DE GRUYTER DOI 10.1515/reveh-2014-0002 — Rev Environ Health 2014; 29(4): 277–292

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Understanding exposure from natural gas drilling puts current air standards to the test

Abstract: Case study descriptions of acute onset of respiratory, neurologic, dermal, vascular, abdominal, and gastrointestinal sequelae near natural gas facilities contrast with a subset of emissions research, which suggests that there is limited risk posed by unconventional natural gas development (UNGD). An inspection of the pathophysiological effects of acute toxic actions reveals that current environmental monitoring protocols are incompatible with the goal of protecting the health of those living and working near UNGD activities. The intensity, frequency, and duration of exposures to toxic materials in air and water determine the health risks to individuals within a population. Currently, human health risks near UNGD sites are derived from average population risks without adequate attention to the processes of toxicity to the body. The objective of this paper is to illustrate that current methods of collecting emissions data, as well as the analyses of these data, are not sufficient for accurately assessing risks to individuals or protecting the health of those near UNGD sites. Focusing on air pollution impacts, we examined data from public sources and from the published literature. We compared the methods commonly used to evaluate health safety near UNGD sites with the information that would be reasonably needed to determine plausible outcomes of actual exposures. Such outcomes must be based on the pathophysiological effects of the agents present and the susceptibility of residents near these sites. Our study has several findings. First, current protocols used for assessing compliance with ambient air standards do not adequately determine the intensity, frequency or durations of the actual human exposures to the mixtures of toxic materials released regularly at UNGD sites. Second, the typically used periodic 24-h average measures can underestimate actual exposures by an order of magnitude. Third, reference standards are set in a form that inaccurately determines health risk because they do not fully consider the potential synergistic combinations of toxic air emissions. Finally, air dispersion modeling shows that local weather conditions are strong determinates of individual exposures. Appropriate estimation of safety requires nested protocols that measure real time exposures. New protocols are needed to provide 1) continuous measures of a surrogate compound to show periods of extreme exposure; 2) a continuous screening model based on local weather conditions to warn of periodic high exposures; and 3) comprehensive detection of chemical mixtures using canisters or other devices that capture the major components of the mixtures.

Keywords: acute toxic actions; toxic materials; unconventional natural gas development (UNGD).

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Introduction

> Recent and projected growth in the oil and gas production sector has underscored the need for EPA to gain a better understanding of emissions and potential risks from this industry sector. Harmful pollutants emitted from this industry include air toxics such as benzene, toluene, ethylbenzene, and xylene; criteria pollutants and ozone precursors such as NO_x and VOCs; and greenhouse gases such as methane. These pollutants can result in serious health impacts such as cancer, respiratory disease, aggravation of respiratory illnesses, and premature death. However, EPA has limited directly-measured air emissions data on criteria and toxic air pollutants for several important oil and gas production processes. [These] limited data, coupled with poor quality and insufficient emission factors and incomplete NEI data, hamper EPA's ability to assess air quality impacts from selected oil and gas production activities.
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> – US Environmental Protection Agency (EPA) Office of Inspector General (1)

The question we, and others, have asked is: do the levels of exposure to the mixture of unconventional natural gas development (UNGD) emissions constitute a potential human health hazard to those living very near UNGD activities (2–7)? The answer hinges on the emissions themselves, their synergistic effects, the methodology used for collecting and analyzing data, and the standards for gauging human health risk. More specifically, the answer hinges on whether the methodology used is designed to

capture the important features of episodic and fluctuating emissions and exposures that characterize UNGD activity.

In this article, UNGD refers to the complete process of extracting, processing and transporting natural gas, including all associated infrastructures, such as flare stacks, flowback pits, compressors, and condensate tanks. Each stage of UNGD produces a different combination of emissions and the levels of release are also variable. Colburn et al. (8) collected air samples weekly for 1 year and reported that emissions were highest during the drilling phase of development. However, estimates provided by industry for the New York State Revised Draft SGEIS (9) suggest that VOC emissions may be greater during the production phase. In any case, emissions vary at each well pad because of several factors, including the type of gas being extracted, the mixture of fluids used, the quality of equipment, as well as the methods of extraction and processing. For example, flowback fluids may be trucked off a well pad or held in impoundments onsite, whereas in the finishing process, gases may be flared or vented.

Another variable in terms of human exposure risk is state setback regulations. Among the states that have them, each has different requirements for well setbacks from buildings and/or water sources. A survey on setback regulations for natural gas drilling reports that, for buildings, the setback distance can vary from 100 to 1000 feet, with an average of 308 feet (10). Water source setbacks can vary from 50 feet (Ohio) to as much as 2000 feet (Michigan). This same report finds "extensive regulatory heterogeneity among the states" for those with active gas production (10).

