1,492 (75.0)	<0.001*
Mill building, obs (%)			
Hickman	342 (6.4)	129 (6.5)	0.861
Horse Creek	1,560 (29.2)	635 (31.9)	0.043*
Plant Services	150 (2.8)	32 (1.6)	<0.001*
Swint	1,667 (31.2)	543 (27.3)	<0.001*
Townsend	1,624 (30.4)	650 (32.7)	<0.001*

Definition of abbreviation: BMI = body mass index; obs = observations.

Note: Between the pre- and postchlorine groups, significant group differences were determined either by one-way analysis of variance or χ^2 analysis.

*Statistically significant at $\alpha = 0.05$.

Accelerated FEV₁ Decline

In 2005, 53% of workers ($n = 566$) were identified as “rapid” decliners (>90-ml annual FEV₁ volume loss), as compared with 41% during the prechlorine years (Table 3). Clinically significant or “severe” decline (i.e., $\geq 15\%$ annual FEV₁ reduction) was seen in 11.4% ($n = 122$) of the 2005 mill workers. This represented a 78% increase from 2004 proportions (Table 4). Postchlorine mill workers (both 2005 and 2006) were 24% more likely to experience a greater than 15% annual FEV₁ reduction (PR = 1.24 [1.11, 1.38]; $P < 0.001$; Table 3). Other significant independent determinants for accelerated FEV₁ annual decline were age, smoking (i.e., for rapid decline, not severe decline), sex, race, and primary building of employment (closest mill building from crash site, ~25–50 m) (Tables 3 and 4).

Smoking and Smoking $\times$ Year of Assessment Interaction

Almost 47% of mill workers were identified as current smokers before the train

derailment (Table 1). Smoking independently predicted FEV₁/FVC ratio, whereby, average results were 1.31% below those of nonsmokers ($F = 35.38$; $Pr > F$: < 0.001). Significant smoking and year of assessment interactions also occurred during the postchlorine period (see Tables E2 and E3). In 2005 and 2006, both FEV₁ and FVC were affected by smoking status. FVC volumes were reduced in smokers by an additional 67 ml in 2005 (Tukey $P < 0.001$), and again by 45 ml in 2006 (Tukey $P = 0.017$) (see Tables E2 and E3). Similar results were seen for FEV₁ mean volumes (–44 and –34 ml, respectively). Significant smoking $\times$ year of assessment interactions were not seen in the years before the chlorine incident (see Tables E2 and E3).

After the accident, smoking was an independent determinant for an increased prevalence in mill worker rapid FEV₁ decline ($P = 0.043$; Table 3), but not for severe FEV₁ decline ($P = 0.241$; Table 4). This indicated that additional factors, such as a possible chlorine $\times$ smoking

interaction may have contributed to the increased prevalence of severe FEV₁ decline immediately after the accident.

Season and Season $\times$ Year of Assessment Interaction

Spring was independently associated with FEV₁/FVC ratio. On average, there was a –0.5% decrease in the FEV₁/FVC ratio when compared with winter ($P = 0.042$; Table E3). We also identified significant seasonal main effects for FEV₁ and FVC (see Tables E2 and E3). On average, FVC % predicted and FEV₁ % predicted estimates were greater during the summer months compared with winter months (FVC summer mean, +4.84 [$P < 0.001$] and FEV₁ summer mean, +5.09% [$P < 0.001$]). Significant spring $\times$ year interactions were also seen (see Tables E2 and E3). Most notable were the spring 2005 FEV₁ and FVC mean volume increases (spring mean, +115 ml [$P < 0.001$] and spring mean, +119 ml [$P < 0.001$], respectively). Furthermore, the 2005 winter-to- spring volume increases

Table 2. Annual FVC, FEV₁, and FEV₁/FVC ratio least-squares mean volumes and NHANES III % predicted values, and annual change in absolute volumes and NHANES III % predicted estimates

