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Association between spill-related exposure to fine particulate matter and peripheral motor and sensory nerve function among oil spill response and cleanup workers following the Deepwater Horizon oil spill

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Abstract

Background: Burning/flaring of oil/gas during the *Deepwater Horizon* oil spill response and cleanup (OSRC) generated high concentrations of fine particulate matter ($PM_{2.5}$). Personnel working on the water during these activities may have inhaled combustion products. Neurologic

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Author contributions
CLN conducted the data analyses and drafted the manuscript. LSE and DPS oversaw the analyses. GCP, MRS, PAS, CG and SB generated the exposure data. All authors reviewed and approved the manuscript.

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effects of $PM_{2.5}$ have been reported previously but few studies have examined lasting effects following disaster exposures. The association of brief, high exposures and adverse effects on sensory and motor nerve function in the years following exposure have not been examined for OSRC workers.

Objectives: We assessed the relationship between exposure to burning/flaring-related $PM_{2.5}$ and measures of sensory and motor nerve function among OSRC workers.

Methods: $PM_{2.5}$ concentrations were estimated from Gaussian plume dispersion models and linked to self-reported work histories. Quantitative measures of sensory and motor nerve function were obtained 4 to 6 years after the disaster during a clinical exam restricted to those living close to two clinics in Mobile, AL or New Orleans, LA (n=3,401). We obtained covariate data from a baseline enrollment survey and a home visit, both in 2011 to 2013. The analytic sample included 1,186 participants.

Results: We did not find strong evidence of associations between exposure to $PM_{2.5}$ and sensory or motor nerve function, although there was a suggestion of impairment based on single leg stance among individuals with high exposure to $PM_{2.5}$. Results were generally consistent whether we examined average or cumulative maximum exposures or removed individuals with the highest crude oil exposures to account for co-pollutant confounding. There was no evidence of exposure-response trends.

Significance: Our study is the first to investigate estimates of $PM_{2.5}$ in relation to neurological function among oil spill-exposed individuals. While evidence of an overall effect measured several years after the spill was limited, high cumulative $PM_{2.5}$ exposure was associated with impaired single leg stance performance.

Keywords

$PM_{2.5}$; peripheral nerve outcome; oil spill; air pollution; combustion exposures

1. Introduction

The *Deepwater Horizon* (*DWH*) oil spill disaster began with the explosion and sinking of the *DWH* oil drilling rig in April 2010 and remains the largest oil spill in the history of United States (US) marine oil drilling.(1) Prior to the mechanical capping of the wellhead on July 15, 2010, an estimated 4.9 million barrels of crude oil were discharged into the Gulf of Mexico.(2) The oil spill response and cleanup (OSRC) effort was one of the largest to date;(3) approximately 4.7% of residents in Gulf communities impacted by the *DWH* disaster and thousands from outside the Gulf region and across the US participated.(4) The effort involved intermittent, controlled *in situ* burns of oil on the surface of the water and almost continuous flaring of oil and natural gas at the wellhead between May 17th and July 16th 2010.(5) Of individuals involved in the response and cleanup effort, 3.7% participated in wellhead cleanup or controlled burning.(4) The total amount of oil burned (~300,000 barrels) accounted for approximately 6% of the total oil discharged. Burning and flaring generated fine particulate matter ($PM_{2.5}$) and other pollutants to which the OSRC workers were potentially exposed.

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Air pollution comprises particulate matter (PM), metals, organic compounds, and gases, each with different effects on health. For $PM_{2.5}$ (particulate matter ≤ 2.5μm in diameter) these effects may relate to the size and composition of the particulate (which varies by source), and whether the particles are chemically active. $PM_{2.5}$ from the combustion of oil and gas can result in the generation of ultrafine particles and may contain transition metals that can adversely affect health when inhaled.(6, 7) These particles can translocate to the brain, where they start a cascade of inflammation and oxidative stress potentially resulting in neuronal toxicity. (8–11) Associations between acute and chronic exposure to various forms of $PM_{2.5}$ and respiratory and cardiovascular effects in the short- and long-term are well-documented.(12–15) There is a growing body of research linking $PM_{2.5}$ exposure and increased risk of some neurological outcomes (cognitive decline, development or exacerbation of dementia, Alzheimer's disease, and Parkinson's disease(16–18)) but data on peripheral nervous system (PNS) effects are scant. However, peripheral neuropathy — peripheral nerve damage resulting in pain, numbness, tingling, or muscle weakness — can affect an individual's quality of life and risk of injury and is estimated to have a prevalence of 6–9% in the general U.S. population.(19) In addition, peripheral neuropathy may be associated with increased risk of falls,(20, 21) and impairment in lower extremity peripheral nerve function may be associated with subsequent diagnosis of dementia.(22, 23)

Some studies of exposure to ambient air pollution indicate possible associations between PM exposure and neurological outcomes in elderly Korean women,(24) American adults,(25) and elderly German persons.(26) In this last study, stronger associations were observed among obese than non-obese individuals. In one crossover chamber study of exposure to diesel exhaust (which contains $PM_{2.5}$) or filtered air, only weak evidence of a trend of reduced postural stability was reported in response to diesel exhaust exposure.(27) Some studies among children also illustrate adverse effects of PM exposure on cognitive and motor function.(16, 28)

The exposures described above are mostly chronic and low concentration. In contrast, some *DWH* OSRC workers encountered exposures to high concentrations of $PM_{2.5}$ for comparatively short periods of time (i.e., months). To our knowledge, burning and flaring of oil or gas was not employed in the remediation following other spills, making the high, short-term exposure to $PM_{2.5}$ from burning during the *DWH* response novel for this context. Due to some similarities in the exposure, studies of the Kuwait oil fires of 1991 may be informative; in this work among veterans, nervous system diseases were not associated with smoke from oil well fires.(29) However, in experimental studies in rats, exposure to high concentrations of $PM_{2.5}$ resulted in decreased sensory function, which the authors hypothesized was due to increased reactive oxygen species, oxidative stress, decreased myelination, and overexpression of Caspase-3 and -9 (apoptosis-related proteins).(30)

Effects of exposure to combustion-related $PM_{2.5}$ on the PNS might peak and wane or could be incremental and occur over years. It is crucial to understand the long-term health consequences of cleaning up environmental disasters; this can inform actions during the remediation of future spills, thus minimizing the harm to those involved in the cleanup. As such, the objective of this study was to assess the relationship between exposure to burning-related $PM_{2.5}$ and measures of sensory and motor nerve function (i.e., visual

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contrast sensitivity, single leg stance, postural sway, and vibrotactile threshold) among OSRC workers in the ~4–6 years following the *DWH* spill response.

