HABER’S LAW, SHIFT WORK, AND COTTON DUST

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Recently much of the textile workforce in the United States has changed from an 8 hour work day to 12 hour work days. The pattern of work has shifted from a 40 hour work week to a 36 or 48 hour workweek (3 or 4 days at 12 hour shifts). The Cotton Dust Standard is based on an 8 hour time weighted average of 0.2 mg/m^3 for a 40 hour workweek. Some enforcement agencies have indicated that for those working 12 hour shifts, either cotton dust levels must be reduced from 0.2 to 0.133 mg/m^3 or respirators should be used for a portion of the shift. The basis for the dust level adjustment is Haber’s law which states that toxicity or effect (EL) is a direct function of time (t) and concentration (C): EL = t C. This paper reviews the use of Haber’s law for adjusting exposure levels for novel workshifts in the cotton industry, the influence of shiftwork on pulmonary function measures, and the strategy of partial shift use of respirators as a compliance mechanism for novel workshifts.

Introduction

Over the past several years a large portion of the textile industry has changed from an 8 hr/day, 5 day 40 hour workweek to 12 hr workshifts at variable workweek intervals (e.g. 3 days on- 2 days off; 4 days on - 2 days off). The average workweek over a two-week period is 42 hours long. This change has raised questions about the adequacy of the current cotton dust standard for protecting the health of workers on novel workshifts. The cotton dust standard is set at an 8 hour time weighted average exposure level of 0.2 mg/m^3. This exposure level was designed to prevent chronic effects from exposures of 8 hrs/day, 40 hours/week for a working lifetime. In addition to controlling dust, the Standard uses monitoring of the acute overshift change in FEV_1 as an indicator of possible risk for chronic respiratory disease. Workers showing overshift changes of greater than 5% from their preshift baseline must be retested at six-month intervals rather than annually. Several intervention strategies have been proposed to resolve exposure concerns associated with novel workshifts. This paper will review the basis of these intervention strategies and discuss non-exposure-associated factors that can affect acute pulmonary responses.

Regulatory Adjustments for Novel Shifts

Two possible solutions have been considered for reducing exposure during 12 hour or other novel workshifts. First, exposure can be reduced by the partial shift use of respirators. Embedded in this solution is the question of which part of the shift should be targeted for partial use. If the first or the last four hours of the shift is chosen, the exposure period (assuming efficient respirator usage) is the same as the normal 8 hour schedule, however, clearance times between shifts would be different. It is unclear how these patterns of respirator usage would affect the pulmonary response to cotton dust. For example, if a worker wears a respirator for the last four hours of a 12 hour shift, and the effects of dust exposure on pulmonary function occur predominantly in the first four hours then the pulmonary response may be no different from wearing no respirator. Conversely, if a worker wears a respirator for the first four hours then their baseline value for the next morning could be depressed because of the shorter recovery time. Clearly a better understanding of the effect of cotton dust on the pattern of change in pulmonary function over a 12-hour shift is needed to make physiologically appropriate decisions regarding partial shift respirators. The alternative to partial shift use of respirators is to require full shift respirator use, a solution that is unsatisfactory to regulators, the industry, and the workers.

A second option would be to reduce the exposure level by some designated amount to account for the additional 4 hours of exposure. The simplest solution would be a proportionate application of Haber's Law. Initially developed in 1921 by Flury and later attributed to Haber in 1924, the relationship describes a proportionate association between concentration, time of exposure and toxicity (1).

$$EL = aC^{n} \times T$$

Where:

- C = Concentration (a and n are empirically derived coefficients)
- T = Time
- EL= Effect Level

From its initial use, the proportionate use of Haber's law was questioned (except for war gases) and subsequent expressions have included coefficients to account for differences in toxic endpoints, physiologic parameters (e.g. breathing rates), and other variables that influence the toxicity of a compound. However, to adjust exposure levels for novel workshifts, regulatory agencies have used a proportionate application of Haber's law. For the cotton dust standard, 12 hours shifts would require that the existing dust standard of 200 :g/ m^3 be reduced by one-third to 133:g/m^3 (200 x 8 = 133 x 12). Such a reduction does not take into account other variables that may reduce or enhance the toxicity of a cotton dust.