Toxicity of a chemical to the human body is determined by the concentration of the agent at the receptor where it acts. This concentration is determined by the intensity and duration of the exposure. All other physiological sequelae follow from the interaction between agent and receptor. Once a receptor is activated, a health event might be produced immediately or in as little as 1 to 2 h (11, 12). Alternatively, future exposures might compound the impact of the first one, eventually producing a health event. In some instances where there is a high concentration of an agent, a single significant exposure can cause injury or illness. Federal and state health standards for water and air, which are applied to UNGD emissions, ought to reflect and be evaluated in reference to these physiological realities; currently they do not. Thus, in order to understand and define the gap between air standards and the process by which UNGD exposures cause health effects, we examined the literature on UNGD emissions and exposures and then evaluated widely accepted health standards in light of environmental data we have collected.

Our interest in closing the gap between standards and the mechanisms of environmental health effects stems from the work we do in communities in southwest Pennsylvania, USA. Individuals in these communities have taught us a great deal about their health concerns and their unease with the air in and outside of their homes. There are similar issues with the potential for well water contamination from UNGD in the region. In this paper, we specifically address the risks posed by episodic, high concentration air exposures. Commonly used standards and benchmarks are particularly ill-equipped to consider this set of exposures.

Standards and monitoring protocols

The air standards and guidelines often used by the federal government, state governments, and by many independent researchers are those set by the National Ambient Air Quality Standards (NAAQS). These standards approach, but do not meet, the physiological criteria for how exposures cause damage at the individual level. This is not, however, a failure of the NAAQS. The standards have been designed to benchmark *regional air quality*, which refers to whether the overall pollution level in a region, *over time*, is within the ambient air target zone EPA deems safe. The standards are a tool for the regulatory system, which requires averaging of samples taken. How these data are collected, averaged, and interpreted varies by pollutant. It should also be noted that one of the criteria for determining standards is that the targeted level must be measurable, that is, if a chemical is not readily measurable at a given level, its use cannot be monitored, regulated or enforced. This criterion precludes standards being set to a very low level.

As seen in Table 1, the form (i.e., application) of the standard varies by compound. However, regardless of the substance, each standard relies on averages of exposures, sometimes over long periods of time. By seeking to provide overall regional air quality guidance, NAAQS and other air quality benchmarks have the following critical weaknesses when applied to individuals or very local areas: 1) current NAAQS do not address the interactions of the chemical agents in the air and then in the body; 2) long-term averages fail to capture the frequency or magnitude of very high readings; and 3) with periodic data collection, important spikes or episodic exposures (common in UNGD) can be missed. In those few cases where short-term or hourly ambient air levels are measured, the purpose is generally to avoid poisoning from catastrophic releases (13).

Table 1 National ambient air quality standards.

Pollutant		Primary/secondary	Averaging time	Level	Form
Carbon monoxide		Primary	8 h	9 ppm	Not to be exceeded more than once per year
			1 h	35 ppm	
Nitrogen dioxide		Primary	1 h	100 ppb	98th percentile, averaged over 3 years
		Primary and secondary	Annual	53 ppb	Annual mean
Ozone		Primary and secondary	8 h	0.075 ppm	Annual fourth-highest daily maximum 8-h concentration, averaged over 3 years
Particle pollution	$PM_{2.5}$	Primary	Annual	12 μg/m³	Annual mean, averaged over 3 years
		Secondary	Annual	15 μg/m³	Annual mean, averaged over 3 years
		Primary and secondary	24-h	35 μg/m³	98th percentile, averaged over 3 years
	PM_{10}	Primary and secondary	24-h	150 μg/m³	Not to be exceeded more than once per year on average over 3 years
Sulfur dioxide		Primary	1-h	75 ppb	99th percentile of 1-h daily maximum concentrations, averaged over 3 years
		Secondary	3-h	0.5 ppm	Not to be exceeded more than once per year

Adapted from: www.epa.gov/air/criteria.html.

In addition, researchers use other guidelines for determining whether an exposure is within or beyond safe limits. Some researchers and regulatory agencies, for instance, use EPA's Integrated Risk Information System (IRIS), a database of research on human health exposures. Guidance provided through IRIS covers hundreds of chemicals and their possible effects on humans. The database assists researchers with hazard identification and dose-response assessment as well as with oral reference doses (RfDs), inhalation reference concentrations (RfCs), and carcinogenicity assessments. The RfD or RfC reflects an estimate of the highest daily exposure across a lifetime, which is likely to be without significant risk of health effects. The science underlying these reference levels, however, does not necessarily apply to the risk circumstances brought about by UNGD. Furthermore, RfDs and RfCs have no direct regulatory application and no legal enforceability. Researchers have also evaluated the wisdom of looking at peak exposures as compared to averages over longer periods of time. Delfino et al. (14) posited that maxima of hourly data, not 24-h averages, better captured the risks to asthmatic children, stating, "it is expected that biologic responses may intensify with high peak excursions that overwhelm lung defense mechanisms". Additionally, they suggest that "[o]ne-hour peaks may be more influenced by local point sources near the monitoring station that are not representative of regional exposures".

Similarly, Darrow (15) writes that peak exposures can sometimes better capture relevant biological processes. This is the case for health effects that are triggered by short-term, high doses. They write, "Temporal metrics that reflect peak pollution levels (e.g., 1-h maximum) may be the most biologically relevant if the health effect is triggered by a high, short-term dose rather than a steady dose throughout the day. Peak concentrations ... are frequently associated with episodic, local emission events, resulting in spatially heterogeneous concentrations".