Annual FVC, FEV ₁ , and FEV ₁ /FVC Ratio Least-Squares Mean Volumes and NHANES III % Predicted Values*					Annual Change in Absolute Volumes and NHANES III % Predicted Estimates†			
Year	n	Adjusted FVC: L (SE) % Predicted (SE)	Adjusted FEV ₁ : L (SE) % Predicted (SE)	FEV ₁ /FVC: % (SE)	Between- Year Δ	Δ FVC‡: ml (SE) % Predicted (SE)	Δ FEV ₁ §: ml (SE) % Predicted (SE)	FEV ₁ /FVC : % Change (SE)
2001	1,220	3.352 (0.04) 82.2 (0.96)	2.750 (0.03) 82.2 (1.02)	81.6 (0.59)				
2002	1,435	3.326 (0.03) 82.0 (0.69)	2.687 (0.02) 80.8 (0.73)	80.6 (0.41)	2001–2002	–26 (0.04) –0.22 (1.0)	–62 (0.03) –1.41% (1.1)	–1.4% (0.64)
2003	1,395	3.447 (0.06) 82.5 (1.57)	2.845 (0.05) 83.1 (1.68)	82.3 (1.0)	2002–2003	+121 (0.06) +0.48 (2.4)	+159 (0.05)[¶] +2.36% (1.7)	+1.7% (1.0)
2004	1,303	3.438 (0.02) 84.1 (0.61)	2.827 (0.02) 83.9 (0.66)	81.7 (0.37)	2003–2004	–9 (0.06) +1.6 (1.6)	–22 (0.05) +0.82% (1.7)	–0.5% (1.0)
Chlorine spill, January 2005								
2005	1,104	3.370 (0.05) 81.6 (1.21)	2.695 (0.04) 79.8 (1.29)	80.1 (0.78)	2004–2005	–68 (0.05) –2.53 (1.2)	–130 (0.04)^{**} –4.2 (1.3)^{††}	–1.6% (0.8)
2006	885	3.403 (0.08) 82.0 (2.26)	2.734 (0.07) 79.5 (2.42)	77.7 (1.4)	2005–2006	+33 (0.09) +0.42 (2.5)	+41 (0.08) –0.29 (2.7)	–2.5% (1.6)

Definition of abbreviations: Δ = change; NHANES III = Third National Health and Nutrition Examination Survey.

Entries in boldface represent significant annual change (i.e., $P \leq 0.05$ after Tukey multiple comparison adjustment).

*All estimates were adjusted for age, sex, race, height, obesity, smoking history, season, technician, season × year of assessment interaction, and smoker × year of assessment interaction ($n = 1,807$; observations, 7,332).

†Annual change in absolute volumes and NHANES III % predicted estimates (percent predicted estimates derived from Hankinson and colleagues [27]).

‡FVC: Not statistically significant (grand means, –29 ml/yr and 0.16%/yr predicted).

§FEV₁: Statistically significant (grand means, –29 ml/yr and –0.35%/yr).

||FEV₁/FVC: Not statistically significant (grand mean, –0.17%/yr).

[¶] $P < 0.040$.

^{**} $P < 0.020$.

^{††} $P < 0.019$.

occurred within the 4 months immediately after the chlorine spill (Tables E2 and E3).

Discussion

Significant reductions in mill worker spirometry were found after the Graniteville chlorine disaster. However, this was observed only when we compared spirometry from before and after the accident. Throughout 2001–2006, population mean estimates remained within NHANES % predicted normal limits. However, in 2005, the adjusted FEV₁ mean volume loss was more than three times that seen in the years immediately preceding the chlorine spill. And FVC mean volume loss was double that seen before the accident. In 2006, there was partial recovery in these parameters (FEV₁, +41 ml; FVC, +33 ml), but the FEV₁/FVC ratio continued to trend toward an obstructive ventilatory pattern. Without access to occupational pre-event spirometry

assessments, we would have “wrongly” concluded that no significant “chlorine effect” was present within this cohort.

Normal physiological FEV₁ and FVC volume loss of approximately 30 ml annually (~1.5%) is expected to begin at 25 years of age, and continue throughout adulthood (32–34). FEV₁ decline increases with age, with expected annual losses between 33 and 38 ml for healthy adults over 65 years of age (32, 35). Also, in smokers or those with underlying lung disease, greater annual FEV₁ reductions are observed when compared with healthy nonsmoking populations (36, 37).

In 2005, we observed a significant –4.2% reduction in adjusted mean FEV₁ % predicted estimates. This far exceeded the losses observed in the preceding 4 years (see Table E3). In addition, FEV₁/FVC ratio was also reduced by –1.6% and mean FVC % predicted by –2.4%. These FVC and FEV₁/FVC reductions were not statistically significant, but when compared with prechlorine years they revealed a consistent

trend for loss in lung function immediately after the chlorine event.