Other solutions for adjusting exposure levels for novel workshifts have been proposed. Brief and Scala (2) focused on a proportionate adjustment based on the length of the

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workweek. This adjustment, shown in the following equation, takes into account the recovery time between workweeks.

$$RF = 40/N * 168 - N/128$$

Where:

- RF = Reduction Factor
- N = Number of hours exposed during novel workshift
- 40 and 128 = Hours of exposure and non-exposure in a week
- 168 = number of hours in a week

Application of this to the cotton dust standard for 12 hour workshifts would require a reduction of the dust level to 187 :g/m^3.

$$RF = 40/42 * (168 - 42)/128$$

$$Dust\ Level = 0.937 * 200 = 187\, ug/m^3$$

Hickey and Reist (3) sought to include biologic uptake and excretion as variables in adjusting exposure levels for novel workshifts. For substances with half-times less than approximately 7 hours and those greater than 60-70 hours, no adjustment would be required of an exposure standard. For substances with biological half-times between this range the maximum adjustment factor would be 0.7 of the 8 hour standard. For cotton dust this maximum adjustment would require a reduction of the dust level from 200 :g/m^3 to 140 :g/m^3 which is similar to the proportionate adjustment using Haber's law. However, if the biological half-time of cotton dust in the lung is 60 hours or greater then only minimal adjustment would be required, confirming the previous calculations regarding dust burden for different shift lengths and clearance time between weeks.

Alternative models for adjusting novel workshifts have been proposed, including the use of physiologically based pharmacokinetic (PBPK) models and elaborate modifications of Haber's law. Several of these have been review in the proceedings from an Environmental Protection Agency Workshop entitled "Relationship Between Exposure Duration and Toxicity" (4). Clearly much work remains to be done to identify, on a compound by compound basis, the most effective basis for adjusting exposure levels that will both protect the health of the worker and have a minimum impact of the industry in question.

Novel Shift Adjustment

A more valid adjustment of exposure levels for novel workshifts may be developed by better understanding the toxicology of cotton dust and particle behavior in the lung. This would address the question: Does the acute toxicological burden from an additional four hours of exposure and concurrent reduction in recovery time (from 16 to 12 hours) alter the chronic risk? This can be determined in part by understanding the biological half-life of particles in the lung and the effect of cotton dust on particle clearance. If a worker were exposed to 200 ug/m^3 of dust for 8 hours, the total lung burden for the shift, assuming no clearance, would be 1.6 mg. This would be followed by a 12 hour period for clearance prior to the next shift. For the same worker exposed for 12 hours, the lung burden would be 2.4 mg, with only an 8 hour period for clearance prior to the next shift. For the 12 hour worker there would be an additional burden of 0.8 mg of dust and a clearance period shorter by 4 hours. While no studies have documented the biologic half-life of cotton dust, half-lives have been reported for bleached respirable cellulose dust and for cellulose fibers. Muhle and Bellman (5) reported a half-life for bleached cellulose dust, in rats, of greater than 1000 days and Warheig (6) reported a half-life of 60 days for cellulose fibers. Long term particle clearance from *the pulmonary region* in nonsmoking humans for a variety of insoluble particles (polystyrene latex, teflon, aluminosilicate, and iron oxide) have ranged from 62-2500 hours (7). Therefore the clearance half-time of 60-1000 days reported for cellulose fibers exceeds the range for other types of particles. Based on these data the difference between 16 and 12 hours for clearance of the pulmonary particle burden would be insignificant if the half-life were at the lower limit reported for clearance from the pulmonary region (>60 hours).

Since the risk from exposure to cotton dust is considered to be chronic, the recovery time between work weeks rather than between workshifts may be more revalent to predicting risk. For normal 8 hr, 5 day, 40 hour workweek, the recovery time over the weekend is approximately 64 hours. For 12 hour shift workers on a 3 day on 4 off followed by a 4 day on 3 day off work schedule the recovery time between work weeks would range from 84-108 hours, thus providing additional time for clearance of the cumulative burden from a 12 hour exposure workweek. For example, assuming no clearance, a cumulative burden over one week for an 8 hr/day, 40 hr/week worker exposed to 0.2 mg/m^3 would be 8 mg. Assuming a half-life of 60 hours, a clearance period of 64 hours prior to the next shift would reduce this burden to approximately 4 mg. For a 12 hour worker exposed to 0.2 mg/m^3 of dust for four shifts the cumulative burden over one week would be 9.6 mg (7.2 mg for three shifts) with a clearance period of 84-108 hours. Prior to beginning the next shift the lung burden would be reduced to between 2.2 and 3.9 mg depending on the number of shifts worked and the clearance period. Under these conditions there would be a greater clearance of total particle lung burden the 12 hour shift workers than for the 8 hour workers. This suggest that 12 hour workshifts may reduce the chronic risk associated with cotton dust to a greater extent than 8 hour workshifts at a higher dust level. However, these calculations do not take into account the possibility that the additional dust burden from a 12 hour shift could impair clearance or exert toxic effects on the lung beyond those from an 8 hour exposure.

