Published in final edited form as:

J Expo Sci Environ Epidemiol. 2018 May ; 28(3): 223–230. doi:10.1038/jes.2017.16.

Development of a Total Hydrocarbon Ordinal Job-Exposure Matrix for Workers Responding to the *Deepwater Horizon* Disaster: The GuLF STUDY

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Abstract

Background.—The GuLF STUDY is a cohort study investigating the health of workers who responded to the *Deepwater Horizon* oil spill in the Gulf of Mexico in 2010.

Objectives.—To develop an ordinal job-exposure matrix (JEM) of airborne total hydrocarbons (THC), dispersants and particulates to estimate study participants' exposures.

Methods.—Information was collected on participants' spill-related tasks. A JEM of exposure groups (EGs) was developed from tasks and THC air measurements taken during and after the spill, using relevant exposure determinants. THC arithmetic means were developed for the EG, assigned an ordinal value, and linked to the participants using determinants from the questionnaire.

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Competing Financial Interests
The authors have no actual or potential competing financial conflicts to declare.

Supplementary information is available at the Journal of Exposure Science and Environmental Epidemiology's website.

Different approaches were taken for combining exposures across EGs. EGs for dispersants and particulates were based on questionnaire responses.

Results.—Considerable differences in THC exposure levels were found among EGs. Based on the maximum THC level participants experienced across any job held, about 14% of the subjects were identified in the highest exposure category. Approximately 10% of the cohort was exposed to dispersants or particulates.

Conclusions.—Considerable differences were found across exposures of the various EGs, which facilitates investigation of exposure-response relationships. The JEM is flexible to allow for different assumptions about several possibly relevant exposure metrics.

Keywords

Deepwater Horizon; exposure assessment; oil drilling; dispersants; job exposure matrix; total hydrocarbons; particulate

Introduction

The GuLF STUDY is a prospective cohort study of workers involved in the oil spill response or cleanup (OSRC) of almost 5 million barrels of oil released following the *Deepwater Horizon* explosion in the Gulf of Mexico on April 20, 2010. Studies of previous oil spills have identified a number of health effects including respiratory, dermal, hematologic, somatic, and mental health disturbances[1], but had limited exposure data. The GuLF STUDY is investigating potential health effects from exposure to chemicals associated with crude oil, dispersants used to break up the oil, and burning oil. Workers completed a structured interview on tasks performed during their OSRC work, health status, and demographic, life style and other factors[2].

Our goal here was to develop a proxy for the oil experience. We had a large number of samples available from BP, the corporation designated as the Responsible Party of the *Deepwater Horizon* disaster. The samples collected total hydrocarbons (THC), benzene, ethylbenzene, toluene and xylene; and, on a subset of the samples, cyclohexane, heptane, hexane, and trimethylbenzenes; and 2-butoxyethanol, a component of one of the dispersants applied. Because THC comprises the oil components measured by the samples and other unmeasured volatile oil components, we chose it to represent the oil experience.

Here, we describe the development of ordinal estimates of exposure to total hydrocarbons (THC), a composite of the volatile chemicals in the crude oil; and qualitative estimates of dispersants and of particulates from oil burning for the study participants. We describe: 1) the measurements used to develop the ordinal THC estimates; 2) development of exposure groups (EGs); 3) construction of a job-exposure matrix (JEM) containing THC exposure estimates for the EGs; and 4) linkage of these estimates to the study participants. We also describe how exposure variables were developed for dispersants and particulates.

Materials and Methods

Background

The GuLF STUDY comprises 32 608 study participants who completed safety training and/or performed spill-related work[2,3]. Participants were administered a computer-assisted telephone interview by trained interviewers. A total of 7671 individuals who took the training but were not hired (“non-workers”) were enrolled to constitute an unexposed population. The remaining 24 937, the subject of this exposure assessment, participated in OSRC work for at least one day between April 20, 2010 and June 30, 2011.

In contrast to most occupational cohort studies that are industry-based, there was no single company or small number of companies that could provide information on work histories, operational procedures or exposures. BP had hired hundreds of contractors and subcontractors to perform OSRC work. Additionally, workers from government, academia and other non-profit organizations and volunteers participated in the OSRC. By the time the GuLF STUDY started, much of the OSRC had been completed, which limited opportunities to observe the OSRC environment and tasks. Air measurements of workers’ personal exposures (see below) collected by BP’s contractors and government agencies and other reports, therefore, provided information on various jobs and tasks and were used to develop OSRC-related questions for the questionnaire.

Total Hydrocarbons

Measurements Description—The number of THC measurements taken by any single government agency was small (<100), of short-duration (≤ 4 h) and generally reported as non-detectable and therefore too limited to support the development of the STUDY’s exposure estimates. Because the data collected by BP contractors generally represented full-shift exposures and covered many more exposure situations, those measurements were used to develop the exposure estimates. Approximately 28 000 full-shift airborne THC measurements were collected from passive dosimeters (3M 3500 or 3520 (3M, St. Paul, Minnesota), or Assay Technology 521 (AFC, DeMotte, Indiana), organic vapor badges) on OSRC workers from late April 2010 to June 2011. Two accredited laboratories analyzed the samples using NIOSH Methods 1500 (hydrocarbons), 1501 (aromatic hydrocarbons) or 1550 (naphthas)[4] to provide results equivalent to THC concentrations. These labs reported the limit of detection (LOD) of ~0.4 ppm for a 12-hour sample, rather than the analytic method’s (lower) sensitivity. We obtained data from the laboratories that allowed us to recalculate the measurement results to reflect the analytical sensitivity of the method, resulting in the lowering of the LODs to 0.1 or 0.01 ppm, depending on the lab (based on a 12-h sample duration), which reduced the percentage of censored THC measurements from 82% to 19%.