To give just one example, we know that 1 to 2 h of a diesel exhaust exposure can cause, for instance, reduced brachial artery diameter and exacerbation of exercise-induced ST-segment depression in people with pre-existing coronary artery disease; ischemic and thrombotic effects in men with coronary heart disease (16); and is associated with acute endothelial response and vasoconstriction of a conductance artery (17).

Given that episodic high exposures are not typically documented and analyzed by researchers and public agencies, health complaints in the area are not being correlated with industry emissions. However, examination of published air emission measurements in gas extraction and processing sites, along with collected health data from the Environmental Health Project (EHP) and others, show very real potential for harm from industry emissions (18). Reports of acute onset of respiratory, neurologic, dermal, vascular, abdominal, and gastrointestinal sequelae near natural gas facilities contrast with research, which suggests that there is limited risk posed by UNGD. By extension, we believe the contrast points to the inadequacy of using current federal standards.

For public agencies to protect human health, they need standards that are sensitive to and consistent with the known routes of exposure, the duration and frequency of exposures, the nature of chemical mixtures, tissue repair rates, plausible target organs, and the increased

sensitivity of susceptible populations. Monitoring efforts must be complex enough to account for the actual mechanisms at work in the exposure-receptor relationship. They must also be sufficiently robust to measure fine-grained, hour-to-hour variability in air concentrations.

The objectives of this paper are to illustrate the shortcomings of the available data as well as the inadequacy of the standards by which they are evaluated. We present new protocols for air monitoring based on the observed health effects produced by exposures and on documented emissions patterns from the industry. The protocols are directed at the needs of the local residents who must be able to determine the safety and welfare of their families. The protocol reflects the following central requirements: 1) continuous measures of a surrogate compound to show periods of extreme exposure, 2) a continuous screening model based on local weather conditions to warn of periodic high exposures, and 3) comprehensive detection of chemical mixtures using canisters or other devices that capture the major components of the mixtures.

Background

Documented emissions[1]

Researchers have begun to document the content and quantities of emissions from UNGD sources, such as engine exhausts, condensate tanks, production equipment, well-drilling and completions, and transmission fugitives. Emissions identified have included four of the five NAAQs pollutants (excluding ozone) and a wide range of volatile organic compounds (VOCs) and other air toxics (19). Research conducted in the Fort Worth, Texas area documented the variation in emissions among locations and forms of UNGD activity. Point source research found a total of 2126 emission points in one 4-month UNGD field study. Pneumatic valve controllers were the most frequent emission sources at well pads and compressor stations. Emissions from storage tank vents proved to be one of the most significant polluters, accounting for 2076 tons of VOCs per year (20).

Among others, Earthworks has found air contaminants in areas, and in combinations, which one would not expect to find outside of industrial activity (21, 22). However, not every chemical in the 2012 Earthworks study was found at every site monitored. That said, there were notable consistencies across sites. For instance, 94% of the samples tested for 2-butanone detected it; 88% of those testing for acetone and 79% of those testing for chloromethane detected it. Moreover, 1,1,2-trichloro-1,2,2-trifluorethane, carbon tetrachloride, and trichlorofluoromethane were also frequently found. Specific emissions were not found uniformly across all locations, indicating that emissions themselves vary from site to site. In addition, there are different emissions recorded in the literature partly due to variations in researchers' ability to capture and document those emissions.

Some studies around UNGD activities have found benzene, particulate matter (PM), formaldehyde, and other chemicals at levels in exceedance of state or federal limits. The Texas Commission on Environmental Quality, for instance, reports that at one source, 35 chemicals were detected above "appropriate short-term comparison values". At some sites, multiple chemicals (carbon disulfide, ethane, isopentane, and 1,2-dibromoethane) exceeded short-term health-based comparison values. Benzene was also detected above the long-term health-based comparison value at 21 monitoring sites (3).

The federal government has not, as yet, gathered the quantity and quality of emissions data that are necessary to properly characterize the environmental conditions around UNGD sites. The Inspector General's Office of the EPA confirms the inadequacy of data in reporting the following: EPA has 1) not developed default emission estimates for oil and gas nonpoint sources, 2) not ensured state submission of nonpoint sources oil and gas data as required by the EPA's air emissions reporting requirement (AERR), and 3) some states' failure to collect emissions data from smaller (i.e., nonpoint) oil and gas production facilities due to a lack of permitting requirements. The Inspector General's Office concludes that, although resource intensive, developing a robust emissions inventory could cover these numerous small, unregulated sources (1).