The Influence Of Shiftwork On Pulmonary Function

Underlying the question of adjusting exposure levels for novel workshifts is the question of whether there is a significant toxic effect for workers exposed to cotton dust for 12 hours at or below the 8 hour TWA standard of 200 :g/m^3. In a recent cross-sectional study of 12 hour shift workers exposed to cotton dust at levels between 133 and 200 :g/m^3, there was a significant decrease in lung function (FEV_1) from baseline at both 8 and 12 hours, however there was no difference the response between 8 hours and 12 hours (8). These data suggest that the severity of the response did not increase with the additional 4 hours of exposure. When these same workers were evaluated prior to the following day's shift there was an overall improvement to their baseline FEV_1, however it was still significantly below their baseline value suggesting there may be a carry over effect from the exposure (Table 1).

When shift (i.e. day or night) was included in the data analysis, the night shift workers exhibited declines in FEV_1, at both 8 and 12 hours that were significantly larger than those of day shift workers. Furthermore, prior to the next day's shift, the day shift workers had returned to their baseline FEV_1 while the night shift workers were significantly below their baseline values (Figure 1). This observation was maintained after controlling for gender, race, and smoking and suggest that shift, not dust was the major variable influencing recovery prior to the next workshift.

The normal diurnal pattern of change in spirometry is characterized by an increase during the day from a minimum at 6 am to a maximum at mid-afternoon. From mid-afternoon there is a gradual decrease through the evening and night to the 6 am minimum (9). Based on this observation one would expect, that if there were no dust effects, workers would experience an increase in FEV_1 during a normal day shift and a decrease, if not acclimated, for evening and night shifts. Acclimation is a physiological adaptation that allows adjustment to other conditions or time periods. For example, workers acclimated to the night shift would exhibit a pattern of change in FEV_1 similar to the daytime pattern (i.e. increases FEV_1 at night and decreases during the day when they sleep). For the workers in this study, there was no acclimation period for night shifts. Furthermore, between workweeks, workers are likely revert to a daytime schedule suggesting that the declines observed for the night shift workers are in part related to the normal diurnal variation in spirometry.

Several studies have evaluated the diurnal pattern of spirometry in working populations. Ghio et al (10) evaluated day and night shift workers in the food preparation industry, assembly plants, and park and nursery workers. An industrial hygiene survey was done to assure there was no exposure to dust that would affect spirometry. Both day and night workers exhibited a mean decrease in FEV_1 of -0.8%. The variance of the night shift workers spirometry was significantly larger than the day shift workers (perhaps reflecting the issue of acclimation) but the general patterns were similar between the two shifts. These data differ from reported normal diurnal pattern of spirometry in that the day workers showed a slight decline in FEV_1 suggesting that work, even without dust exposure may effect the reported normal pattern of spirometry.

A similar variability in spirometric patterns was observed by Love (11) in coal workers and nurses working day and night shifts. The coal workers exhibited the normal diurnal pattern of an increase during the day shift and decreases for evening and night shift workers. It is interesting to note that the changes in spirometry for the evening and night shift workers were independent of the dust concentrations suggesting that the changes in are more strongly related to shift than dust. A different pattern was observed for nurses. Both day and night shift nurses showed declines in FEV_1. The declines shown by the nurses working the night shift were larger than those for the day shift, however their shift was four hours longer so it is not possible to say the difference was solely related to shift. These data suggest that departures from the normal diurnal pattern of spirometry occur in the workforce even when there are no exposures that may affect spirometry.

Few studies have been done to evaluate the diurnal pattern of spirometry in the cotton industry. Walford et al (12) evaluated four categories of day, late, and night shift workers. The categories were: 1. Workers in non-dusty factories; 2. Spinners without Byssinosis; 3. Card and blowroom workers without Byssinosis; and 4. Card and blowroom workers with Byssinosis. For the day workers only group 4 showed a decline over the shift, the remaining groups showed an increase over the day shift. For both the late shift and night shift workers all groups showed a decline with the byssinotics showing the greatest declines.