Samples collected for <4 h or >18 h (<5% of the samples) were excluded as not representative of full-shift exposures (workshifts of 8->12 h). After also excluding invalid samples (e.g., badge not properly capped or no start/end times recorded), 26 588 samples remained.

Development of EGs—Although in the GULF STUDY, the number of measurements compared to the number of participants is much larger than in many epidemiologic studies, most study participants were infrequently or never measured. As is typical of occupational studies with incomplete coverage of measurements, we developed groups of participants (exposure groups, EGs) who were expected to have a similar distribution of exposure based on the participants' job/task and/or other exposure determinants.

The questionnaire formed the basis of information for developing EGs. Questions asked if the participant worked on a drilling rig vessel, on another boat or vessel, or on land. If on a rig, the name of the rig and work at six locations on the rig were sought. Later, the questionnaire was modified to collect job title. Positive responses to having worked on a boat/vessel or on land were followed by questions on 109 tasks. If the response was positive for any of these water- or land-based tasks, the dates worked, the number of h/day, and days/two-wk period were asked for each rig vessel job or each water or land task. The median time to complete this exposure component of the questionnaire was 20 minutes.

Initial EGs were based on job titles (for rig workers) and tasks (for all other participants) obtained from the questionnaire. The EGs were then modified based on additional exposure determinants identified from the questionnaire to include: vessel/vessel type (four rigs; 14 remotely operated vehicle (ROV) vessels; and 28 research vessels), area, state, and time period (Table 1). Rig workers worked on one of four drilling rig vessels directly involved in stopping the oil release, collecting leaked oil and drilling relief wells in the area. Each EG was defined by a job title, rig, and time period. The vessels that operated ROVs generally were located near the wellhead and performed a variety of operations on the Gulf floor. Research vessels monitored the water, the oil plume, and wildlife. Because we did not collect job title in the questionnaire on either of these vessels types, all workers on each identified ROV or research vessel comprised a single EG. The other almost 9000 vessels involved in OSRC throughout the Gulf and along the shoreline[5], included barges; marine and fishing vessels; tug and crew boats; and smaller recreational boats. These vessels supported the rigs' and other vessels' operations, scouted for oil, deployed/retrieved boom and skimmed or burned oil. On land, workers scouted for oil on beaches, cleaned beaches, decontaminated equipment, and supported all operations (supplying food and water, storing and positioning equipment, security, administration, etc.). We based the other vessels and all land EGs on task/area/state/time periods.

The physical location of the oil spill effort primarily covered the Gulf of Mexico along the >1100 linear mi coastline east from Louisiana to Florida and from the coastline to approximately 75 nautical mi (nmi) south of the southernmost point of Louisiana. Because exposures may have varied considerably over this region, we identified six areas: the hot zone (≤1 nmi from the wellhead); source (>1–5 nmi from the wellhead); offshore (>5 nmi from the wellhead to >3 nmi from the shore); nearshore (≤3 nmi from the shore); land/beaches and marshes; land/ports and docks; and land/other. The time period also affected exposure because OSRC tasks changed over time and the concentration of the oil components changed as the released oil weathered over time. To reflect these changes we identified seven time periods (Table 2). The determinant of state had four values: Louisiana, Mississippi, Alabama and Florida. Thus, we developed EGs that were unique combinations of participants with the job title or task/vessel or vessel type (if on water)/area/state/time period, where members of each EG were expected to have a similar distribution of exposures. The exposure estimate for a specific EG was assigned to all days within the time period.

Development of the Exposure Estimates—The goal of the exposure assessment effort was to assign exposure estimates of THC, dispersants and particulates. For THC, the large database of measurements allowed us to develop ordinal exposure categories developed from the measurements to represent the range of THC exposure levels experienced by the study participants. In contrast, there were less than 1000 personal measurements of dispersant vapor concentration, and one of the major sources of dispersant applications (aerial application to the water surface) was not directly measured at all. There were no particulate measurements of the two primary sources of particulate (oil/gas burning at the wellhead and *in situ* burning offshore). For this reason, we based our estimates for dispersants and particulate exposure on the questionnaire responses alone.

Categorization of Study Participants

OSRC work: Previous epidemiologic analyses of oil spill studies have evaluated workers' exposures qualitatively (Aguilera et al, 2010). To allow for a comparable evaluation of potential health effects associated with specific types of OSRC work, we categorized the EGs into six broad OSRC classes that roughly reflect a hierarchical classification of exposure to oil-related chemicals: 1) Response workers worked on the rig vessels or vessels supporting the response in the hot zone or source areas (e.g., dispersant application or ROV vessels); 2) Support/operations workers handled oily waste, generally on land; 3) Cleanup/water workers worked on vessels, not included in 1) above; 4) Decontamination workers decontaminated vessels, equipment, personnel and wildlife of oil; 5) Cleanup/land workers performed beach cleanup tasks; and 6) Support/administration workers (e.g., cooks, security, administration).