Connections between emissions and health

Two important obstacles prohibit researchers from comprehensively assessing the health risks posed by UNGD activities. The first obstacle has to do with the incomplete list of chemicals used and air emissions generated by the industry. Companies and their sub-contractors are not mandated by the federal government to disclose the complete list of chemicals used in the hydrofracking process; nor are they required by state or local governments to provide a full accounting of the chemicals used at a given site. Second,

1 Other research confirming emissions are presented in our review of research in the Findings section of this paper.

there is a problem of assessing risk of known chemicals. Many of the chemicals that have been identified at UNGD sites or nearby do not have established comparison values by which to measure their potential health effects. Furthermore, chemicals are released into the air contemporaneously and there is little to no information on the toxicity of these mixtures. This is not a unique problem posed by UNGD. What is unusual is the proximity of emission sources to people's homes and to places where they carry out their daily activities. To provide a sense of the urgency of addressing this issue, in a study of 290 households in Washington County Pennsylvania, collected as a convenience sample, we found that 707 unique, "active" wells or compressor stations were identified as located within three miles of all residences combined (Unpublished). It has been reported in the *Wall Street Journal* that as many as 15 million people live within one mile of a natural gas wellhead (http://stream.wsj.com/story/latest-headlines/SS-2-63399/SS-2-365197/).

Despite the limitations in data, some studies have been conducted on correlations between health risks and UNGD emissions. For instance, based on toxicity values for six carcinogenic contaminants in one Garfield County, Colorado study, researchers found low but increased risk of developing cancer in residents living near UNGD activity. Additionally, based on the presence of noncancer hazards, close proximity to UNGD activity was associated with low but increased risk of developing acute noncancer health effects; however, the authors report that insufficient data makes this finding inconclusive. Many air contaminants surrounding UNGD had no established toxicity levels so researchers could not identify and include those risks in their report (23).

Another Colorado study found that a noncancer chronic Hazard Index was greater for residents living ≤0.8 km from wells than it was for those more than 0.8 km out. Cumulative cancer risks were also greater for residents within 0.8 km of wells than for those living further out. Benzene and ethylbenzene were the primary contributors to cumulative cancer risk for residents living in close proximity to UNGD facilities (24).

An assessment of Pennsylvania birth outcomes, released as a working paper, compared birth outcomes for infants born to mothers living within 2.5 km of a permitted but not yet built gas well site and those within 2.5 km of an active gas well site. Results suggest that exposure to UNGD before birth increases the overall prevalence of low birth weight and the overall prevalence of small for gestational age; in addition, exposure reduces 5 min APGAR scores compared with births to mothers living near sites that have not yet been developed (25). In Colorado, a similar study found an increased prevalence of congenital heart defects, and possibly of neural tube defects in neonates for mothers residing within a 16 km radius of natural gas wells, based on density and proximity (26).

While not including all substances used or emitted from UNGD sites, the EPA's IRIS provides data on known heath effects from exposure to toxic contaminants. The database contains information on more than 550 chemicals, including VOCs such as acrolein and formaldehyde, which are known to be emitted from UNGD sites. IRIS also provides information concerning acute toxicity.

Rationale

The Southwest Pennsylvania EHP examined whether UNGD emissions data collection, analysis, and comparison to standards reflect real-time exposures and their known pathophysiological mechanisms. EHP aimed to investigate the assumptions driving existing research and how such assumptions might mislead researchers in ways that undermine, even invalidate, their findings.

An initial appraisal of the literature led us to hypothesize that the application of federal standards to research on health impacts from industry air pollution failed to sufficiently address the periods of highest risk for people living near UNGD sites. We found a disconnection between the standards that do not address short-term exposure peaks, and how those actual exposures might put people at risk. In addition to examining existing research, we used data from real-time exposure measurement to shed light on the relationship between exposure measurement and the standards by which they are deemed safe or unsafe. These data came from monitoring efforts previously conducted by EHP in the homes of residents living near UNGD sites in Washington County, Pennsylvania. We measured PM because it poses well understood health risks, serves as a surrogate for other UNGD exposures, and is a synergist that intensifies the risks of other airborne toxins.

Materials and methods

We undertook analyses in three areas. First, we assessed the emerging literature on health risks posed by UNGD. Then, we analyzed EHP's previously collected data on $PM_{2.5}$ and $PM_{0.5}$ micron levels in homes near UNGD activity as a proxy to assess real-time air pollution exposures. Finally, we created a simple weather screening model to capture the role of meteorological conditions on the dispersion of air emissions from industry sources. All three were aimed at understanding the relationship between actual human exposures and the standards by which they were deemed safe or unsafe.

Based on what we suggest as the necessary monitoring protocols for determining hazards to human health, we analyzed whether current methods of data collection, as revealed in published articles and reports, provide adequate measures. Our recommended protocols included the following: 1) continuous measures of a surrogate compound to show periods of extreme exposure, 2) a continuous screening model based on local weather conditions to warn of periodic high exposures, and 3) comprehensive detection of chemical mixtures using canisters or other devices.

Our examination of the aptness of federal ambient air standards began with a review of relevant standards and their rationales. We then reviewed the sampling methodologies and data analyses in a subset of emissions research on UNGD emissions and their associated health risks. For this review (Tables 2a–f) we selected six studies

Tables 2a–f Review of sampling methods and averaging times in six shale gas development air emissions studies. A Glossary of abbreviations is in Appendix A.