2. Methods

2.1. Study design and population

Individuals in this analysis were participants in the Gulf Long Term Follow Up (GuLF) Study, a prospective cohort study (n=32,608) initiated shortly after the *DWH* oil spill began. (3) Participants were ≥21 years of age and either participated in the OSRC effort for at least one day or completed safety training but did not work on the spill cleanup effort. At enrollment (March 2011 to March 2013), participants provided socio-demographic, health, and lifestyle data, as well as detailed information about their *DWH* oil spill cleanup jobs and activities via computer-assisted telephone interviews. Participants were eligible for a home visit (n=25,304 eligible, 13,355 of whom were contacted) if they spoke English or Spanish, and resided in Louisiana, Mississippi, Alabama, Florida, or eastern Texas. The home visit was completed by 11,193 participants between May 2011 and May 2013. At this time, additional data (lifestyle and health), samples (biological and environmental), and measurements (anthropometric and clinical) were obtained. Lastly, from August 2014 to June 2016, a subset of participants (n=3,401) completed an in-person clinical assessment including a follow-up health interview, clinical measurements, and neurological/neurobehavioral tests. Eligible participants lived within 60 miles of a study clinic site in either New Orleans, Louisiana or Mobile, Alabama. Participants provided verbal consent for the telephone enrollment interview and written informed consent at the time of the home visit and the in-person assessment. The study was approved by the Institutional Review Board of the National Institute of Environmental Health Sciences.

Of the 3,401 participants who completed the in-person assessment, 743 were not involved in the OSRC work when the burning/flaring took place, and 1,390 worked solely on land during this period and were excluded from analysis. Land-only workers were excluded because their $PM_{2.5}$ exposures from burning/flaring were likely confounded by $PM_{2.5}$ exposure from diesel and gasoline exhaust from land-based vehicles and equipment used in the OSRC effort that could not be quantified. Individuals who reported that they had had a diagnosis of peripheral neuropathy prior to the spill (n=15) and those who indicated a pre-spill diagnosis of diabetes (n=67), for which peripheral neuropathy is a common complication, were also removed from analysis. Diabetes is very common in the United States, with approximately 21 million adults (≥20 years old) with confirmed diabetes in 2010.(31) After removal of these individuals, the final analytic sample included 1,186 participants consisting of 214 higher exposed individuals who worked offshore on the *in situ* burns or within 5 nautical miles (nmi) of the flaring and 972 referent workers who worked nearshore, offshore (but not on the *in situ* burns), or at unknown locations on the water.

2.2. Modeled $PM_{2.5}$ exposure estimates

While certain volatile hydrocarbon levels were monitored during the response and cleanup effort, $PM_{2.5}$ monitoring efforts failed due to analytical issues with the methods; attempts to monitor $PM_{2.5}$ were undertaken but under the conditions encountered, the instrumentation

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could not accurately characterize exposure. Therefore, exposures to $PM_{2.5}$ for OSRC workers were modeled to investigate the relationships between exposures experienced during this burning/flaring activity and adverse health effects. Exposures to two primary sources of $PM_{2.5}$ were estimated.(32, 33) Workers on the water during the spill response and cleanup were exposed to $PM_{2.5}$ from *in situ* burnings of the oil on the water's surface and from the flaring of oil and gas at the wellhead. A third source, exhaust from vessels and land vehicles and equipment used during the cleanup, was not included in $PM_{2.5}$ exposure estimates. The process of estimating $PM_{2.5}$ for workers is explained in more detail in the Supplementary Information (Figure S1.) but we provide a brief overview here. Hourly concentrations of $PM_{2.5}$ were estimated for receptors (i.e., specific locations) across the Gulf of Mexico using previously generated emissions factors(34, 35) and an estimated volume of oil burned for each *in situ* burn and separately, each day of oil and gas flaring to calculate the emissions for each burn/flare day. Meteorological data were used with these estimated emissions as inputs for the AERMOD(36) air dispersion model to estimate concentrations of $PM_{2.5}$ for each of three study work areas in the Gulf and one activity (*in situ* burns). Individual workers were linked to an area from their self-reported work activities to estimate their maximum exposure over the course of their OSRC work, which was converted to an average and cumulative $PM_{2.5}$ exposure for each individual. For those who did any response or cleanup work on the water, work locations were identified as: the hot zone (≤1 nmi from the wellhead), the source (>1 and ≤5 nmi from the wellhead), offshore (>5 nmi from the wellhead and >3 nmi from shore), and near shore (≤3 nmi from shore). For offshore workers, a distinction was made between those working on the *in situ* burns and those not working on the burns, as the burn workers likely experienced higher exposures to $PM_{2.5}$. Two estimates of exposure (average maximum 12-hour average, henceforth "average" exposure, and cumulative maximum 12-hour average, henceforth "cumulative" exposure) were generated.

Among our study sample, five participants had an average $PM_{2.5}$ exposure of 10 μg/m^3; 185 of 29 μg/m^3; and 24 of 97 μg/m^3. This represents *in situ* burns, source, and hot zone concentrations, respectively. The concentrations for the cumulative $PM_{2.5}$ exposure among the exposed ranged from 29 to 3199 μg/m^3-days, with a median of 1005 μg/m^3-days. The distribution of cumulative $PM_{2.5}$ exposures was clustered by virtue of the small number of work areas used to assign exposures (Figure S2.). During the months when burning/flaring occurred, the median work duration for individuals in our analytic group was 28 days (range: 1–49 days). Cumulative total hydrocarbon (THC) exposure was examined as a potential confounder of the associations with $PM_{2.5}$. The correlation of THC with average and with cumulative $PM_{2.5}$ was 0.24 and 0.26, respectively.