Ordinal THC levels: Most EGs (90%) had <20 measurements or a high degree of censoring (>50%), which could result in error in the exposure estimates. We evaluated several statistical methods to determine how well they estimated arithmetic and geometric means (AM and GMs, respectively), geometric standard deviations (GSDs) and 95th percentiles in the presence of high censoring, small n, large variability and various LODs (i.e. situations encountered in our data)[6,7]. The Bayesian approach proposed and implemented in Huynh et al.[7] was adopted because it had a bias and root mean squared error comparable to the best of the methods evaluated. Also, the estimates generally fell within the 95% credible intervals (similar to 95% confidence intervals) of the estimate, intervals that could not be calculated from the other method. Based on these results, ≥5 measurements with ≤80% censoring was considered to be the minimal criteria for developing THC ordinal exposure estimates for an EG. The number of samples, the Bayesian estimated AM, and GSD were calculated for each EG. The AM was assigned to a log-mimicking ordinal intensity category: 1=<0.03, 2=0.03–0.09, 3=0.1–0.29, 4=0.3–0.99, 5=1.00–2.99, 6=3–9.99, 7=≥10 ppm.

For each EG, we assigned a relative confidence level on a scale of 1–5 that represented the confidence in the exposure estimate (Table S1) to allow epidemiologists to use in sensitivity or subgroup analyses.

When an AM was calculated for a specific EG, all study participants were assigned that estimate. For most EGs (83%), however, an AM was not estimated due to <5 measurements or >80% censoring. In these situations, hierarchical rules were developed for assigning an estimate to an EG based on comparability of determinants (e.g., similar job title, job group, similar ship, location of the job, and same time period) (Table 1).

Study participants often reported the same dates for performing multiple tasks. Some tasks, however, tended to cluster among the workers, so we grouped closely-related water tasks or land tasks that had similar ordinal exposures or few measurements and assigned new ordinal estimates from the AMs of the grouped measurements, reducing the number of water and land tasks from 109 to 57.

Dispersant and particulate ordinal categories: Two mixtures were applied to disperse the oil in and on the water: Corexit 9500A, containing petroleum distillates, propylene glycol and an organic sulfonic acid salt, and Corexit 9527, containing 2-butoxyethanol, an organic sulfonic acid salt and propylene glycol[8]. Three application techniques were used. The *Skandi Neptune* regularly injected Corexit 9500A at the source of the leak, 5000 ft below the surface of the water from May 15-July 15, 2010. Four vessels sprayed Corexit 9500A on the water surface in the hot zone/source area from May 15 to about July 7 when volatile organic chemicals (VOC) levels exceeded 50 ppm. Planes applied dispersant to the water surface offshore (Corexit 9527A between April 22 and May 22 and Corexit 9500A from April 27-July 19.) There were insufficient measurements and support documentation related to the dispersants to reliably estimate exposure levels across the Gulf, so we used questionnaire responses to develop EGs for dispersants. Participants were considered exposed if they responded that they had spent more than half their time: 1) working on a vessel that: handled dispersants, pumped dispersants to the wellhead or sprayed dispersants on the water surface; 2) applying dispersants by plane; 3) working outside on a deck while dispersant was sprayed by another vessel; 4) maintaining/working on dispersant-containing pumps/tanks; 5) handling/pumping dispersants; or 6) connecting/disconnecting lines containing dispersants.

Particulates from burning oil, which may be a surrogate for $PM_{2.5}$, arose from two sources. In the hot zone, the *Enterprise* flared gas May 17-July 15 and the *Q4000* flared oil with entrained gas June 15-July 15, burning ~10 000 barrels of gas (*Enterprise*) and ~10 000–15 000 barrels of oil and gas (*Q4000)* every 24 h. Four firefighting vessels in near proximity to the flares sprayed water to keep the rigs cool. Identification of these vessels came from two open-ended questions asking the name of the vessel on which the participant worked or slept. Study participants who indicated they worked on any of these six vessels were considered to have “high” particulate exposure.

Many other vessels in the hot zone and source areas could have been exposed to particulates from the *Enterprise* and *Q4000* flares. Because we do not have names of all these vessels, we used a positive response to “Did you ever work in an area where you could see the individual ships or rigs that were working in the wellhead area?" as a rough indicator of possible medium particulate exposure, as, if one were on the deck of a ship, the line of sight would be approximately 5–10 mi.

Oil on the water surface was concentrated into a thick layer by boom and ignited to burn the oil (*in situ* burns). Between April 28 and July 19, 411 *in situ* burns were conducted by 10 teams of vessels, each burn burning between 1–30 000 gal of oil and lasting <1 min-23 h (median=36 min per burn). We assigned a "low" particulate exposure category to participants who indicated they worked on a vessel that burned or helped burn oil on water, because participants were positioned upwind from the burn and because of the low number of burns compared to participants.

Assignment of OSRC workers to particulate exposure categories was hierarchical, with participants on the rig/firefighting vessels being assigned first; participants who worked near the well being assigned from the unassigned pool next; and participants involved in the *in situ* burns being assigned next. The remaining participants were categorized as "unexposed" to burning.

For both dispersants and particulates, although participants may have reported dates outside of the event dates (e.g., April 28 and July 19 for *in situ* burns), exposure was only considered in the time period within the date boundaries.

