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Exposure to oil spill chemicals and lung function in *Deepwater Horizon* disaster response workers

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Abstract

Objective—To assess the relationship between total hydrocarbon (THc) exposures attributed to oil spill clean-up work and lung function 1-3 years after the *Deepwater Horizon (DWH)* disaster.

Methods—We used data from the GuLF STUDY, a large cohort of adults who worked on response to the *DWH* disaster and others who were safety trained but not hired. We analyzed data from 6,288 workers with two acceptable spirometry tests. We estimated THc exposure levels from a job exposure matrix. We evaluated lung function using the forced expiratory volume in one second (FEV_1; mL), the forced vital capacity (FVC; mL) and the FEV_1/FVC ratio (%).

Results—Lung function measures did not differ by THc exposure levels among clean-up workers.

Conclusions—We did not observe an association between THc exposure and lung function among clean-up workers 1-3 years following the *DWH* disaster.

Keywords

Petroleum hydrocarbons; lung function; spirometry; occupational hygiene

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INTRODUCTION

The large response effort that followed the 2010 *Deepwater Horizon (DWH)* disaster involved tens of thousands of workers (1) and thousands of vessels (2). Response workers engaged in a variety of jobs and activities/tasks that included burning of oil and natural gas, the application of chemical dispersants, booming and skimming of crude oil, and beach clean-up (2). During the mitigation effort, workers were exposed to airborne chemicals from the leaking crude oil, as well as from the dispersant application and burning of crude oil and natural gas (1, 3). Other sources of exposure include fuels, cleaning agents and solvents, and aerosols generated during decontamination work. Analyses of air samples taken during the *DWH* spill identified volatilizing hydrocarbons from the oil slick as the largest source of primary air emissions (4).

Total hydrocarbons (THc), the volatile mixture of crude oil components, includes hundreds of volatile compounds, including aromatic compounds, that are made up of hydrogen and carbon atoms and that vary in size and structure (5). Limited toxicity data are available for many THc chemicals, but some animal studies have demonstrated adverse effects on lungs, including inflammation in the lung epithelium following inhalation of volatile hydrocarbons (5).

Studies of oil spill response and clean-up (OSRC) workers following previous oil spills have reported increased prevalence of respiratory symptoms and increased levels of lung inflammatory markers in workers compared to non-workers, but only a few studies have assessed impacts of oil spill work on measured lung function (6–10). Findings among these studies have cited either short-term reductions in lung function in workers or null findings 2 to 6 years following exposures, though persistent symptoms and lung inflammatory markers were observed (7, 8, 11).

A previous examination of types of OSRC work and lung function in *DWH* response workers found lower lung function associated with high potential exposure to burning crude oil/gas (an indicator of particulate matter exposure) and decontamination work, potentially due to production of aerosols during pressure spraying of oily surfaces (12). *DWH* oil spill work exposures are unique compared to previously studied oil spills due to differences in the magnitude of the spilled oil, duration of release, source of emission (deep sea), and mitigation techniques employed during the response effort (1). The objective of the current study is to assess the impact of THc exposures on pulmonary function in OSRC workers 1-3 years after the *DWH* disaster.

METHODS

Study Design and Population

The Gulf Long-term Follow-up Study (GuLF STUDY) is a prospective cohort of 32,608 of adults who participated in activities related to the oil spill response and clean-up (workers, n=24,937) and those who received safety training but were not hired following the 2010 *DWH* oil spill (non-workers, n=7,671). The GuLF STUDY is described elsewhere (3). In short, participants completed a structured enrollment telephone interview, which collected information on OSRC work histories, demographics, lifestyle, and health. We identified 25,304 participants who lived in the Gulf coast states (eastern Texas, Louisiana, Mississippi, Alabama, and Florida) and spoke English or Spanish as eligible for a home visit exam. Of the total home visit-eligible participants, 11,193 completed a home visit between May 2011-May 2013, which included an additional interview on health and lifestyle factors, anthropometry, biological sample collection, and clinical measurements, including a pulmonary function test (PFT). Among home visit participants, 1,153 did not complete a PFT due to medical exclusions, refusal, or early home visit termination. Of the 10,040 participants who completed spirometry, 10,019 had complete over-read spirometry data. A total of 8,428 home visit participants had two acceptable FEV_1 and FVC tests, as defined by the 2005 American Thoracic Society (ATS) (13). The present analysis included participants who identified having worked at least 1 day on OSRC work and who had complete data on THc exposure and covariates (n=6,288).