Merchant et al (13) also studied the diurnal patterns of spirometry in cotton workers. In this study both asymptomatic and byssinotic workers showed declines in FEV_1 over the day shift suggesting a dust effect. The declines of the byssinotics (-10-15%) were greater than those of the asymptomatic workers (-5%). A second observation, was that at the beginning of the second shift, none of the groups were back to their pre-exposure (first shift of the week) baseline values. This suggest either that there was be a carry over effect from the first day of exposure to the beginning of the shift on the second day or that the lack of recovery to baseline is part of the normal workweek pattern of spirometry.

To determine if this is a carry over effect of the dust or the normal day to day variability in the pattern of spirometry, the weekly pattern of spirometry must be examined. Dimich and Sterling (14) evaluated the diurnal pattern of spirometry for day and night workshifts and over the work week. When the data for both day and night shift workers were combined they observed an overall decline in FEV_1 from the start to the end of the shift; however, when the data were separated by shift they observed an increase in FEV_1 in day shift workers and a decrease in the night shift workers. However, both day and night shift workers failed to recover to their first shift baseline FEV_1 when spirometry was evaluated on successive days.

Similar observations were made in a two day controlled exposure study evaluating the response to rayon, a model inert dust, after exposure on day one to either cotton dust or rayon. In these studies, subjects responded to all cotton dust with a decrease in FEV_1 after the first exposure day, however the post exposure response to rayon was not significantly different from the pre-exposure baseline. Regardless of the exposure on the first day none of the groups returned to their day one pre-exposure baseline at the beginning of the second day, including those exposed to rayon on the first day. These data suggest that the lack of recovery on day two of the workweek may be a normal change in the workweek pattern of spirometry that is independent of dust exposure. Based on these observations the lack of recovery in the 12 hour shift workers at 24 hours (Figure 1) was a combination of a lack of acclimation for the night shift and the normal day to day pattern of spirometry over a work week.

In summary, the use of Haber's law to proportionately adjust the 8 hr PEL for cotton dust does not account for exposure related variables that may alter the toxic response to aerosols of cotton dust. Lung particle clearance data suggest that the half-life of cotton dust is >60 hours which in turn suggest there would be no difference in particle clearance between 8 and 12 hour shifts. Furthermore, if the particle half-life is greater than 60 hours, a more relevant predictor of chronic risk may be particle clearance between workweeks. Even with a heavier burden of particles during a 12 hr/day work week, particle clearance between workweeks would be equal to or greater for 12 hour workshifts than for 8 hour workshifts. The additional particle burden from 12 hour shifts may have toxic effects that alter particle clearance or other chronic risk factors. However, an acute toxic effect was not observed in a study evaluating the effect of low dust levels over a 12 hour workshift. While there was a dust response between 0 and 8 hours, there was no difference in the response between 8 and 12 hours. Furthermore, at the beginning of the second shift there was no difference in baseline FEV_1 and preshift FEV_1 for dayshift workers. However, nightshift workers did not recover to baseline by the beginning of the following day. This lack of recovery was not associated with dust toxicity but with the shift. These data suggest that at the current 8 hour PEL there is unlikely to be an additional chronic risk from a 12-hour exposure.

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Table 1. Percent Change in FEV_1 and FVC Baseline at 8, 12, and 24 hours.

Time (hrs)	N	$\Delta FEV_1 \pm$(sem) (%)	p	$\Delta FVC \pm$(sem) (%)	p
0-8	154	-2.83 (0.56)	<0.0001	-3.11 (0.46)	<0.0001
0-12	154	-3.02 (0.59)	<0.0001	-2.93 (0.51)	<0.0001
0-24	151	-1.19 (0.57)	<0.05	-1.02 (0.53)	<0.05
8-12	154	-0.06 (0.48)	0.897	+0.29 (0.44)	0.514

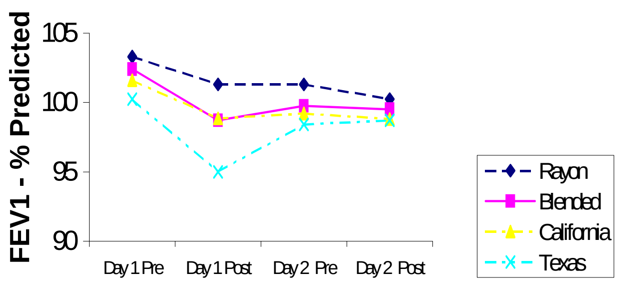

Figure 1. Change in FEV_1 to Rayon (Day 2) Following An Exposure to Cotton Dust or Rayon on Day One.