Results

We found considerable differences in exposures across the 2385 EGs, i.e. the various job title and task, vessel, vessel type, area, state, time period (TP) combinations (TableS2–S4). For example, the estimates for the 686 EGs on the rigs (i.e. rig/job title/time periods) covered almost all exposure ordinal categories (categories 2–7, 0.03-≥10 ppm THC) in TP1a-b, with 60% of the estimates greater than category 4 (>1 ppm) (Table S2). In contrast, in TP3, although ranges were similar (categories 2–6, 0.03–9.9 ppm), only about 5% of the EGs were greater than category 4. Where measurements were available, the estimates for the *Q4000*, *DD2* and *DD3* generally were lower than those of the *Enterpri*se for the same job. The GSDs were fairly high in TP1a and TP1b for the EGs on all four rigs.

Estimates for the 47 EGs associated with the ROV vessels (Outside job/vessel or vessel type/time period) (Table S3) were substantially higher (category 7, ≥10 ppm) in TP1a than on the rigs. For the remaining time periods, however, the levels were about the same as those on the rigs. Exposure estimates for workers on the research vessels (Table S3) were much lower than the rig and ROV vessels workers in TP1a-1b, (categories 3–5, 0.1–2.99 ppm) (70 EGs), but this difference disappeared after TP1b. A total of 1582 estimates were developed for water and land EGs (task/area/state/time period) (Table S4). They generally reflected similar patterns of the rig, ROV and research EGs, i.e. substantial variability across EGs, higher levels in the earlier time periods, and lower and more similar levels in the later time periods. Workers on the water had exposure levels that spanned all exposure categories for TP1a, but by TP6 most estimates were in category 4 (0.3–0.99 ppm). Workers on land had lower exposure levels across all time periods than other workers: generally category 4 (0.3–0.99 ppm).

The distribution of the participants into the six, broad hierarchical OSRC classes resulted in approximately equal numbers of participants in each class (15–20%). In contrast, the distribution of the THC estimates found that about 15% of the participants had their highest full-shift THC AM in categories 6 and 7 ($\geq$3 ppm), while approximately one-third of the participants' highest AM estimate fell in each of categories 4 or 5 (0.3–0.9 and 1.0–2.9 ppm, respectively) (Figure 1, Table 4). About 20% of the workers had their maximum AM in THC categories 1–3 (<0.3 ppm). The frequency of participants by the minimum, median and mean exposure levels across all of their jobs had very different distributions.

Based on positive responses to one of the dispersant-related questions, only about 10% of the cohort was likely to have been exposed to dispersants (not shown). For particulates, 1% were assigned to the highest particulates exposure category, whereas 8% were assigned to the medium exposure category and <1% to the low exposure category based on questionnaire responses.

Discussion

The *Deepwater Horizon* explosion in April of 2010, was the largest marine oil release in US history. The GuLF STUDY was initiated to evaluate the effect of the response and cleanup work on the health of the workers. Here we describe development of ordinal estimates of THC and qualitative estimates of dispersants and particulates. These estimates will be used to evaluate health risks associated with the oil spill experience and to serve as interim metrics until more detailed chemical-specific measures are developed.

The current JEM for THC uses exposure categories rather than quantitative estimates to reflect uncertainty in the estimates. THC is a composite of multiple volatile chemicals contained within crude oil, including the benzene, toluene, ethyl benzene, xylene, hexane, cyclohexane, heptane, hexane, and trimethylbenzenes that were measured in some or all of the samples available in this study. The oil composition changed over time as the released oil weathered due to evaporation, dispersion, emulsification, dissolution, photo-oxidation, sedimentation, and biodegradation. The THC estimates reflect these and other changes (e.g., tasks), but any associations of health outcomes with THC exposures cannot be linked to a specific crude oil chemical. Thus, even though the exposure categories were identified using actual THC exposure measurements, the THC estimates are better viewed as a surrogate representing the totality of the oil-related exposures experienced during the OSRC work, rather than any specific chemical. Future work will investigate exposure to components of THC, i.e. benzene, toluene, ethyl benzene, xylene and hexane using a variety of data sources including VOC area measurements and incorporating new statistical methods to better quantify the exposures of interest while accounting for correlations of the chemicals to THC as well as accounting for measurements below the LOD.

The ordinal levels indicate considerable differences among EGs. The findings that exposure levels varied by rig job and rig, specific vessel or by vessel type (ROV, research), task, area, state, and time period (Tables S2–S4) underscores the need to differentiate among the various EGs. Moreover, these findings agreed with expectations based on chemical and physical laws, job descriptions, and vessel functions. These differences, however, increased the complexity of the exposure assessment, in that to characterize exposure it was necessary to develop 2385 EGs.

The THC levels were low compared to occupational standards. Although no specific 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 mins[4]. Only 15 of 28 000 THC personal samples were >100 ppm, with only 3 exceeding 200 ppm. 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 the various weathering processes within a few days[9]. 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.

It is important to consider factors that affect the accuracy of all exposure assessments because misclassification can have a considerable impact on estimates of disease relative risks. Recall bias may have occurred as the exposure assignments were based on the reports of tasks by the study participants. In addition, many tasks may have been components of a broader job (e.g., putting out boom and collecting oily boom were components of skimming oil off the water surface) and thus, a measurement may have incorporated one or more tasks not indicated in the documentation.