Ethical Approval

This research was approved by the Institutional Review Board of the National Institute of Environmental Health Sciences. Written informed consent was obtained from all participants completing a home visit.

Ordinal total hydrocarbon (THc) exposure levels

The method used for estimating ordinal THc exposure levels has been previously described (3, 14). Briefly, OSRC work histories were collected at enrollment and included job titles, activities and tasks, and job/task-specific dates and locations. Jobs and tasks were classified into job groups based on similarities in job description, location, and calendar dates worked and linked to estimated THc exposure levels generated from personal passive monitoring data collected during the time of the OSRC using a job exposure matrix. Study participants were assigned THc estimates based on their job group, resulting in a daily arithmetic mean in parts per million (ppm) of estimated THc exposure per person per time period for each job/task reported. Ordinal THc exposure levels were defined using a pseudo-log scale based on the empirical range of job/task specific-exposures observed in the population and were as follows: 1 (≤0.29 ppm); 2 (0.30-0.99 ppm); 3 (1.00-2.99 ppm), 4 (≥3.00 ppm).

We used several approaches to estimate an ordinal THc exposure level for each participant over distinct exposure periods related to oil spill response efforts (such as capping the wellhead) and across jobs due to differences in concentrations of THc over time and the fact that on average workers performed 9 job/tasks per time period (3, 14). As our primary approach, we assigned each participant the highest exposure across all of their jobs/tasks and time periods worked (“maximum” exposure). This approach yielded the best exposure distribution for analysis in our population. As alternatives, we considered a “mean/maximum” approach, in which we averaged daily arithmetic mean THc concentrations for all jobs a participant worked within each time period of exposure and selected the highest value across all time periods, and a “maximum/mean” approach, in which we identified the job with the highest exposure in each time period and averaged daily THc concentrations across all time periods.

Pulmonary function testing

GuLF STUDY participants performed pre-bronchodilator spirometry at the home visit 1-3 years following the *DWH* disaster (12). We analyzed the forced expiratory volume in 1 second (FEV_1; mL), the forced vital capacity (FVC; mL), and the ratio of FEV_1/FVC (%). Examiners followed 2005 ATS/ERS guidelines and conducted spirometry using a portable ultrasound transit-time based spirometer (Easy on-PC; ndd Medical Technologies, Chelmsford MA, USA) (13). Participants were considered eligible for our analysis if they achieved two acceptable curves defined by ATS/ERS 2005 criteria: free from artifacts, have a good start, show satisfactory exhalation for both FEV_1 and FVC (13). We did not require specific reproducibility criteria for inclusion in the primary analytic sample. However, a subsample of participants meeting the ATS/ERS 2005 acceptability and reproducibility, or quality deemed comparable by an overreading expert, was assessed in a sensitivity analysis (13). The highest FEV_1 and FVC curves were selected for each participant to use in analyses and were used to derive FEV_1/FVC ratio. Participants with implausibly high values for any of the maneuvers were assigned missing for that maneuver and highest value from the remaining curves was used for analysis (n=1). All tests were reviewed and scored independently by a spirometry expert for quality control.