Most remarkable was the proportion of mill workers suffering rapid or severe FEV₁ annual decline after the disaster. Multiple studies report an increased mortality rate for individuals who exhibit consistent accelerated FEV₁ decline (38–41). In addition, an increased incidence of respiratory symptoms such as increased cough, phlegm, wheezing, and shortness of breath has been reported in these individuals (38, 39).

Mill worker mortality or reasons for “loss to follow-up” were not known. However, records indicated that mill worker attrition increased by 62% in the year of the accident (data not shown). In addition, rapid FEV₁ decline was seen in 53% of the 2005 mill worker cohort (i.e., year of the chlorine incident). This represented a 30% increase from 2004 proportions. However, between 2001 and 2006, only 28 mill workers reported new-onset respiratory symptoms during their respiratory annual assessment (data not

Figure 2. Annual trends in mill worker spirometry (i.e., means with 95% confidence interval) for FVC volume, FEV₁ volume, and FEV₁/FVC ratio. Covariate adjustment was made for sex, height, race, obesity, smoking, testing technician, season of testing, and season $\times$ year effect modification. Adapted by permission from Reference 23.

shown). Therefore, we cannot comment on the prevalence of respiratory symptoms in those who displayed rapid FEV₁ decline. However, previous work with Graniteville residents with known chlorine exposure suggested that underreporting of respiratory symptoms was common in community members with abnormal spirometry (42).

At present, the American College of Occupational and Environmental Medicine (ACOEM) suggests that annual FEV₁ reductions of 15% or more represent “clinically significant levels of concern” and that these workers should be immediately medically evaluated (43). In 2005, there was a 78% increase in mill workers who returned to work and yet suffered more than 15% annual FEV₁ loss from 2004 levels. This supports our hypothesis that “chlorine effect” estimates were likely underestimated due to a “healthy worker” effect.

Das and Blanc (17) report that susceptible individuals such as smokers or

those with underlying chronic lung disease will suffer greater functional losses when exposed to toxic gases such as chlorine. Our findings support this claim, as smokers experienced additional FEV₁ and FVC loss in the years after the accident (*see* Tables E2 and E3). This observed interaction suggests a multiplicative effect on lung function based on smoking status and possible chlorine exposure. Smokers could have quit smoking after the event, but this would have biased our result toward the null. Moreover, we classified mill worker smoking status from questionnaires conducted before the chlorine release to help mitigate smoker misclassification.

Seasonal spirometry mean volume differences were seen both before and after the train accident. Between 2001 and 2006, spring FEV₁ and FVC parameter estimates were consistently greater than winter category estimates (*see* Tables E2 and E3). Nevertheless, in the year of the accident,

FEV₁ and FVC winter-to-spring mean volume increases were at least double those observed in the 4 years preceding the chlorine incident (mean 2005 FVC increase, +115 vs. +38 ml, respectively, and mean 2005 FEV₁ increase, +119 vs. 51 ml, respectively) (*see* Tables E2 and E3).

These results may possibly be explained in two ways: (1) those tested immediately after the chlorine spill were “healthier” workers who were able to return to work, whereas other, “less healthy” workers were unable to return to work right after the accident; or (2) partial “functional recovery” was present within 2 months after chlorine exposure. The latter theory is somewhat supportive of findings by Jones and colleagues (22), wherein lung function recovery was seen within weeks of acute chlorine gas exposure. However, the mill worker “recovery” was incomplete; and mean FEV₁ and FVC volumes remained lower than expected based on the average -29 ml annual rates seen before the accident.

Table 3. Graniteville mill workers identified as FEV₁ rapid decliners in the years before and after the chlorine disaster

Year(s)	Total Observations	Rapid FEV ₁ Annual Decline (>90-ml Annual Decline)	
		Frequency (%)	Prevalence Ratio (95% CI) [Wald P Value]
2001–2004	4,610	1,886 (40.9%)	(Ref)
2005–2006	1,954	941 (48.1%)*	1.10 (1.04, 1.16) [$\chi^2 = 10.6, P = 0.001$] [†]
Other FEV₁ Determinants			
2001	1,005	406 (40.4%)	Age [$\chi^2 = 13.6, P < 0.001$] [†]
2002	1,211	590 (48.7%)	Smoking [$\chi^2 = 4.1, P = 0.043$] [†]
2003	1,246	434 (34.8%)	Sex [$\chi^2 = 12.2, P < 0.001$] [†]
2004	1,148	456 (39.7%)	Race [$\chi^2 = 1.1, P = 0.290$] Building [$\chi^2 = 4.1, P = 0.042$] [†]
2005	1,069	566 (53.0%)	30% increase since 2004
2006	885	375 (42.4)	4% increase since 2004

Definition of abbreviations: CI = confidence interval.