Error may arise from the sampling strategy: taking samples of convenience may have concentrated on higher exposed jobs/tasks, which would introduce bias if measurements on low and high exposed workers were grouped. We based most of our estimates, however, on individual jobs/tasks. Although this likely did not eliminate error we believe that overall, there is likely to be little bias. The differences in jobs over time and space are in concordance with expectations from the extensive qualitative literature on the spill. Perhaps most important, the large number of measurements taken over such a short period of time (28 000 in ~436 days) under conditions of a major disaster may have minimized substantial selection biasing in the measurements. We think, therefore, that error is likely to be primarily random.

Another source of error is the categorization of exposures, rather than the use of the actual quantitative estimates. The use of categories in epidemiologic studies is a typical exposure assessment approach, but it means that everyone assigned the same exposure category gets the same value in the epidemiologic analysis (often the midpoint of the range the ordinal value represents). Although it is recognized that all participants will not, in fact, have the exact same, single exposure level, the use of categories is not likely to lead to differential misclassification. Non-differential misclassification, however, can have a considerable effect on estimates of relative risks.

Despite the very large number of measurements, there were some EGs for which we had no or few measurement data. In such cases, we assigned estimates from EGs we thought were most comparable to the EG with missing or limited data by evaluating both EGs' determinant values, e.g., type of vessel, area or time period. We assigned a relative confidence level to each estimate to allow exploration of the impact of this strategy on the epidemiologic analyses. Participants whose estimates were assigned lower confidences could be excluded from some analyses to assess the impact of potentially greater measurement error.

As is typical of all JEMs, variability of exposure within EGs is ignored within the EG, and in some cases, the GSDs were quite large (Tables S2–S4). A major source is likely the variability of tasks, particularly on the rigs and ROV vessels, when work tasks changed over time in attempts to stop the oil release. Variability also is more of an issue when the exposure categories are narrow (e.g., <0.03 or 0.03–1.0 ppm), but the larger number of categories provides greater flexibility to the epidemiologists to combine exposure groups based on their needs.

Because the "best" metric depends on the health effect being analyzed and selection of only one metric could result in misclassification, we calculated the maximum, minimum, median and mean exposure levels by participant and found very different distributions, (Figure 1). Furthermore, for this JEM we did not account for time (i.e. days) worked (although it will be available for future work) and thus, cumulative exposure cannot be calculated. Use of our current estimates is unlikely to result in the same ranking of participants as cumulative exposure[10], because some participants may have worked one day whereas others may have worked for months. Other sources of exposure misclassification include the lack of exposure estimates at night for participants who spent the night on vessels that remained in the Gulf; dermal exposures; and the long working hours, few days off, and high temperatures and humidity. These exposures will be considered qualitatively in exposure-response analyses. Not considering these determinants of exposure likely results in random misclassification of the study participants and would tend to move the observed risk estimates toward the null.

Originally, we had expected to validate our estimates. The only measurements we know of are a limited number of measurements collected by US government agencies (OSHA, NIOSH and the US Coast Guard). We were unable to validate the BP measurements with these samples because: 1) we had no information on which samples went with which BP samples; and 2) most of the samples were collected for substantially shorter periods of time compared to the BP samples. Government data are, however, consistent with our THC estimates. We are currently evaluating the comparability of the rig personal measurements with a subset of the 26 000 000 direct-reading area measurements taken on these same vessels. The area data on the other 34 vessels for which we have data will be used to supplement relatively scarce THC personal measurements and thus cannot be used for evaluation of the accuracy of the estimates.

This is the first detailed estimation of exposures experienced by OSRC workers for an epidemiologic study. A few other studies have reported a limited number of air concentrations but did not attempt to conduct an exposure assessment for a health study. The airborne THC concentrations at a dwelling nearest the wreck of the *MV Braer* were 6.3 and 0.7 ppm the first two days of the spill[11]. Air concentrations over the first 20 days near where the *Nakhodka* wrecked averaged of 0.04–0.56 ppm THC[12]. VOC measurements of cleaners were equivalent to <0.5 ppm THC after the *Prestige* spill[13]. NIOSH found THC levels up to about 1 ppm for various activities being performed in response to the Exxon *Valdez* oil spill, but most of the measurements were below the LOD[14]. These data from these other spills are roughly equivalent to our data.

The exposure assessment study has several strengths over previous reports. First, there were a large number of measurements taken over a short period of time. Many occupational epidemiologic studies have had many fewer measurements over longer periods of time. Second, although the percentage of THC non-detectable measurements received from BP was 82%, we obtained data from the associated analytic laboratories and, by calibrating the analytic curve to the analytic limits of detection, in contrast to the originally report comparing the limits of detection to occupational standards, we were able to reduce the censored level to 19%. Overall, the percentage of censored THC measurements was well below the minimum amount we considered as acceptable for using Bayesian methods[7] (although the data did not meet the criteria for all EGs). Third, we used a Bayesian method that provided bias comparable to more traditional methods for developing summary statistics with censored data and small sample sizes but also provided credible intervals (similar to confidence intervals) that the other methods did not[6,7]. Fourth, we had information on a large number of tasks enabling us to develop estimates for various time periods and locations, reflecting different events and tasks that often resulted in considerable differences in exposure levels over this highly complex situation. Fifth, we defined transparent rules to impute estimates when the measurements were insufficient for individual EGs and identified a confidence level for each estimate, which will allow the epidemiologists to conduct sensitivity analyses.