Covariates

For adjusted analyses, we selected model covariates using a minimally sufficient set identified by a directed acyclic graph based on a review of prior studies (15). Covariate data collected at the enrollment interview using a structured questionnaire included: age; gender (male, female); race (White, Black, Asian, Other); Hispanic ethnicity (Hispanic, non-Hispanic); smoking status (heavy current (≥20 cigarettes/day), light current(<20 cigarettes/day), past, never); education (less than high school, high school equivalent, some college, 4 years of college or greater); employment at the time of enrollment (employed, looking for work, other); previous (to the spill) diagnosis of lung disease; previous diagnosis of diabetes; and occupational history including whether a participant had previous oil industry experience (yes, no) or oil spill clean-up experience (yes, no). We categorized residential proximity at enrollment, defined as living in a coastal county/parish directly affected by the oil spill, an affected county adjacent to a coastal county, or in a Gulf state county further from the spill since all home visit participants lived in a Gulf state. Exposure to secondhand smoke (currently living with at least one person who smokes, not currently living with anyone who smokes) was collected at the home visit. Height and weight were measured in triplicate at the home visit and the mean value was used for statistical analyses. Since home visit dates spanned 1-3 years age at home visit was calculated from enrollment age. Height squared was used based on previously described quadratic relationship with lung function (16). Therefore, to adjust for BMI, weight was separately added to the model.

Statistical Analysis

We restricted our analysis to workers to address a previously identified possible healthy-worker effect (12). We compared adjusted means of lung function measurements by maximum ordinal THc exposure levels (1 (lowest) through 4 (highest)) accounting for age, height, height^2, gender, race, and smoking status. We then estimated the mean differences and 95% confidence intervals in lung function measurements associated with the ordinal THc exposure levels using multivariable linear regression using the full covariate set. We conducted a sensitivity analysis to see if effect estimates differed by approaches used to assign participants' ordinal THc exposure levels.

We also conducted several stratified and sub-analyses to address possible bias and effect measure modification. We restricted to participants who reported no work involving burning oil/gas (an indicator of particulate matter) based on previous associations found between exposure to burning oil/gas and lung function. We also stratified analyses of maximum ordinal THc exposure levels and lung function by pre-spill diagnosis lung disease to assess any differential effects. We restricted analyses to never-smokers as a subgroup of interest, and separately, to a subgroup of workers who met the stricter 2005 ATS/ERS spirometry quality criteria of three acceptable curves with ≤150 mL reproducibility for both FEV_1 and FVC or those with comparable spirometry quality as deemed by an overreading expert (n=5,591) to assess if associations differed compared to among those participants who had two acceptable spirometry tests with no reproducibility criteria requirement in our primary analysis. We also restricted to individuals who worked during the time the oil was being released (April 22nd-July 15th, 2010) and separately to those who had no previous oil industry experience to further assess possible healthy worker bias. Finally, we assessed potential differences in the associations for participants examined ≤1 year, >1 and ≤2 years, and >2 years since last day of OSRC work. Statistical Analysis Software (SAS) version 9.4 was used to conduct all statistical analyses (Cary, NC). An alpha level of 0.05 was considered statistically significant for all analyses.

RESULTS

Population characteristics by exposure to the maximum ordinal THc exposure levels experienced by workers are summarized in Table 1. Compared to workers in the two lowest THc exposure categories, workers in the two highest THc exposure categories were more likely to be male (90.0% vs. 70.0%; p<0.001) and heavy smokers (13.7% vs. 10.8%; p<0.001). Compared to participants with lower THc levels, those with higher levels were also more likely to be exposed to secondhand smoke (31.2% vs. 27.3%; p=0.001) and less likely to be Black (29.9% vs. 36.3%; p<0.001). A higher percentage with higher maximum ordinal THc exposure levels attained an education level less than high school or equivalent (22.3% vs. 16.5%; p<0.001) and were employed (59.0% vs. 54.7%; p=0.01) compared to the lower exposed, and more participants with higher THc lived in indirect proximity to affected counties along the Gulf of Mexico (adjacent to coastal counties that were closer to the oil spill) compared the lesser exposed (8.3% vs. 5.9%; p<0.001). Those exposed to more THc were also more likely to have participated in previous oil spill clean-up work compared to those with lower THc exposure (9.5% vs. 7.1%; p<0.001) and to have previously worked in the oil industry (22.3% vs 12.2%; p<0.001).