2.3. Assessment of sensory/motor function

The battery of clinical tests indicative of PNS function included assessments for visual acuity and contrast sensitivity; the ability to maintain a single leg stance; vibrotactile threshold; and postural sway/standing steadiness. These outcomes were evaluated at the clinical exam by trained clinical examiners who were blinded to participants' exposure level.

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Visual acuity, or the sharpness of a participant's vision, was tested simultaneously in both eyes. Individuals with an acuity score of less than 20/50 were classified as having poor vision and were excluded from the contrast sensitivity analyses (n=44 participants in the exposed group [21%] and n=185 in the referent group [20%]). For the single leg stance, participants were asked to balance upright for 30 seconds while standing on one leg; results were statistically modeled as the inability to maintain an upright stance in any of three trials.(37) Vibrotactile threshold, a measure of the acuity of cutaneous vibration perception, was measured on the skin of the ventral side of the great toe, bilaterally. To measure postural sway (sometimes called *posturography*), participants were asked to stand on a commercially available strain-gauge force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) without moving, twice with eyes open and twice with eyes closed, for 60 seconds in each trial. Mean postural sway speed (the distance in mm traveled by the participants' sway center of pressure divided by 60 seconds) in units of millimeters/second was included in the analyses separately for these test conditions.(38) A more comprehensive description of each test is provided in the Supplementary Information.

2.4. Statistical modeling

We considered individuals who worked in the hot zone, at the source, or on *in situ* burns as exposed to $PM_{2.5}$. Those who worked offshore (but not on the *in situ* burns, n=167), nearshore (n=701), or at an unknown location (n=104) in the burning/flaring period were included in the referent group as they were estimated to have the lowest $PM_{2.5}$ exposures of on-water workers (Table S2.). Due to the noncontinuous, clustered distribution of the data – a result of how the exposure estimates were generated rather than the underlying true distribution of the exposures – we evaluated the relationship between $PM_{2.5}$ exposure and the outcomes using categorized exposure data. This allowed us flexibility beyond an assumption of linearity or log-linearity. Participants working at *in situ* sites (n=5) and within the source area (n=185) were combined in the main analyses as low average $PM_{2.5}$ exposure, while participants working in hot zone areas (n=24) were considered high average $PM_{2.5}$ exposure. As there was greater variation in the values estimated for cumulative $PM_{2.5}$ due to the differences in participants' work duration, we categorized the exposed individuals into tertiles – low, medium, and high – for this metric; however, due to tied values at the tertile cutoffs, these categories are not evenly sized (Table S2., Figure S2.).

For continuous outcomes (i.e., postural sway and vibrotactile threshold), we used multivariate linear regression to estimate the continuous difference comparing outcomes for each exposure category (low/high or low/medium/high) to those in the referent group. For single leg stance we used log-binomial regression (with the copy method(39) as needed to facilitate model convergence) to estimate prevalence ratios (PR) and 95% confidence intervals (CI), as this outcome was binary (i.e., did not/did successfully hold the single leg stance for 30 seconds during any of the three trials), comparing those in the exposed groups to those in the referent group. For contrast sensitivity, we compared the mean difference in contrast scores between all exposed individuals and the referent group at each spatial frequency. Due to the smaller sample size for this analysis after excluding those with poor vision we did not evaluate associations at different levels of exposure (i.e., low/medium/high or low/high) as was done for the other outcomes.

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To assess trends in the associations between exposures and outcomes, we additionally assigned each individual the median value of their cumulative $PM_{2.5}$ exposure category and then treated these as continuous measures in regressions (subsequently referred to as the test of trend). This approach reduces the impact of extreme datapoints which may distort associations. As average $PM_{2.5}$ exposure data were clustered to begin with, we assigned a value of 29 μg/m^3 to individuals in the low exposure group (which comprised all individuals originally with values of 10 or 29 μg/m^3 – the latter being much more prevalent) and 97 μg/m^3 (the only value in that group) to individuals in the high exposure group.

We used a directed acyclic graph(40) to identify potential confounders of the relationships of interest and used Dagitty software to identify a minimally sufficient adjustment set (Figure S3.)(41). Models were adjusted for age (years; collected at the home visit), alcohol use (current, former, or never drinker; collected at enrollment), OSRC-related cumulative total hydrocarbon exposure (ppb-days, sum of the average daily exposure across all days of work; continuous(42)), smoking status (heavy current [≥20 cigarettes/day], light current [<20 cigarettes/day], former, or never smoker; collected at enrollment), educational attainment (less than high school/equivalent; high school diploma/GED; some college/2 year degree; 4 year college graduate or more; collected at enrollment), and self-identified race(43) (White, Black, Other; collected at enrollment). For analysis, self-identified race was collapsed into White, Black, and Other due to a small number of respondents who were not Black or White, although when asked to self-identify, participants were given more than three options (see Supplementary Information for all response options). We adjusted for THC rather than for benzene, toluene, ethylbenzene, and xylene separately because our study population contained only a relatively small number of PM-exposed workers and models containing multiple chemical exposures did not converge. We did not adjust for ethnicity as Hispanic participants (n=28) comprised <2.4% of the analytic sample. Education was used as a proxy for socioeconomic status. We additionally adjusted for body mass index (BMI) measured at enrollment in models of vibrotactile threshold, postural sway, and visual contrast sensitivity. There were issues of model convergence when attempting to adjust for BMI in models of the single leg stance. This additional adjustment did not appreciably change our findings and will not be reported on further. Models of vibrotactile threshold were additionally adjusted for height (continuous; measured at the home visit).(44) We also adjusted for vision correction in models of contrast sensitivity.