In summary, we developed EGs to characterize the work experience and ordinal exposure estimates to THC for thousands of workers involved in the OSRC work of the *Deepwater Horizon* oil release, throughout the Gulf of Mexico's waters and during beach cleanup and oil decontamination and various other onshore tasks. The estimates were based on a large number of measurements, and the procedure to assign the estimates was based directly on these measurements using a hierarchical and transparent process. These estimates are being used to investigate potential adverse health effects arising from the *Deepwater Horizon* response effort.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements:

We wish to express our appreciation for the invaluable support and feedback of the GuLF STUDY Scientific Advisory Board and the Exposure Assessment Working Group. We would also like to thank Wendy McDowell and Caitlin Rousch of McDowell Safety and Health Services, and GuLF STUDY staff at Social & Scientific Systems, Inc. who assisted with programming and analysis for this effort.

This study was funded by the NIH Common Fund and the Intramural Program of the NIH, National Institute of Environmental Sciences (ZO1 ES 102945).

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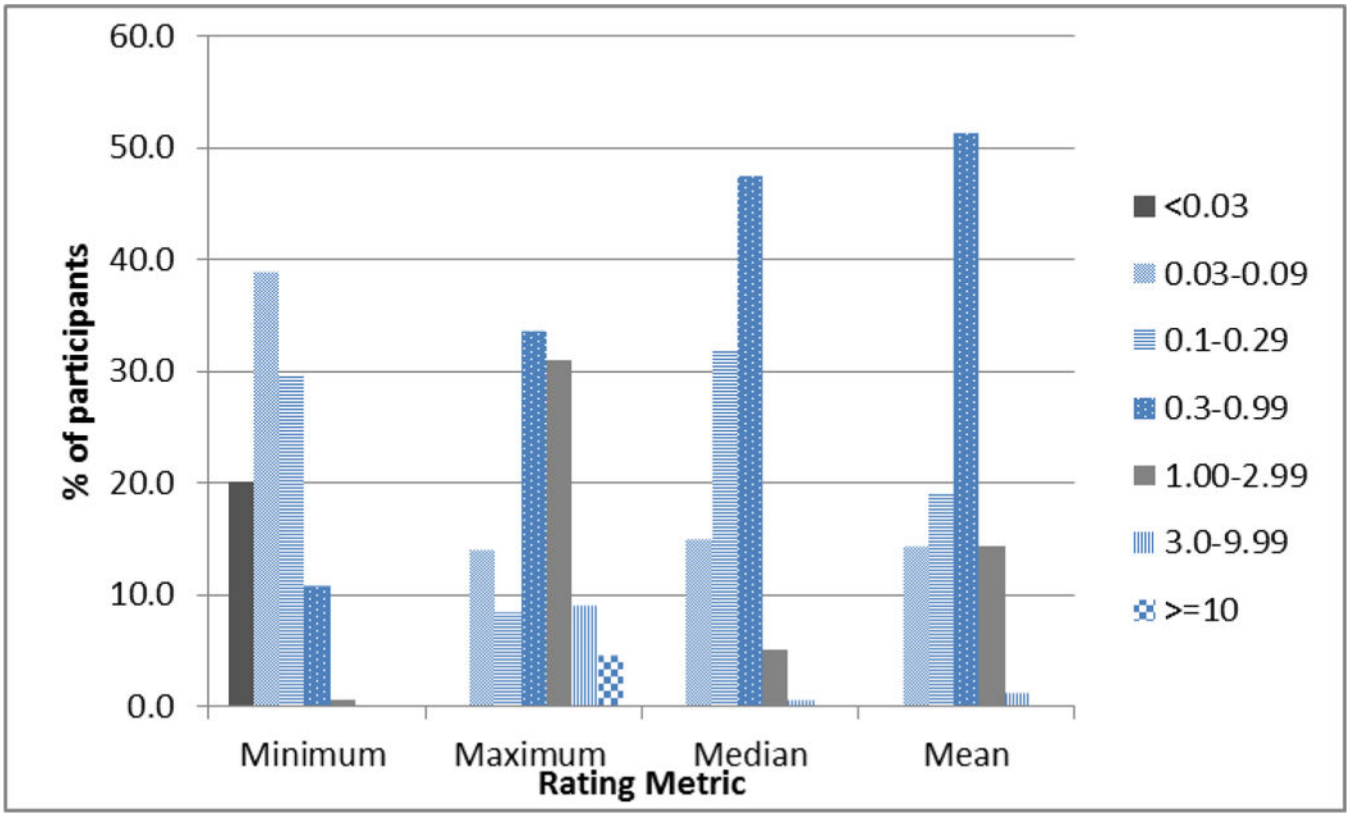

Figure 1.
Distribution of Study Participants by Various Metrics See Table 4 for definitions

Table 1.