Minimally adjusted mean values for FEV_1, FVC, and FEV_1/FVC showed no apparent trends with maximum ordinal THc exposure level (Table 2). The adjusted mean FEV_1 was slightly lower in workers with the highest THc level compared to workers with the lowest ordinal

THc level (2,998 mL (SE: 24) vs 3,025 mL (SE: 24)). The FEV_1/FVC was also marginally lower in the highest versus lowest THc level (78.55% (SE:0.29) vs. 79.20% (SE: 0.28)).

Fully adjusted associations between maximum ordinal THc levels and lung function measures among workers showed no clear differences in FEV_1 or in FVC by ordinal THc level (Table 3). FEV_1/FVC (Mean difference: −0.62%, 95% CI: −1.25%, 0.003%) was suggestively lower in workers with the highest THc level compared to workers with the lowest level but this difference did not reach the level of statistical significance. We observed similar point estimates and 95% confidence intervals when using THc estimates derived using the alternative approaches of selecting maximum/mean and mean/maximum (*not shown*).

Among workers in our analytic sample who had no exposure to burning oil/gas (n=5,603), we did not see any clear patterns in any of the lung function measurements by maximum ordinal THc exposure levels (Table 4). The estimated difference in FEV_1/FVC for the highest THc exposure level versus the lowest was slightly attenuated, but similar, to our primary analysis (Mean difference: −0.56%, 95% CI: −1.35%, 0.23%).

In analyses among workers stratified by pre-spill diagnosis of lung disease, we observed a lower but not statistically different FEV_1/FVC in those with the highest THc exposure level (Mean difference: −0.62%, 95% CI: −1.27%, 0.03%) among those with no pre-spill lung disease diagnosis (n=5,435) (Table 5).

In analyses among workers stratified by smoking status an inverse association with highest versus lowest THc level appeared slightly stronger among never-smokers (n=2,688) for FEV_1/FVC (Mean difference: −0.73%, 95% CI: −1.58%, 0.11%), although results did not achieve statistical significance (*not shown*).

Analyses in the sub-group of workers who achieved the stricter spirometry quality criteria yielded no substantial differences in THc level and lung function associations compared to the primary analytic sample (Supplementary Table 1). Similarly, restricting to those who worked during the time of the active oil spill did not substantively change results (n=6,027) (*not shown*) and separately to those who had no previous oil industry experience (n=5,214) also did not substantively change results (*not shown*). Supplemental Table 2 shows associations between THc exposure level and lung function stratified by time since participant's last day of work on OSRC. Among those who took a PFT within the first year, workers with THc Level 4 had a suggestively lower FEV_1 (−63 mL; 95% CI: −219 mL, 93 mL) and FEV_1/FVC (−1.72%, 95% CI: −3.66%, 0.22%) compared to workers with THc Level 1, though these differences did not reach statistical significance. These differences were less apparent among those whose PFT visits were later.

DISCUSSION

In the present study, we did not observe an association between THc exposure levels and lung function in *DWH* response workers 1-3 years after the oil spill. A suggested but not statistically different decrease in FEV_1/FVC among workers exposed to maximum ordinal THc exposure levels ≥3.0ppm was observed compared to those with THc exposure levels

≤0. 29ppm.This small decrement remained, but was also not statistically significant when we excluded workers exposed to burning oil/gas. Previous studies have found that on average heavy smokers (>60 pack-years) can have FEV_1/FVC that is up to 10% lower compared to prior smokers, although this effect can vary greatly (17, 18). The effect size that we observed among all workers with the highest potential THc exposure for FEV_1/FVC (Mean difference: −0.62%; 95% CI: −1.25, 0.003) was smaller than this.