In sensitivity analyses, we ran models with additional adjustment for gender, and models restricted to male participants; small numbers of female participants precluded conducting analyses stratified by gender. To investigate modification by age, we created a dichotomous age variable (<50 years, ≥50 years) and examined estimates within age strata. This approach was used for all outcomes (continuous and dichotomous) except contrast sensitivity. We then used likelihood ratio tests to compare models with and without a multiplicative interaction term between age category and each exposure category. For contrast sensitivity, we compared the age stratum-specific differences to determine if they were substantive and assessed the significance of a multiplicative interaction term for dichotomized age included in the model. We examined the correlations between spill-related $PM_{2.5}$ and THC to evaluate whether collinearity of these pollutants was likely to be an issue when estimating the associations between $PM_{2.5}$ and the PNS outcomes. To further assess confounding by

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THC exposure, we excluded workers in the top 10% and, separately, top 25% of the THC exposure distribution. In this analysis we retained the original range that defined our tertiles of $PM_{2.5}$ exposure rather than generating tertiles based on the new distribution of $PM_{2.5}$ exposure. The development of the THC exposure estimates is described elsewhere.(42, 45) We additionally adjusted for ambient styrene to assess confounding by this pollutant as it was associated with some of our outcomes in previous GuLF Study work.(46)

All statistical analyses were conducted in SAS version 9.4 (Cary, NC, USA, SAS Institute Inc.). Figures were created using RStudio version 1.3.1073 (Vienna, Austria. R Foundation).

Results

2.5. Study cohort

There were several differences between the individuals in the exposed and the referent groups (Table 1). Notably, over half (51.6%) of the exposed group identified as Black while only 20.6% of the referent group did. Although the cohort in general was predominantly male, the proportion was even larger in the exposed group, with only 8.9% female participants compared to 12.8% in the referent group. Among workers who worked on the water, a smaller proportion was Black (16.2%) than White (68.5%); however, among these workers, we saw different distributions of race by work area: 5.2% of Black workers worked only in the hot zone, 29.7% worked in the hot zone/source, and 0.7% worked on the *in situ* burns; among White workers, the corresponding percentages were 0.8%, 10.2%, and 0.3%. The remainder of workers worked offshore, nearshore, or on the water but with the specific location unknown.

2.6. Associations between $PM_{2.5}$ and PNS outcomes

Standing steadiness, measured by postural sway, did not differ appreciably by average or cumulative $PM_{2.5}$ exposure for tests with eyes either open or closed. (Figure 1.) There was no evidence of an exposure-response relationship (p value for trend, average $PM_{2.5}$, eyes closed: 0.49; eyes open: 0.19; cumulative $PM_{2.5}$ exposures, eyes closed: 0.97; eyes open: 0.30).

For tests of vibrotactile threshold, the high average $PM_{2.5}$ group was less sensitive to vibrotactile stimuli than the low average $PM_{2.5}$ group although the estimates were not substantially different (Figure 1.). Similar associations were observed for each level of exposure compared to the referent for cumulative $PM_{2.5}$ exposure and 95% confidence intervals for all estimates included the null. There was no evidence of a trend in the exposure-response relationships (p value for test of trend, average $PM_{2.5}$ exposure: 0.11; cumulative $PM_{2.5}$ exposure: 0.23).

For visual contrast sensitivity, five exposed participants and 30 referent group participants who did not have a result for visual acuity were excluded. Mean differences in visual contrast sensitivity scores did not differ appreciably between the exposed and the referent groups overall (Figure 2).

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For the single leg stance test, individuals in the high average $PM_{2.5}$ exposure level were 30% more likely (PR: 1.30; 95% CI: 0.66, 2.55) and those in the low average $PM_{2.5}$ exposure level were 37% more likely (PR: 1.37; 95% CI: 1.02, 1.84) than those in the referent level to lose balance (Figure 3.). However, the high exposure group did not reach statistical significance. Those in the high cumulative $PM_{2.5}$ level were 62% more likely than those in the referent level to lose balance (PR: 1.62; 95% CI: 1.08, 2.42). The estimates for the low and medium cumulative $PM_{2.5}$ groups were closer to the null. Trend of average $PM_{2.5}$ exposures on single leg stance was not significant (p for trend=0.11) but trend of cumulative $PM_{2.5}$ exposures was significant (p for trend=0.03).

2.7. Sensitivity analyses

Restrictions/adjustments for gender, and adjustment for styrene made no substantive difference to our findings. For postural sway, age-stratified estimates did not diverge substantially (interaction p values: range=0.48–0.91) from each other (Figure S4.). For vibrotactile threshold, low cumulative $PM_{2.5}$ exposure was associated with less sensitivity (compared to the referent) to vibrotactile stimuli for the older group, but little difference was observed for the younger group. We found no other important age-related differences in vibrotactile threshold (interaction p values: range=0.28–0.57) (Figure S4.). For visual contrast sensitivity, we observed slightly better performance among the exposed at 6 and 12 cycles/degree in the older subjects and no effect in the younger subjects for any cycles/degree (Figure S5). For the single leg stance, prevalence ratios were higher among younger workers, with apparent exposure-response trends in this group for average and cumulative $PM_{2.5}$ exposures; based on the presence of monotonic trends. There was some evidence of modification by age (p value from the likelihood ratio comparing models with and without interaction terms: 0.01 for average $PM_{2.5}$ exposure, 0.06 for cumulative $PM_{2.5}$ exposure) (Figure S6.).

After removal of the individuals most highly exposed to THC (the top 10% and, separately, the top 25% of the exposure distribution) the high cumulative $PM_{2.5}$ group had somewhat strengthened associations for postural sway and vibrotactile threshold (Figures S7). Otherwise, there were no notable differences for postural sway, vibrotactile threshold, or visual contrast sensitivity (Figures S7., S8.). For the single leg stance, estimates were slightly closer to the null and much less precise for average $PM_{2.5}$ exposure but stronger than our main findings for high cumulative $PM_{2.5}$ exposure (Figure S9). However, there was no clear exposure-response trend, as removal of the highest THC exposed participants resulted predominantly in estimates closer to the null for the low and medium cumulative $PM_{2.5}$.

3. Discussion

We examined the relationship between $PM_{2.5}$ exposure and four measures of sensory and motor nerve function. The source of the $PM_{2.5}$ was the combustion of oil and gas, which was used as a remediation tactic following the *DWH* oil spill. Other mitigation measures exist and could be implemented following such disasters, so it is critical to understand to what extent mitigation practices may be harmful to the workers involved in the cleanup. Our

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results provide weak evidence of an adverse association between average $PM_{2.5}$ exposure and the ability to maintain a single leg stance, and some evidence of an association between cumulative $PM_{2.5}$ exposure and this outcome among younger workers. We did not observe associations with any of the other neurological measures and found no other effect measure modification by age. Excluding individuals with the highest THC exposures from analyses to account for possible co-pollutant confounding did not change our interpretations, although this exclusion did somewhat strengthen the effects observed for the single leg stance, postural sway, and vibrotactile threshold among workers with high cumulative $PM_{2.5}$ exposure.