Research article (27)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
Michael McCawley, WVU School of Public Health (27)	Measurements of air contaminants were taken to characterize levels that might be found at 625 feet from the well pad center at unconventional gas drilling sites during the activities at those sites.	– Summa canisters (24-h) – Flame ionization detector and gas chromatograph (FID -GC) – Two-hour average OC and EC concentrations: aerosol carbon field analyzer – TEOM for PM (24-h) – PID photoionization detector	Minutes – 1 min averages for four criteria pollutants Hours Days	Range of averages given for $PM_{2.5}$, O_3, NO_X, CH_4, SO_2 and benzene[a]. Used RfC, HQ and HI

Comments: High levels of fluctuation found: "The duration of the specific activity of interest at each of the sites was a week or less". Authors note that more appropriate sampling periods than the 3-year averaging period required for the NAAQS are needed, as is a health effects study. Weather and topography are also considered important factors. [a]The HQ for benzene was above MRL – of 9.5 μg/m³ for chronic (>365 days), 19 μg/m³ for intermediate (14 to 364 days) and 28.5 μg/m³ for acute (1–14 days) exposure. $PM_{2.5}$ dust levels at the 625 foot setback distance had 1-h average values above the annual NAAQS limit occurring over the course of several days at all but one site.

Table 2b

Research article (23)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
Health Consultation Garfield County (2010)	Evaluation of 2008 sampling data to identify public health implications	– Four sites for 1 year: well sites <1.5 miles from sample sites – Summa canisters (24-h) weekly (SNMOC) – DNPH-coated cartridges (24-h) once every 2 weeks	Day Year	90 speciated non-methane organic compounds (SNMOC) and carbonyls Used EPA and ATSDR values

Comments: "It cannot be determined if breathing ambient air in the monitored areas of Garfield County could harm people's health … because the cancer risks and noncancer hazards for 65 of the 86 contaminants cannot be quantitatively estimated due to limited toxicological information and/or the unavailability of accepted inhalation toxicity values". Authors note that the current state of the science is unable to assess exposures to complex mixtures of air toxics, especially synergistic and antagonistic interactions at low levels, and that insufficient data are available to evaluate intermittent short-term peak exposure.

Table 2c

Research article (24)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
McKenzie et al. (24)	Isolated health risks to residents living near wells during the flowback stage of UNGD using air quality data collected at the perimeter of wells	– Ambient air once every 6 days – Summa canister (24-h) near wells during short-term UNGD stages – 14 homes within a 0.5-mile range of a UNGD site	Day Year	Tested for up to 78 hydrocarbons; used RfCs HQ and HI for carcinogens used IUR

Comments: The greatest risk corresponds to the relatively short, subchronic but high emissions during well completion: "[Could] not consider health effects from acute (<1 h) exposures to peak hydrocarbon emissions because there were no appropriate measurements". The authors call for the use of more specific sampling periods.

Table 2d

Research article (20)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
City of Fort Worth Natural Gas Air Quality Study (20)	Assess air pollution from UNGD in Fort Worth	– Two-month study period, eight sites – Ambient air–once every 3 days with (DNPH) cartridges, Summa canisters (24-h) – Mass flow control system, two sites – Also screened for fugitive emissions	Day Year	139 pollutants considered; reported 59 VOCs, methane, carbonyls; used LCLs for cancer and noncancer values; used TCEQ ESLs and AMCVs, EPA limits

Comments: No pollutant concentration exceeded any short-term health benchmark of the Texas Commission on Environmental Quality (TCEQ), EPA, or the Agency for Toxic Substances and Disease Registry (ATSDR). "It is only appropriate to compare annual average concentrations, not individual measurements, to long-term health benchmark values such as the EPA NATA values". The authors consider specific wind effects, but not topography.

Table 2e

Research article (28)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report (28)	Short-term screen for ambient air concentrations of target pollutants near certain Marcellus Shale gas drilling operations; assess potential air quality impacts; assess potential health risks from exposure to ambient concentrations	– OP-FTR open path sampler: six seven-hour sampling sessions within 1 week – GC/MS: 5 min each hour for six seven-hour sampling sessions within 1 week – Summa canister (24-h) Infrared camera for screening fugitive emissions	Hours Days	48 VOCs; used RfC, REL, AEGL and ERPG standards; HQ and HI, NAAQS OP-FTR 2-min maximum used as a 1-h average for HQ

Comments: Nothing above NAAQS or other reference points. Concentrations of acetone, benzene, n-heptane, propene, and toluene were close to levels detected in the DEP monitoring network sites. The authors note that combined effects from operations in an area, along with other sources, may contribute to exceedance of the NAAQS. We also note that 33 of the 45 target compounds have an associated RfC.