THc compounds, particularly those aromatic in nature, can induce lung inflammation in animals and humans (5, 19, 20). This inflammation is believed to arise through oxidative stress mechanisms (19, 21, 22). Previous studies of oil spill clean-up workers have observed increased rates of respiratory symptoms and increased markers of oxidative stress in lungs among individuals exposed to oil spills compared to those unexposed (6–9, 23). Clean-up workers from the *Tasman Spirit* oil spill (n=51) had reductions in FEV_1 and FVC directly following the spill compared to non-workers, though improvement in lung function parameters was seen at 1 year follow-up (11, 24). Fisherman who aided in clean-up following the *Prestige* oil spill (n=678) did not have reduced lung function compared to unexposed fisherman at 2-year follow-up, although those exposed did have higher rates of lower respiratory tract symptoms compared to the unexposed. Among non-smokers, workers also had higher levels of 8-isoprostane compared to non-workers (7). In a study of these workers (n=215) 6 years after exposure, those highly exposed to oil had FEV_1/FVC and Forced expiratory flow at 25-75% values that were qualitatively lower compared to those moderately exposed, though differences did not reach statistical significance(10).

Previous studies that have assessed oil and lung function have used qualitative data derived from questionnaires as exposure surrogates (e.g. duration of clean-up work, distance from spill) and have not utilized air measurement data taken during the exposure period in relation to lung function, which may explain our ability to identify a suggested signal between highest THc exposure and FEV_1/FVC where others have not. Additionally, lung function effects may not be comparable across studies due to differences in the nature of the oil spills (e.g. size, duration, source, grade of oil, and response effort techniques) and subsequent exposure differences (1, 5).

The use of THc levels estimated from personal monitoring data measured at the time of oil spill work is a primary strength of this study. This study was able to assess effects in relation to estimated spill-related chemical exposures using ordinal exposure estimates, which allows for the investigation of the effects of a group of oil spill chemicals. Nonetheless, there are limitations. The exposure estimates are ordinal, which is known to result in greater non-differential misclassification than quantitative estimates (25). Exposure metrics used in this study do not incorporate time-weighted estimates, or account for multiple jobs across time periods which may cause non-differential misclassification in exposure status, though the direction of this bias is not known, as non-differential misclassification can either exaggerate risks or move risks to the null with a polytomous exposure (26). However, we did evaluate different ways to integrate measures over time periods of work and across multiple jobs worked in sensitivity analyses and found no substantive differences in results across the different approaches.

Although no occupational guidelines/regulations exist for THc, a similar compound, petroleum naphtha, provides some guidance as to an exposure limit. OSHA's Occupational Exposure Limit for naphtha is 500 ppm and NIOSH's Recommended Exposure Limit is ~85 ppm for 15 minutes (5, 27). Only 15 of 28,000 THc personal samples were >100 ppm, with only 3 exceeding 200 ppm (14). In part, these low levels are likely due to the rapid weathering of oil in the water and after reaching the surface: 75% of the volatiles were eliminated via various weathering processes within a few days (28). Also, BP had direct-reading instruments on many of the vessels in the hot zone/source areas where the oil was reaching the surface within hours of release. When air concentrations exceeded 20 ppm, as measured by direct-reading instruments, water was sprayed, and above 70 ppm, dispersant was sprayed, to disperse the sheens.

Spirometry is an objective and widely used measure of lung function and has been used in previous large cohort studies (29, 30). This analysis assessed lung function at one point in time, compared to longitudinal lung function, which is a more desirable clinical measurements (31). Spirometry was also conducted in an atypical setting at a home visit, which may have resulted in a lower proportion of our population meeting ATS/ERS 2005 acceptability and reproducibility criteria. However, for our primary analyses, we included any participant who attained two acceptable curves without reproducibility criteria. This decision was based on previous findings of potential selection effects from discarding non-reproducible tests in an epidemiologic setting (32). Sensitivity analysis further restricting the sample to the stricter ATS/ERS 2005 criteria showed no difference in results.