The size distribution, composition, and associated health effects of exposure to $PM_{2.5}$ from burning/flaring of oil/gas may differ from those for other sources of $PM_{2.5}$. The particle size distribution from combustion can vary depending on the conditions of the combustion and the fuel; in one study of the controlled combustion of residual oil fuel, ultrafine particles were almost exclusively produced when the fuel was burned most efficiently.(7) A second study found higher particle number concentrations at higher temperatures but found the lifetime of ultrafine particles was on the scale of seconds; over time, the particle number concentrations decreased as the particle size increased.(6) Although the generation and movement of smoke plumes resulting from *in situ* combustion of oil on water have been described in a handful of studies the composition of $PM_{2.5}$ in these plumes has not been well characterized.(47, 48) During gas flaring events, black carbon is produced in high quantities although the yield is impacted by the flare gas composition.(49) A previous examination of the genotoxic effects of $PM_{2.5}$ from the Kuwait oil fires on human cells did not find these differed substantially from the genotoxic effects of $PM_{2.5}$ from a comparison sample from Washington, D.C., although the authors noted differing methodological approaches that limited direct comparisons. (50) In a recent effort to investigate the specific components of PM that may be driving neurotoxic effects, researchers examined adult and gestational exposure to a) total nanoparticles and b) nanoparticles depleted in polycyclic aromatic hydrocarbons (PAHs) and transition metals using a mouse model. They found similar responses to both types of nanoparticles overall and hypothesized that these effects might relate to the specific transition metals and organics still present in both types of samples.(51) Importantly, inhaled particles can translocate to the brain via the olfactory nerve.(8, 9) Once there, they can induce inflammation and oxidative stress (11), thus causing neuronal toxicity and highlighting a potential mechanism of effect for these exposures.(10)

Impairments in the function of sensory and motor peripheral nerves are common as individuals age, and can lead to challenges in mobility as they progress, thereby having far-reaching impacts on quality of life.(52) Unlike aging, the exposures we examined are preventable. Among the measures used in the current study, vibrotactile threshold of the great toe and postural sway with eyes closed are the most sensitive for detecting distal axonal neuropathy. However, we did not find broad evidence of an association between exposure to $PM_{2.5}$ and these measures.

We found a higher prevalence of failure to perform the 30-second single leg stance among those exposed to the high vs. referent cumulative levels of $PM_{2.5}$. Although also related to balance, our results were largely null for the postural sway outcomes. Both

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measures require maintenance of an upright stance; this behavior requires intact lower extremity musculature (muscle strength), motor coordination of the lower extremity muscles (cerebellar function), motor neurons (peripheral nervous system), proprioception (joint position sensation), peripheral nervous system sensory nerves, vestibular function, and vision. Visual impairment and changes in postural coordination may also lead to greater sway.(53) In the current work, we are unable to identify distinct physiological causes of the observed deficits in balance; if the association is causal, any of these systems could be implicated. In addition, factors such as ankle strength and range of motion, which were unmeasured but which can affect an individual's ability to complete the single leg stance,(54) may have differed between our analytic groups and resulted in the observed differences. However, we lack the data necessary to assess this issue further (i.e., to evaluate whether these effects may be non-differential). In our analytic sample, there was low but significant correlation (Spearman) between mean length of the single length stance attained across all three trials and mean response across trials on the postural sway tests, assessed separately for trials with eyes open (correlation: −0.25) vs eyes closed (correlation: −0.19). It is possible that the significant finding for single leg stance for cumulative exposure was due to chance as we found no exposure-response trend for average exposure and in fact the association for low but not high average exposure was significant. In the literature, there is some evidence of impairment in balance tasks among those exposed to higher concentrations of air pollutants(46) including diesel exhaust (which contains $PM_{2.5}$), although little of this work has focused on $PM_{2.5}$. In a study in three Mexican cities, young, healthy individuals exposed to $PM_{2.5}$ above the U.S. Environmental Protection Agency (EPA) annual standard displayed deficits in balance and gait.(55) The average $PM_{2.5}$ level estimated for the highest exposed group in our study exceeds the EPA's 24-hr average for the general population.

Deficits in visual contrast sensitivity have previously been associated with exposure to a range of contaminants including tetrachloroethylene,(56) styrene,(57, 58) mixed solvents, (59, 60) lead, mercury,(61) and algae (*Pfiesteria sp.*).(62, 63) However, we did not find strong evidence of an association between $PM_{2.5}$ and visual contrast sensitivity. Contrast sensitivity generally declines with age, even in the absence of pathology; this decline may be attributable to changes in the neural rather than the optical system, although this is a topic of debate.(64) While we did find some suggestive differences by age group, to our knowledge no biological basis has been proposed for observed differences by age at some, but not all, frequencies.

Our study has several strengths. First, our use of quantitative exposure estimates for PM rather than relatively crude proxies of exposure (e.g., job category, distance from spill - approaches used in previous studies of oil spill workers) provides a more refined metric of exposure. The methods used to generate these quantitative estimates went beyond those used previously, giving us high confidence that there is minimal misclassification in our categories of exposure. Second, the GuLF Study collected data from study participants on a wide range of covariates allowing for adjustment of numerous potential confounders and facilitating a more accurate estimate of the $PM_{2.5}$ – PNS associations. Third, we used objective, quantitative measures of sensory and motor nerve function that are sensitive to subclinical impairments. These measures have high test-retest reliability and validity, (38, 65–68) and have been used successfully in previous studies of worker populations

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and of individuals living near environments where known neurotoxicants are used (e.g., farms, dry-cleaning facilities).(69–72) Additional details on the measures are provided in the Supplementary Information. Last, our sample was relatively large for a study using these measures; most other studies employing these measures had fewer than one hundred participants.