Exposure Group Basis of Job/Task and Vessel or Vessel Type

Vessel and vessel type, description	Types of jobs/tasks	Estimation strategy: ≥5 measurements and ≤80% censoring. If absent:
Drilling rig vessels 4 vessels relatively stationary in the wellhead area (hot zone) and present from late April-early May to as late as December, 2010. There were approximately 100–200 people on a rig at any time.		
Enterprise: led the efforts to stop the oil release, capturing and separating the oil from the entrained gas and flaring the gas	41 job groups across the rigs: • 38 specific jobs (examples found under each job group below) • Crew: operated the rig and helped directly with the response, e.g., roustabout, crane operator, derrickhand • Operations: people were often on the rig temporarily, performing technical tasks related to stopping the oil, e.g., ROV technician, methanol operations, mudlogger • “All jobs”: identified participants who received the first version of the questionnaire and so were not asked to provide a job title.	• Similar Job Title (e.g., ROV technician/supervisor) • Job Group (e.g., crew, operations). Crew, for example, comprised crane operators, seamen, roustabouts, and others. Operations included jobs such as mudloggers and ROV technicians. • Location of the job (inside vs. outside the vessel’s living areas and offices). Where these rules were insufficient: • The same job/vessel in a similar time period (time periods 1a and 1b were considered similar, as were time periods 2–4. Vessels had left the area by time period 5). • The same job on a sister ship in the same time period. The Enterprise and Q4000 were considered sister ships (both were involved in plugging the leaking well and flaring), as were the DD2 and DD3 (both drilled the relief wells).
Q4000: supported the *Enterprise* by pumping materials into the damaged well and flaring of the oil/gas, having no ability to separate the two		
Development Driller II (***DD2***) : drilled a relief well		
Development Driller III (***DD3***): drilled a relief well		
Vessels with remotely operated vehicles (ROV) Most of these ROV vessels were fairly stationary. The ROV vessels arrived between April and June and had left the area by mid-September, 2010.		
14 ROV vessels including the 2 ROVs vessels below: inspected and performed equipment repair work, assisted in the installation and removal of equipment, and provided the video to monitor the repair/ positioning of work and the oil release on the Gulf floor 5000 ft below the water surface	• All outside workers on each vessel • All outside workers on all vessels	All participants on these vessels were assigned the job title “outside worker” because few workers likely worked only indoors. Where measurements were insufficient: • Pooled all “outside worker” measurements across all of the vessels of the same type and time period to form “all ROV” or “all research” vessel estimates. Where these rules were insufficient: • Grouped time periods (1a and 1b, vs. 2, 3, and 4 (the vessels had generally left the area by time period 5).
Skandi Neptune: injected dispersant near the Gulf floor at the point of the oil release		See above
REM Forza: sprayed dispersant as needed onto the water surface in the hot zone and source area in response to high (>70 ppm) volatile organic chemicals (VOC) levels as measured on ships with direct reading instruments.		See above
Research vessels Operated primarily under the auspices of the National Oceanic and Aeronautics Administration, Most research vessels went on multiple cruises, which typically lasted 1–3 weeks in duration and primarily covered the hot zone, source and offshore areas. The first cruise generally occurred in May or June and the last cruise generally was completed by August or September 2010		
27 research vessels: collected data on various water characteristics, monitoried the oil plume, took water samples for later analysis, and monitored wildlife	• All outside workers on each vessel • All outside workers on all vessels	See ROV vessels above
Other vessels Included barges; marine, fishing, charter vessels; commercial boats, such as tug and crew boats; and smaller air and recreational boats located throughout the Gulf and along the shoreline. Generally worked from late April through the end of December, 2010.		
Thousands of other vessels; 28 tasks[1]: supported the rig vessels’ operations; transported workers,	• Various tasks, e.g., transport, scouting for oil, deploying boom, handling oily boom, skimming, burning	• A similar time period (i.e. 1a and 1b; 2 to 4; 5 and 6) from the same state Where the criteria still were not met:

Vessel and vessel type, description	Types of jobs/tasks	Estimation strategy: ≥5 measurements and ≤80% censoring. If absent:
chemicals and equipment to and from the vessels offshore; scouted for oil, laid boom to enclose the oil, maintained and removed it; skimmed or burned the oil; decontaminated vessels offshore to prevent oil on the hulls from contaminating waters as the vessel moved to shore; patrolled the beach and marsh areas.		• Alabama and Florida were considered sister states (as were Louisiana and Mississippi,), using one state as a proxy for the other. If an estimate was not available from the sister state: • an estimate was calculated across measurements from all states.
Land Includes all tasks performed on land. Generally worked between late April, 2010 to June 2011		
26 tasks[1]: scouted for oil on the beaches, cleaned these areas; put out boom and retrieved it along the shore; collected and cleaned wildlife; decontaminated vessels, equipment and personnel; and supported all of the aforementioned operations (supplying food and water, storage and positioning of equipment, security, administration, etc.).	• Various tasks, e.g., patrolling beaches, cleaning beaches, decontaminating vessels, decontaminating boom, kitchen workers, office workers	See other vessel tasks above

[1] 14 other activities were performed both on water and on land, including deconning workers; entering tanks, handled booms in shallow water, handling wildlife, hazardous waste handling, IH/safety, cleaning jetties

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Table 2.