The GuLF STUDY is the largest study of oil spill clean-up and response workers. In our analysis, we were able to detect small differences in lung function due, in part, to the large sample size, and to detailed covariate information that allowed us to address a range of potential confounders. Additionally, we were able to investigate associations with ordinal THc exposure estimates derived from monitoring data collected during the spill clean-up. In this study, we did not find associations between THc level and lung function even after accounting for exposure to burning oil/gas. Future assessment of lung function changes over time in relation to time-weighted exposures of THc and THc components will aid in understanding the full impact of oil exposures on lung function in response and clean-up workers following the *DWH Disaster*

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Characteristics of *Deepwater Horizon* disaster response and clean-up workers with 2 acceptable FEV_1 and FVC curves by maximum ordinal total hydrocarbon exposure level (n=6,288)

Characteristics	**THc Levels 1–2***	**THc Levels 3–4***	**p-value**
	(n=3,247)	(n=3,041)	
	Mean (SD)	Mean (SD)	
Age at home visit, years	43.61 (12.72)	42.84 (12.60)	0.02
Height, inches	67.99 (3.74)	68.91 (3.38)	<.0001
Weight, lbs	197.40 (48.04)	202.68 (46.21)	<.0001
	n (%)	n (%)	
Gender			<.0001
Female	974 (30.00)	305 (10.03)	
Male	2273 (70.00)	2736 (89.97)	
Race			<.0001
Black	1180 (36.34)	909 (29.89)	
White	1764 (54.33)	1801 (59.22)	
Other	303 (9.33)	331 (10.88)	
Ethnicity			1.00
Hispanic	204 (6.28)	191 (6.28)	
Non-Hispanic	3043 (93.72)	2850 (93.72)	
Smoking status			<.0001
Heavy current smoker	352 (10.84)	417 (13.71)	
Light current smoker	788 (24.27)	751 (24.70)	
Former smoker	647 (19.93)	645 (21.21)	
Never smoker	1460 (44.96)	1228 (40.38)	
Secondhand smoke			0.001
Yes	885 (27.26)	950 (31.24)	
No	2362 (72.74)	2091 (68.76)	
Education			<.0001
<High school/equivalent	535 (16.48)	678 (22.30)	
High school diploma/GED	1072 (33.02)	1066 (35.05)	
Some college/2-year degree	1036 (31.91)	950 (31.24)	
≥4-year college graduate	604 (18.60)	347 (11.41)	
Employment at time of enrollment			0.01
Looking for work/unemployed	916 (28.21)	741 (24.37)	
Other	556 (17.12)	505 (16.61)	
Working now	1775 (54.67)	1795 (59.03)	
Residential proximity to Gulf Coast†			<.0001
Direct	2358 (72.62)	2191 (72.05)	

Characteristics	THc Levels 1–2*	THc Levels 3–4*	p-value
Indirect	190 (5.85)	253 (8.32)	
Other Gulf state residence	699 (21.53)	597 (19.63)	
Previous oil spill clean-up work			<.0001
Yes	232 (7.15)	289 (9.50)	
No	3015 (92.85)	2752 (90.50)	
Previous oil industry experience			<.0001
Yes	395 (12.17)	679 (22.33)	
No	2852 (87.83)	2362 (77.67)	
Reported pre-spill lung disease diagnosis			0.91
Yes	442 (13.61)	411 (13.52)	
No	2805 (86.39)	2630 (86.48)	
Reported pre-spill diabetes diagnosis			
Yes	182 (5.61)	148 (4.87)	0.19
No	3065 (94.39)	2893 (95.13)	

Abbreviations: THc Level, maximum ordinal total hydrocarbon exposure level; SD, standard deviation

*Level 1(≤0.29ppm); Level 2(0.30–0.99ppm); Level 3(1.00–2.99ppm); Level 4(≥3.00ppm)

†Direct proximity is defined as living in a county directly adjacent to the Gulf of Mexico; indirect is defined as living in a county adjacent to coastal counties; other Gulf state residence is defined as living in a Gulf state further from the spill

Table 2

Lung function by maximum ordinal total hydrocarbon exposure levels among *Deepwater Horizon* disaster response and clean-up workers with 2 acceptable FEV_1 and FVC curves (n=6,288)