Table 2f

Proposed Research Protocol (29)	Purpose of study	Sampling method and time per location	Averaging time	Tested chemicals and reference values
Technical Support Document for Long-Term Ambient Air Monitoring Project, (29)	One year of monitoring to determine any chronic or long-term risks to the public from individual or multiple shale gas sources, including HAPs and criteria pollutants	– EPA-based analysis – Five NAAQS pollutants, continuous or semicontinuous measurement – Methane/nonmmethane compounds, FLIR – Summa canisters; HAP, VOC and carbonyls, sample once every 6th day for 24 h	Hours Days Month Three to Five years	VOCs, Carbonyl, Ozone, NOx, CO, $PM_{2.5}$, methane/nonmethane Hydrocarbons, H_2S USEPA TO-15 method ref. values; PA DOH HQ

Planned analysis: NAAQS and arithmetic means used for VOCs and HAPs below MDL. Cumulative excess cancer risk will trigger more review, cumulative noncancer risk HQ >1 will trigger more review: "This comparison will be a direct comparison of estimated mean concentrations of pollutants … observed mean concentration estimates will be compared to 3-year average pollutant concentrations".

that focused on air contamination and health impacts of UNGD. The studies had a wide geographic range and were conducted by a variety of organization types. The studies were located in West Virginia, Colorado, Texas and Pennsylvania, and were conducted or commissioned by Schools of Public Health, a state Department of Public Health, independent consulting firms, and state Departments of Environmental Protection. Given that emissions factors and monitoring practices may have improved since the early years of UNGD, we selected studies published from 2010 to 2013 in peer-reviewed journals and from public access sites in different states. We paid particular attention to how researchers grappled with the problem of multiple exposures and how hazard indexes were effectively employed.

To compare real-time fluctuations in air contamination to the results and conclusions found in the studies, we analyzed previously collected data on $PM_{2.5}$ exposures in homes near UNGD sites. From June 2012 to August 2013, EHP placed Dylos™ air particle monitors (Dylos Corporation, Riverside, CA, USA) in 14 homes near UNGD sites. The data from these homes constitute an opportunity sample, because the homes were self-selected. The residents had approached EHP for assistance in determining whether their health might be

affected by their proximity to UNGD sites. The Dylos™ monitor measures and records levels of $PM_{2.5}$ and $PM_{0.5}$ every minute for up to 24 h. The data are downloaded daily and readings can continue indefinitely. In the research presented here, indoor air was monitored between 44 and 353 consecutive hours in homes near drilling-related activities. PM is of interest not only because of its association with health risks, but also because it is a surrogate for other substances to which people may be exposed. The Dylos™ particle monitor measures counts of particles per meter cubed and is sensitive to humidity. EPA measures the mass of particles and sets a standard based on 30% humidity. Counts are not directly comparable to mass; therefore scaling factors are needed to compare the data.

Weather patterns and other atmospheric conditions have a well documented effect on the dispersion of air emissions (30). Based on the work of Frank Pasquill, D.Sc., EHP developed a targeted air pollutant dispersion screening model using the following: 1) estimates of UNGD source emissions documented in the literature and from 2012 Pennsylvania Department of Environmental Protection (PADEP) oil and gas inventory reports (31), 2) distance to a hypothetical residence, and 3) the impact of local (Pittsburgh) weather patterns. This resulted in a situationally relevant assessment of the dispersion of emissions in areas around UNGD activity (32).

Findings

In reviewing the selected studies on air emissions and health impacts from UNGD, we looked at the methods used to collect air samples and the averaging time used to analyze the sampling results. In studies a–d (Table 2), results were compared primarily to federal and state standards and guidelines to determine the impact of air emissions on human health. EHP found evidence of inadequate sampling protocols for capturing meaningful data. We also found inconsistencies between researchers' interpretations of findings on exposures based on current standards and their potential impact on health.

Sampling and averaging methods

A typical method of air sample collection is the use of Summa canisters. These canisters collect air emissions over a 24-h period. Levels of pollutants are thus averaged over the 24-h period. Spikes in emissions within that period cannot be quantified.

The research in West Virginia and in Pennsylvania had (or will have in the case of one PA study) some shorter-term averaging. McCawley, in West Virginia, reported 1-min average samples for four criteria pollutants, 1-h averages for PM samples and 2-h averages for organic carbon and elemental carbon samples. These shorter-term results allowed McCawley to determine high levels of fluctuations in emissions. Unfortunately, there are few meaningful standards to which his results can be compared because current federal standards do not accurately address periods of short-term peak exposures.

In its 2010 Southwestern Pennsylvania study, the Pennsylvania DEP used 7-h sampling periods (six periods within a week at each of the five sites). The gas chromatography/mass spectrometry (GC/MS) instrument sampled 5 min/h for each 7-h period. The open path sampler (OP-FTR) reported the highest 2-min value of any detected compound per sampling period (reported as approx. 8 h). If the compound was detected at a high enough level during the sampling session to produce an average greater than the method detection limit (MDL), that average was also reported.

For the Health Consultation in Garfield Co. (2010), Summa canisters and 2,4-dinitrophenylhydrazene (DPNH)-coated cartridges were used for 24-h collection periods. McKenzie et al. collected 24-h samples with Summa canisters and sampled ambient air once every 6 days. The City of Fort Worth (2011) sampled once every 3 days with (DNPH) cartridges and Summa canisters for 24-h periods and screened for fugitive emissions.