Heavy line indicates boundary between prechlorine (2001–2004) and postchlorine (2005–2006) years.

*An 18% increase in rapid FEV₁ decline during the years after the chlorine event when compared to its average prevalence between 2001 and 2004 ($P < 0.0001$).

[†]Statistically significant at $\alpha = 0.05$.

The major strength of this work was that we had access to employee spirometry records, performed to OSHA standards, from before the disaster. This allowed us to control for within-subject variance to estimate the expected annual loss in individual mill worker lung function. We know of no other study, wherein individuals who were acutely exposed to high levels of chlorine gas had preexisting baseline spirometry available for comparison. Furthermore, our large sample size provided

adequate power to determine between-year spirometry changes. We also had preexisting height, weight, and smoking history, allowing adjustments for these variables.

Our greatest limitation was that we did not have individual chlorine exposure information. Hence, we assumed equal chlorine exposure for all mill workers. This assumption is unrealistic, as not all mill workers were exposed to chlorine or exposed at the same chlorine gas concentrations for the same duration. Therefore, our results

likely underestimated the true chlorine effects on “exposed” mill workers. We also believe a “healthy worker” effect further biased our results; as only “exposed” mill workers who could perform the required physical labor were able to return to the mill. Because of the mill’s location, six of the nine acute exposure fatalities were mill workers.

Generalizability to the entire Graniteville population was limited because these were occupational cohort data. Yet, more than 97% of mill workers performed annual spirometry. In addition to employees directly exposed to cotton fiber; office workers, human resource personnel, and management were represented within the annual spirometry screening data (data not shown). Therefore, we believe our analysis to be generalizable in the 18- to 65-year age group. According to the 2010 U.S. Census records this represented 58% of the Graniteville population (44).

Additional limitations were also observed. We did not have mill worker medical history or reliable respiratory symptom information beyond what was reported in each employee’s annual byssinosis questionnaire. Furthermore, more than 2,300 mill workers (43% of the mill worker cohort) had only one spirometry assessment and were not included within the analytical data set. The postchlorine spirometry assessment period was also limited to 18 months because of mill closure. Despite these limitations, we still observed significant reductions in spirometry measures immediately after the incident.

Conclusions

The Graniteville mill worker cohort revealed significant reductions in lung function immediately after the chlorine incident. Improvement was seen in the second year; but the proportion of mill workers experiencing accelerated FEV₁ annual decline significantly increased during the 18 months after the chlorine incident. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

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Table 4. Graniteville mill workers identified as FEV₁ severe decliners in the years before and after the chlorine disaster

Year(s)	Total Observations	Severe FEV ₁ Annual Decline (>15% Annual Decline)	
		Frequency (%) [*]	Prevalence Ratio (95% CI) [Wald χ^2, P Value]
2001–2004	4,610	289 (6.3%)	(Ref)
2005–2006	1,954	185 (9.5%)	1.24 (1.11, 1.38) [$\chi^2 = 14.2, P < 0.001$] [†]
Other FEV₁ Determinants			
2001	1,005	71 (7.1%)	Age [$\chi^2 = 124.8, P < 0.001$] [†]
2002	1,211	88 (7.3%)	Smoking [$\chi^2 = 1.4, P = 0.241$]
2003	1,246	57 (4.6%)	Sex [$\chi^2 = 185.6, P < 0.001$] [†]
2004	1,148	73 (6.4%)	Race [$\chi^2 = 7.4, P = 0.007$] [†] Building [$\chi^2 = 8.8, P = 0.003$] [†]
2005	1,069	122 (11.4%)	78% increase since 2004
2006	885	63 (7.1%)	11% increase since 2004

Definition of abbreviations: CI = confidence interval.

*A 51% increase in severe FEV₁ decline during the years after the chlorine accident when compared to its average prevalence between 2001–2004.

[†]Statistically significant at $\alpha = 0.05$.

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