Lung function	THc Level (ppm)*	n (%)	Adjusted Mean (SE)*
FEV_1, mL			
	Level 1 (≤0.29)	913(14.52)	3025(24)
	Level 2 (0.30–0.99)	2334(37.12)	3009(19)
	Level 3 (1.0–2.99)	2113(33.60)	3047(20)
	Level 4 (≥3.00)	928(14.76)	2998(24)
FVC, mL			
	Level 1 (≤0.29)	913(14.52)	3816(28)
	Level 2 (0.30–0.99)	2334(37.12)	3816(22)
	Level 3 (1.00–2.99)	2113(33.60)	3852(24)
	Level 4 (≥3.00)	928(14.76)	3818(29)
FEV_1/FVC%			
	Level 1 (≤0.29)	913(14.52)	79.20(0.28)
	Level 2 (0.30–0.99)	2334(37.12)	78.90(0.22)
	Level 3 (1.00–2.99)	2113(33.60)	79.12(0.24)
	Level 4 (≥3.00)	928(14.76)	78.55(0.29)

Abbreviations: THc level, maximum ordinal total hydrocarbon exposure level; ppm, parts per million; SE, standard error

*Adjusted for age, height, $height^2$, gender, race, ethnicity, smoking status

Table 3

Maximum ordinal total hydrocarbon exposure levels and lung function among *Deepwater Horizon* disaster response and clean-up workers with 2 acceptable FEV_1 and FVC curves (n=6,288)

Lung function	THc Level (ppm)	n (%)	Mean differences (95% CI)*	p-value
FEV_1, mL				
	Level 1 (≤0.29)	913(14.52)	Ref	Ref
	Level 2 (0.30–0.99)	2334(37.12)	−5(−49, 38)	0.81
	Level 3 (1.00–2.99)	2113(33.60)	36(−9, 81)	0.12
	Level 4 (≥3.00)	928(14.76)	−17(−70, 36)	0.53
FVC, mL				
	Level 1 (≤0.29)	913(14.52)	Ref	Ref
	Level 2 (0.30–0.99)	2334(37.12)	2(−49, 52)	0.95
	Level 3 (1.00–2.99)	2113(33.60)	40(−12, 93)	0.13
	Level 4 (≥3.00)	928(14.76)	15(−46, 77)	0.62
FEV_1/FVC%				
	Level 1 (≤0.29)	913(14.52)	Ref	Ref
	Level 2 (0.30–0.99)	2334(37.12)	−0.07(−0.58, 0.44)	0.79
	Level 3 (1.00–2.99)	2113(33.60)	0.19(−0.35, 0.72)	0.49
	Level 4 (≥3.00)	928(14.76)	−0.62(−1.25, 0.003)	0.05

Abbreviations: THc Level, maximum ordinal total hydrocarbon exposure level, ppm, parts per million; CI, confidence interval

*Model adjusted for: age, height, $height^2$, weight, gender, ethnicity, race, pre-spill diabetes, pre-spill lung disease, education, employment, other oil industry experience, previous oil spill clean-up, residential proximity to Gulf Coast, smoking, and secondhand smoke

Table 4

Maximum ordinal total hydrocarbon exposure levels and lung function among *Deepwater Horizon* disaster response and clean-up workers with 2 acceptable FEV_1 and FVC curves and no exposure to burning oil/gas (n=5,603)