Our study also has several limitations. First, while the GuLF Study cohort is large (n=32,608), the outcome measures used in these analyses were obtained during the clinical exam, which, for practical reasons, was administered to only a subset of the cohort (n= 3,401), selected via stratified random sampling of subjects residing within 60 miles of either of two study clinics. After exclusions, our sample size was at most 1,186 individuals, 214 of whom were classified as exposed to $PM_{2.5}$. The relatively small number of exposed individuals led to some imprecision in our estimates of association. This was especially problematic for the assessment of contrast sensitivity, as only those with adequate visual acuity (n=915) were included in the analysis. This sample size also limited our ability to adjust for all potential confounders, although we believe that we were able to include the most important confounders in our analyses. The small sample size may also limit generalizability to the larger group of cleanup workers. Second, while our use of estimated $PM_{2.5}$ for each individual goes beyond what has been used previously in similar studies, it still leaves room for exposure misclassification. The estimates themselves were prone to error.(32) In addition, we did not know the exact days when most of the individuals worked, nor their exact work areas during those days. As a result, we assigned average $PM_{2.5}$ exposures to water workers over large areas of the Gulf of Mexico, modified by the proportion of days that the burning/flaring period occurred over each individual's employment period, and all of the jobs/activities performed over the burning/flaring period. Modeling the $PM_{2.5}$ size distribution and chemistry for these highly variable burn events is inherently challenging as these factors can change over the course of the burn, with more complete combustion typically occurring earlier in the burn. The Gaussian air dispersion models do not account for chemistry or changes in particle size distribution, although these may be important factors in understanding the potential health effects of these exposures. In addition, the groups were defined based on model estimates of air concentrations from flaring (on-going) and in-situ burning (event-based) that do not include background concentrations or emissions from vessel operations. As such they represent estimates of the potential increase in exposure from the flares and burns and thus underestimate total exposure from all sources. Also, the estimates are for points in space and time that do not account for worker movements or variations in breathing rates.

Third, there may have been selection bias into the GuLF Study or the clinical examinations, as not all potentially eligible workers could be reached or chose to participate in the study. In addition, there is the possibility of a healthy worker effect among those included in our analysis, such that individuals who participated in the cleanup and response were likely healthier than the general population. This may limit the generalizability of our findings. Fourth, our ability to understand exposures to $PM_{2.5}$ experienced in the intervening years is limited to ambient air quality data available through regulatory monitors. From the USEPA, we can see that the annual average $PM_{2.5}$ for the Southern US (here comprising Arkansas, Kansas, Texas, Louisiana, Mississippi, and Oklahoma) has remained $<13 \mu g/m^3$ since 2010.

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(73) While this does not negate potentially higher exposures for brief periods of time during these intervening years we do not have any reason to believe that individuals in our analytic sample would have experienced concentrations of $PM_{2.5}$ following the cleanup effort that were on par with the higher exposures experienced during the cleanup. Last, although our outcome measures can point to deficits in peripheral nerve function, these measures also rely on the proper functioning of other biological systems.

In conclusion, our measures of sensory and motor nerve function provided sensitive, subclinical tests of neurotoxicity, and our estimates of exposure go beyond the exposure metrics previously used in research of oil spills and health. We found an association between exposure to high levels of cumulative $PM_{2.5}$ and the single leg stance but no associations for other outcome measures or levels of exposure. Overall, our results provide limited evidence of a neurotoxic effect of $PM_{2.5}$ from burning/flaring of oil/gas during the response and cleanup effort following the *DWH* oil spill.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

The data are not available on-line for replication, but requests for study data to be shared under individualized Data Sharing Agreements may be made through the GuLF Study management site (see instructions at https://gulfstudy.nih.gov/en/forresearchers.html).

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Impact statement:

Remediating environmental disasters is essential for long-term human and environmental health. During the Deepwater Horizon oil spill disaster, burning and flaring of oil and gas were used to remove these pollutants from the environment, but led to potentially high fine particulate matter exposures for spill response workers working on the water. We investigate the potential adverse effects of these exposures on peripheral nerve outcomes; understanding the potential health harm of remediation tactics is necessary to inform future clean up approaches and protect human health.

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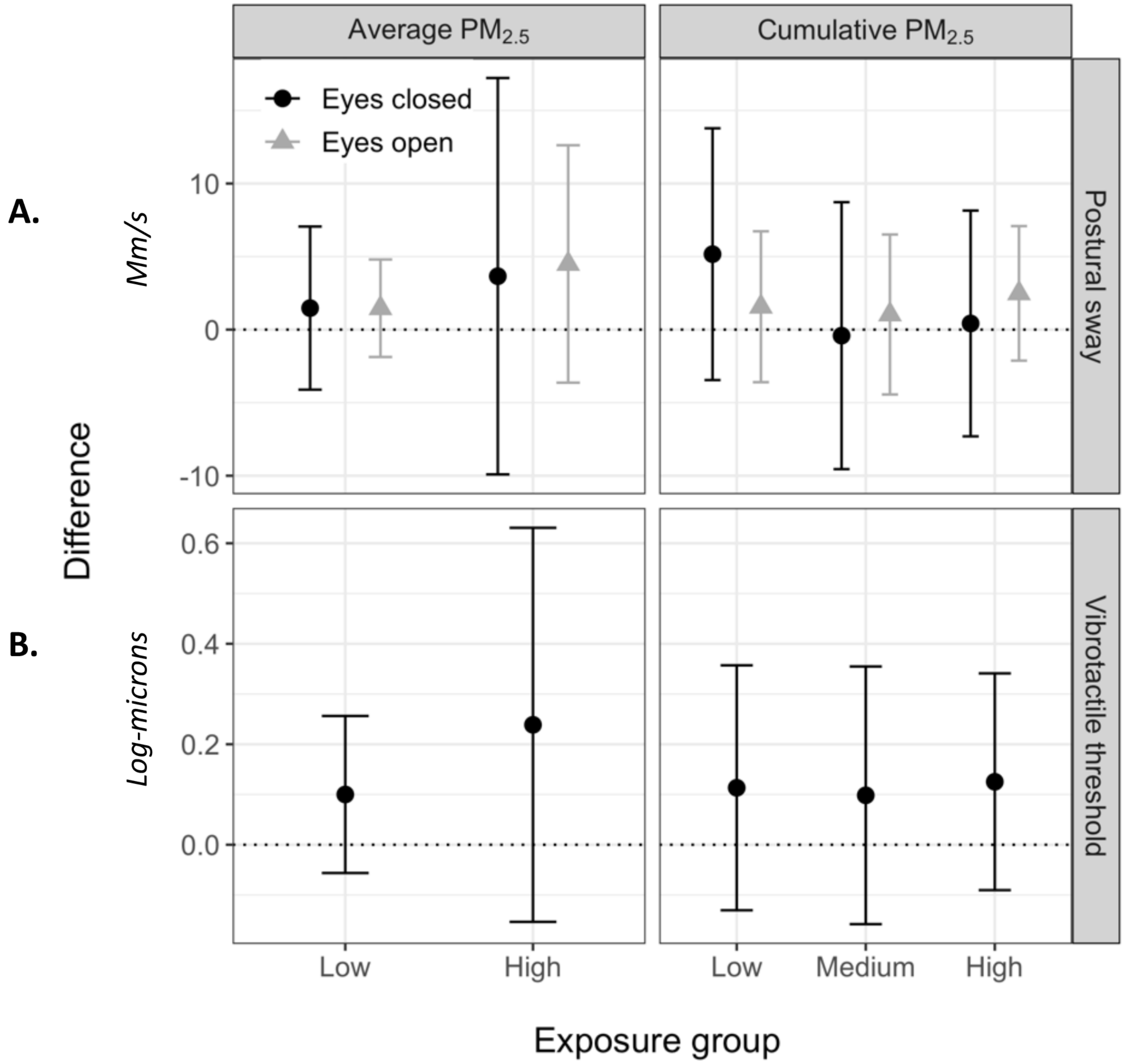