The proposed PA DEP long-term study in Southwestern Pennsylvania will collect data for 1 year. Periodic sampling with 24-h canister samplers will be used for hazardous air pollutants (HAP), VOCs, and carbonyls. Methane and non-methane compounds will be detected with Forward-looking infrared (FLIR) VOC imaging technology. Continuous or semi-continuous samplers will be used for ozone, NO_x, CO, H_2S, and $PM_{2.5}$ for comparison to NAAQS. The review above illustrates the variety of measurement approaches and reference values used by researchers. In studies a to d, the authors refer to difficulties in assessing health risks for various reasons (Table 2). McCawley (2013) referred to the variability in exposures, the short-term duration of specific activities, and the long-term averaging period for NAAQS. In the Garfield County Study (2010) the researchers found that some of the necessary chronic inhalation toxicity values were not available and that complex mixtures could not be adequately assessed. Both McKenzie et al. (2012) and the City of Fort Worth (2011) found no appropriate method for assessing acute exposures. This will be addressed in the discussion section, but it is worth noting here that there is no relationship among the form of data collection, the standards applied, and the physiological effects of exposure to toxins.

The problem of risk assessment of mixtures (Hazard quotient/Hazard index)

To date, most studies on health risks associated with UNGD rely on 24-h canister samples to calculate a Hazard index

(HI). Acute effects most often occur after a few minutes or an hour of exposure. In fact, the 24-h average exposures are not even predictive of the 24-h maximum exposure. The 24-h averages underestimate exposures by a factor of two to three times (see Figure 1). The problem is further complicated by the interactions among multiple agents in the body that can produce greater than additive effects.

An illustration of the problem using published data

For this example, we chose four of the chemicals used in the UNGD industry that were measured at one site, at multiple times, and reported to the PA DEP. They included acrolein, benzene, toluene, and chloromethane (28). When we attempted to evaluate the interaction using the Hazard quotient (HQ) and reported average, the effect of omitting the highest values became apparent.

The HQ for each chemical can be established by taking the chemical measurement and dividing it by the level at which no adverse effects are expected (referred to here as the standard and derived from standards or guidance values found in IRIS). The HQs are added together to form the HI. If the sum is ≤1.0 the mixture is not considered to produce a harmful interaction.

Example

$$\frac{acrolein}{standard}+\frac{benzene}{standard}+\frac{toluene}{standard}+\frac{chloromethane}{standard}\leq 1.0$$

Using a sample of averaged canister data from the PADEP Marcellus Shale Short-Term Air Sampling Report, the calculation is as follows (measurements in μg/m^3) (28):

$$3.7/6.9+0.35/28.8+0.94/3770+1.40/1030=\underline{0}.55.$$

Measured chemical amounts are reported in Appendix A, p. 36. RfCs are found in Appendix E, p. 45.

The result is <1.0, which would lead to the conclusion that it is not likely to result in pathophysiologic effects. However, this calculation is not an accurate way to measure acute toxicity. The standards used are relevant to acute exposures but the measurements are of 24-h average emissions. These averages underestimate the acute exposures by a factor of 2 to 3. The correct HI is much greater than can be determined using the conventional approach.

Evidence of short-term high values of air contaminants: particulate matter

EHP used Dylos™ air particle monitors to assess indoor air quality in homes near UNGD. The air monitor records real-time levels of $PM_{2.5}$ and $PM_{0.5}$ each minute for up to 24 h. The Dylos™ monitor records counts of $PM_{2.5}$ and above or $PM_{0.5}$ microns and above. By contrast, EPA measures the mass of $PM_{2.5}$ microns and below to avoid having heavier particles distort the data. Given that the Dylos™ monitor counts particles, a few larger particles will not affect the data. In both cases relative humidity is a factor to control. The houses in which data were collected represent an opportunity sample near UNGD sites. In the data, we saw intervals with extremely high values. To understand the frequency of these high PM counts, we established a standard for "peak exposure" by taking the median reading for each house (Table 3) and from that found the median for all houses. The original data came from 14 homes (a total of 2117 h).

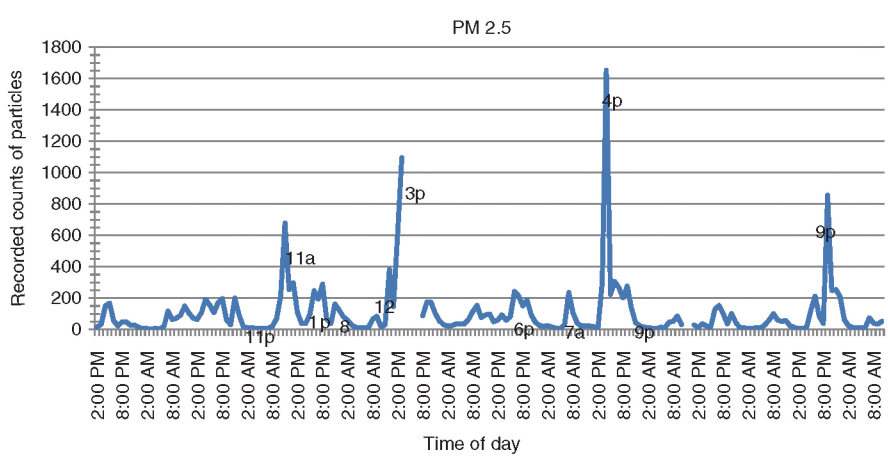

Figure 1 $PM_{2.5}$ Measurements collected in House 7 from March 7, 2013 to March 14, 2013 (counts/0.01 cubic feet). Dylos Readings for $PM_{2.5}$ from March 7, 2013 to March 14, 2013. a, am; p, pm.