Lung Function	THc Level (ppm)	n (%)	Mean differences (95% CI)*	p-value
FEV_1, mL				
	Level 1 (≤0.29)	893 (15.94)	Ref	Ref
	Level 2 (0.30–0.99)	2271 (40.53)	−4 (−48, 40)	0.86
	Level 3 (1.00–2.99)	2028 (36.19)	37 (−9, 82)	0.11
	Level 4 (≥3.00)	411 (7.34)	−12 (−79, 55)	0.72
FVC, mL				
	Level 1 (≤0.29)	893 (15.94)	Ref	Ref
	Level 2 (0.30–0.99)	2271 (40.53)	5 (−46, 56)	0.84
	Level 3 (1.00–2.99)	2028 (36.19)	42 (−11, 95)	0.12
	Level 4 (≥3.00)	411 (7.34)	25 (−53, 102)	0.53
FEV_1/FVC%				
	Level 1 (≤0.29)	893 (15.94)	Ref	Ref
	Level 2 (0.30–0.99)	2271 (40.53)	−0.09 (−0.61, 0.43)	0.74
	Level 3 (1.00–2.99)	2028 (36.19)	0.22 (−0.32, 0.76)	0.43
	Level 4 (≥3.00)	411 (7.34)	−0.56 (−1.35, 0.23)	0.17

Abbreviations: THc Level, maximum ordinal total hydrocarbon exposure level; ppm, parts per million; CI, confidence interval

*Model adjusted for: age, height, $height^2$, weight, gender, ethnicity, race, pre-spill diabetes, pre-spill lung disease, education, employment, other oil industry experience, previous oil spill clean-up, residential proximity to Gulf Coast, smoking, secondhand smoking

Table 5

Maximum ordinal total hydrocarbon exposure levels and lung function among *Deepwater Horizon* disaster response and clean-up workers with 2 acceptable FEV_1 and FVC curves by pre-spill diagnosis of lung disease (n=6,288)

		No pre-spill diagnosis of lung disease (n=5,435)			Pre-spill diagnosis of lung disease (n=853)		
Lung function	**THc Level (ppm)**	**n(%)**	**Mean differences (95% CI)***	**p-value**	**n(%)**	**Mean differences (95% CI)***	**p-value**
FEV_1, mL							
	Level 1 (≤0.29)	783 (14.41)	Ref	Ref	130 (15.24)	Ref	Ref
	Level 2 (0.30–0.99)	2022 (37.20)	−3 (−49, 43)	0.91	312 (36.58)	−24 (−154, 105)	0.71
	Level 3 (1.00–2.99)	1816 (33.41)	44 (−4, 92)	0.07	297 (34.82)	−20 (−150, 111)	0.77
	Level 4 (≥3.00)	814 (14.98)	−15 (−71, 41)	0.60	114 (13.36)	−26 (−188, 135)	0.75
FVC, mL							
	Level 1 (≤0.29)	783 (14.41)	Ref	Ref	130 (15.24)	Ref	Ref
	Level 2 (0.30–0.99)	2022 (37.20)	−4 (−58, 50)	0.88	312 (36.58)	34 (−113, 181)	0.65
	Level 3 (1.00–2.99)	1816 (33.41)	48 (−8, 104)	0.09	297 (34.82)	−13 (−161, 135)	0.87
	Level 4 (≥3.00)	814 (14.98)	21 (−44, 87)	0.52	114 (13.36)	−30 (−214, 154)	0.75
FEV_1/FVC%							
	Level 1 (≤0.29)	783 (14.41)	Ref	Ref	130 (15.24)	Ref	Ref
	Level 2 (0.30–0.99)	2022 (37.20)	0.15 (−0.38, 0.68)	0.58	312 (36.58)	−1.30 (−2.95, 0.35)	0.12
	Level 3 (1.00–2.99)	1816 (33.41)	0.27 (−0.28, 0.83)	0.34	297 (34.82)	−0.29 (−1.96, 1.40)	0.73
	Level 4 (≥3.00)	814 (14.98)	−0.62 (−1.27, 0.03)	0.06	114 (13.36)	−0.25 (−2.31, 1.82)	0.81

Abbreviations: THc Level, maximum ordinal total hydrocarbon exposure level; ppm, parts per million; CI, confidence interval

*Model adjusted for: age, height, $height^2$, weight, gender, ethnicity, race, pre-spill diabetes, education, employment, other oil industry experience, previous oil spill clean-up, residential proximity to Gulf Coast, smoking, secondhand smoke