Figure 1.

Associations between average or cumulative $PM_{2.5}$ and (A.) postural sway (trials: eyes open and eyes closed, measured in mm/s) and (B.) vibrotactile threshold (measured in log-microns); each point estimate with 95% confidence interval depicts the difference between the estimate for that exposure level and the estimate for the referent level. Estimates were adjusted for age, alcohol consumption, smoking status, total cumulative hydrocarbon exposure, education and race, with vibrotactile threshold additionally adjusted for height. The number of observations used in analysis is as follows: postural sway (eyes open) – 1,146; postural sway (eyes closed) – 1,141; vibrotactile threshold – 1,144.

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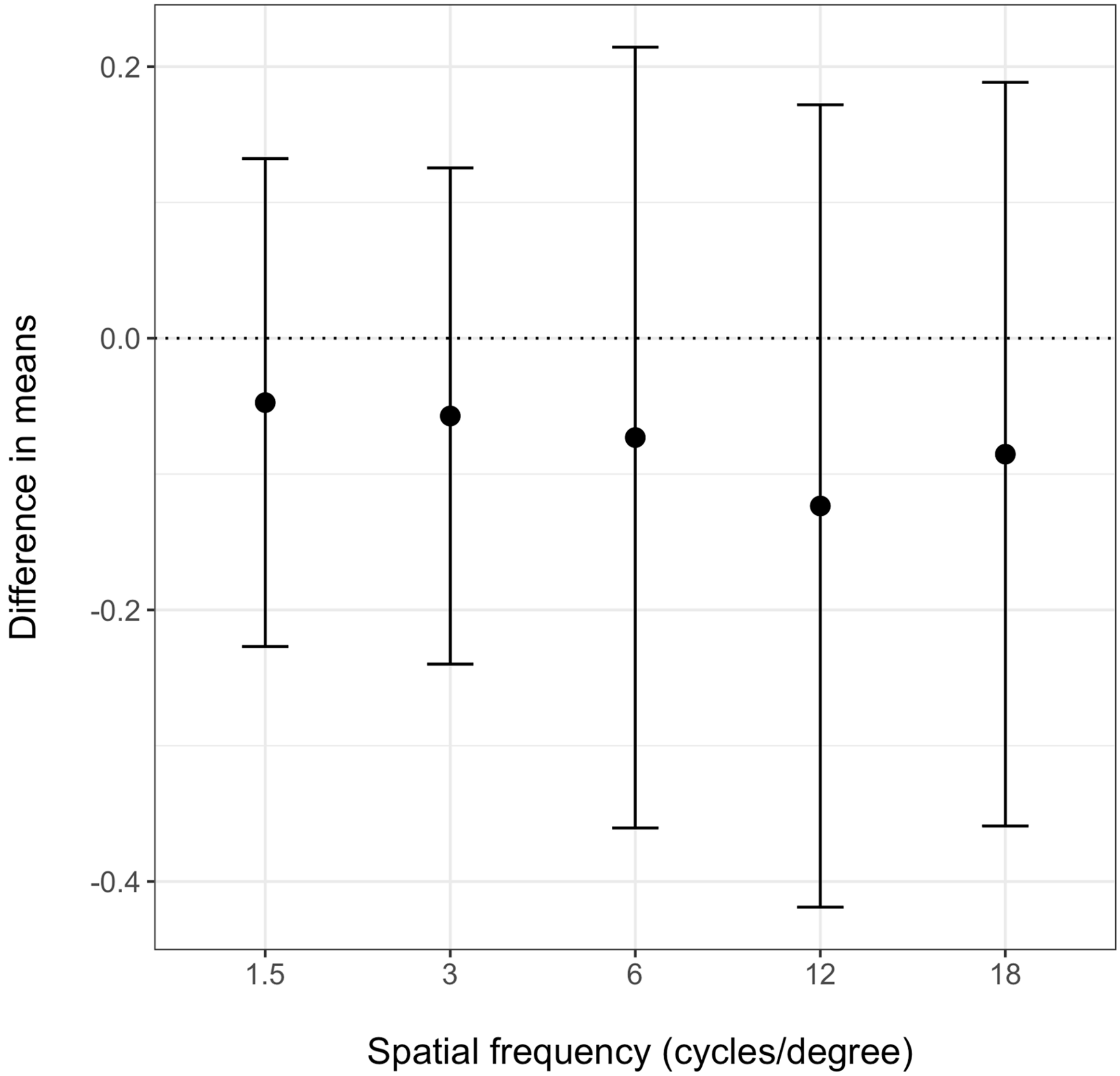

Figure 2.
Mean differences (and 95% confidence intervals) in visual contrast sensitivity scores, measured at five spatial frequencies, between the exposed (n=155) and the referent groups (n=711). Models are adjusted for age, alcohol consumption, smoking status, total cumulative hydrocarbon exposure, education, race, and vision correction. Values below 0 indicate a better performance for the exposed group than the referent group.