Salient Features and Activities Performed during Specific Time Periods Used in Estimating Exposures for Exposure Groups and Participants in the GuLF STUDY

Time period	Dates	Major activities
1a	April 22-May 15, 2010	Oil was being released at the wellhead near the floor of the Gulf. Efforts to stop the release by containment were unsuccessful. Drilling started on a relief well. Aerial application of dispersant to the water surface began across the Gulf. *In situ* burns started. Oil reached the LA and MS shore, and beach cleanup started.
1b	May 16-July 15, 2010	Drilling began on a second relief well. Dispersant continued to be applied by plane. Dispersant was injected at the wellhead to break up the oil and applied by ship to the surface of the water near the wellhead to reduce THC air concentrations. *In situ* burning continued. Offshore skimming of oil and flaring by the rig vessels started. Beach cleanup continued, but now included AL and FL; and onshore and offshore decontamination of vessels and equipment started. On July 15 the well was mechanically capped and the oil flow stopped but the well cap and well casing were still under considerable pressure from the oil formation.
2	July 16-August 10, 2010	The well was “static killed” (stopping the oil flow by pumping drilling mud and other components into the well) on August 10. *In situ* burning ended by July 19. Offshore skimming ended in early August but nearshore skimming continued. Beach cleanup and decontamination of vessels and equipment continued.
3	August 11-September 30 , 2010	The first relief well intersected the original well about 18 000 feet below the Gulf floor on September 16. Heavy mud and cement were delivered at the base of the well to close off the well. The well was permanently sealed on September 19. Underwater equipment used in the response was removed or repositioned. Large-scale decontamination of the vessels started. Nearshore skimming continued on a limited basis. Beach cleanup continued but started to decline.
4	October 1-December 31, 2010	Decontamination of the vessels and equipment continued. By December 31, essentially all vessels had been decontaminated. Beach and marsh cleanup continued, along with the cleaning of rock jetties, by an increasingly smaller number of people. Nearshore skimming ended in October.
5	January 1-March 31, 2011	Beach cleanup continued by an increasingly smaller number of people.
6	April 1-June 30, 2011	Beach cleanup continued by an increasingly smaller number of people. Distinguished from time period 5 because of the warmer ambient air temperatures, which resulted in higher THC exposure levels.

Table 3.

Illustration of Total Hydrocarbon (THC) Ordinal Exposure Categories of Selected Exposure Groups[1]

Exposure Group	THC Ordinal Exposure Category[2]						
	TP 1a (April 22-May 15, 2010)	**TP 1b (May 16-July 15, 2010)**	**TP 2 (July 16-August 10, 2010)**	**TP 3 (August 11-September 30, 2010)**	**TP 4 (October 1-December 31, 2010)**	**TP 5 (January 1-March 31, 2011)**	**TP 6 (April 1-June 30, 2011)**
IH-safety/Enterprise	6	6	4	4	NA	NA	NA
IH-safety/DD2	4	4	4	4	NA	NA	NA
Technician/DD2	4	4	3	2	NA	NA	NA
All jobs/All ROV vessels	7	6	4	4	NA	NA	NA
All Jobs/All research vessels	4	4	3	3	NA	NA	NA
Vessel patrolled beaches/Louisiana	5	5	4	4	4	2	2
Transport vessel/Louisiana	4	4	4	4	4	2	2
Vessel handled oily booms/Louisiana	4	4	4	3	3	2	2
Cleaned beaches/Florida	1	4	3	3	3	2	2
Cleaned beaches/Louisiana	3	3	3	4	3	2	2
Office work/All states	2	2	2	2	2	1	1
Deconned equipment on land	4	4	4	4	4	2	2

[1] See Tables S2–4 for more detail

[2] 1=<0.03, 2=0.03–0.09, 3=0.1–0.29, 4=0.3–0.99, 5=1.00–2.99, 6=3–9.99, 7≥10 ppm THC

Table 4.

Distribution of Study Participants by Various Metrics[1]

Metric	% of cohort (N=24,937)
OSRC class	
Response	18.0
Support of Operations	17.5
Cleanup on Water	17.4
Decontamination	14.3
Cleanup on Land	14.6
Administrative Support	18.3
Maximum total hydrocarbon level	
<0.03	0.0
0.03–0.09	13.8
0.1–0.29	8.3
0.3–0.99	33.6
1.00–2.99	30.9
3.0–9.99	9.0
>=10	4.4
Minimum total hydrocarbon level	
<0.03	20.2
0.03–0.09	38.9
0.1–0.29	29.7
0.3–0.99	10.6
1.00–2.99	0.6
3.0–9.99	0.1
>=10	0.0
Median total hydrocarbon level	
<0.03	0.2
0.03–0.09	14.9
0.1–0.29	31.9
0.3–0.99	47.5
1.00–2.99	5.1
3.0–9.99	0.4
>=10	0.0
Mean total hydrocarbon level	
<0.03	0.0
0.03–0.09	14.1
0.1–0.29	19.0
0.3–0.99	51.4

Metric	% of cohort (N=24,937)
1.00–2.99	14.3
3.0–9.99	1.1
>=10	0.0
Potentially Exposed to Dispersants	
No	84.8
Yes	9.4
Unknown	5.8
Potentially Exposed to Burning	
None	89.2
Low	0.2
Medium	7.6
High	1.0
Unknown	2.1

[1]Maximum=the highest THC exposure estimate experienced by each study participant across all EGs within and across all time periods was identified and then assigned to one of the ordinal categories. Minimum=the lowest THC exposure estimate experienced by each study participant across all EGs within and across all time periods was identified and then assigned to one of the ordinal categories. Median=the median of all exposure estimates across all EGs within and across all time periods experienced by each study participant was calculated and then assigned to one of the ordinal categories. Mean=the mean of all exposure estimates across all EGs within and across all time periods experienced by each study participant was calculated and then assigned to one of the ordinal categories