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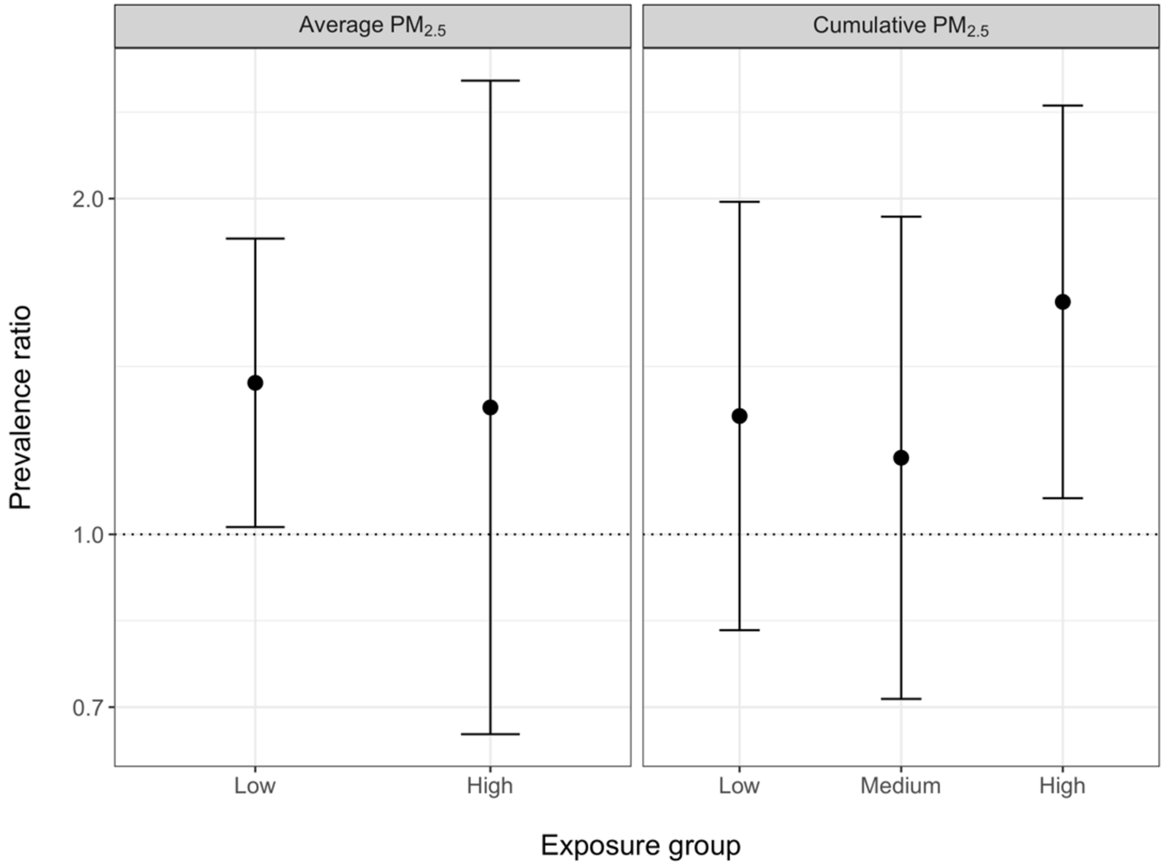

Figure 3.
Prevalence ratios and 95% confidence intervals for failure to hold the single leg stance for 30 seconds, comparing individuals at each exposure level to the referent group (total n=1,136). Models were adjusted for age, alcohol consumption, smoking status, total cumulative hydrocarbon exposure, education, and race.

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Table 1.

Characteristics of the analytic study population by $PM_{2.5}$ exposure status. Age and height were collected at the home visit. Sex, smoking, alcohol, education and race data were collected at enrollment.

	Above-referent $PM_{2.5}$ exposed workers (n=214)	Referent (n=972)
	n (%)	*n (%)*
Sex		
Female	19 (8.9)	124 (12.8)
Male	195 (91.1)	848 (87.2)
Missing	0	0
Lifetime smoking		
Heavy current smoker	20 (9.5)	130 (13.5)
Light current smoker	69 (32.7)	190 (19.7)
Former smoker	44 (20.9)	232 (24.1)
Never smoker	78 (37.0)	411 (42.7)
Missing (n)	3	9
Lifetime consumption of alcohol		
Current drinker	165 (77.1)	699 (72.1)
Former drinker	33 (15.4)	206 (21.3)
Never drinker	16 (7.5)	64 (6.6)
Missing (n)	0	3
Highest educational attainment		
Less than high school/equivalent	64 (29.9)	242 (24.9)
High school diploma/GED	79 (36.9)	299 (30.8)
Some college/2-year degree	47 (22.0)	298 (30.7)
4 Year college graduate or more	24 (11.2)	132 (13.6)
Missing (n)	0	1
Race		
White	85 (39.9)	670 (69.0)
Black	110 (51.6)	200 (20.6)
Asian	1 (0.5)	10 (1.0)
Other	5 (2.4)	69 (7.1)
Other/Multi-racial	12 (5.6)	22 (2.3)
Missing (n)	1	1
	Mean (standard deviation)	*Mean (standard deviation)*
Age (years)	42.6 (12.3)	46.4 (13.4)
Missing (n)	0	0
Height (inches)	69.3 (3.4)	68.7 (3.5)
Missing (n)	1	8
Body mass index (kg/m^2)	28.9 (6.6)	29.0 (6.3)
Missing (n)*	1	7
Total hydrocarbon exposure (ppm-days)**	125.4 (95.3)	78.0 (58.4)

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	Above-referent $PM_{2.5}$ exposed workers (n=214)	Referent (n=972)
Missing (n)	0	0

*The body mass index calculation used data from the home visit, hence the different number of missing values between height and body mass index.

**Sum of average daily exposures across all days of work