Table 3 Number of hours monitored and the median number of $PM_{2.5}$ counts per house (counts/0.01 cubic feet).

House	Number of hours monitored	Median $PM_{2.5}$ counts
1	141	54
2	215	65
3	120	40
4	168	4
5	308	51
6	142	45
7	353	38
8	190	30
9	71	69
10	72	75
11	44	49
12	138	57
13	69	38
14	166	78

We found that the median value for all houses combined was 50. This median value was then multiplied by three to establish the criterion for a "peak" exposure. The minimum "peak exposure" value for this study was established at 150 counts of $PM_{2.5}$. We then calculated the number of peaks at each house and the percent of hours with peak exposures. The particle monitor data in Table 4 show that peaks over 150 counts can occur over 30% of the time in a given house (33).

Table 4 Peak $PM_{2.5}$ count values for each house, number of hours,% total hours, times of day, and maximum peak value (counts/0.01 cubic feet).

House	Number of hours with peaks	% of total hours with peaks	Times of day of peaks[a]	Maximum peak value of $PM_{2.5}$ counts	Median value of $PM_{2.5}$ counts
1	12	8.5	N	2711	54
2	11	5	M, N	756	65
3	3	2.5	M	171	40
4	1	0.5	N	201	4
5	8	2.5	A, E	556	51
6	11	7.7	A, E, N	576	45
7	31	8.7	M, A, E	1654	38
8	29	15	M, A, E	991	30
9	9	12.6	M, E, N	1057	69
10	23	32	M, A, E, N	844	75
11	7	16	M, E	3846	49
12	2	1.4	E	203	57
13	3	4.3	M	164	38
14	57	34.3	M, A, E, N	1761	78

[a]Times of day: Morning: 6:00 a.m. to 12 noon; Afternoon: 12 noon to 6:00 p.m.; Evening: 6:00 p.m. to 12 midnight; Night: 12 midnight to 6:00 a.m.

Attempts to capture these peaks with 24-h Summa canisters, through periodic or one-time spot sampling (under 24 h) or after a complaint has been filed, will most often miss times of peak exposure. Even with continuous monitoring such as ours, averaging of the peaks with the lower levels of PM obscures the most important feature of the data from a public health perspective because high level exposures can cause the most physiological harm (14). Only through continuous, real-time monitoring with short reporting periods, will peaks likely be captured.

Fluctuations in indoor PM levels are expected, regardless of outside activity, and can be the result of cooking, vacuuming, and children at play. The duration, magnitude, and timing of some of the peaks seen in this study, however, could not be readily explained by normal daily activity.

Research on indoor and outdoor PM levels near highways confirms the relationship between outside and indoor particle pollution. Fuller et al. found both indoor and outdoor particle levels to be the highest <100 m from the highway, whereas both indoor and outdoor levels were lowest in and around homes more than 1000 m from the highway (34). The researchers concluded that outdoor particle pollution was "the most important predictor of indoor [particle number concentration]" (34). Other significant predictors of indoor particle levels cited by the authors included temperature, weekday, time of day, wind speed, and wind direction.

Air pollution dispersion model estimates

The EHP model looks at the estimated impact of one emissions source, while in many cases a residence may have more than one source within a radius of two to three miles.

In order to estimate the effect of local weather conditions on ground level exposures, 2012 hourly weather data reported at the Pittsburgh International Airport (wind speed, wind direction, and cloud cover) were applied to the air screening model developed by EHP (32). A single VOC emission level of 300 g/min from a compressor station was used for the point source. The influence of local air movement and vertical dilution (mixing depth) on the levels of ambient air emissions one mile from a surface source in part explained periods of peak exposures.

The modeled findings shown in Table 5 indicate that ambient VOC concentrations are underestimated when averages are used to evaluate the health risk associated with a source (as is recommended in the "Form" of the

Table 5 Effects of averaging the variability of exposures that occur in 6 h increments, for each month of the year.[a]

Month	Monthly average[b]	Six-hour average for the 75th percentile	Six-hour average for the 90th percentile
January	43	50	132
February	58	85	123
March	58	88	137
April	52	75	148
May	81	124	189
June	66	103	155
July	59	115	157
August	89	147	206
September	85	136	177
October	80	131	189
November	80	111	167
December	74	111	157
Yearly average	68.5		

[a]Based on Pittsburgh, PA weather data in 2012. [b]all 6-h periods for each month.

NAAQs air monitoring strategy). When the "midnight to midnight" 24-h periods were divided into 6-h intervals, the scale and frequency of this underestimation of exposure risk became apparent. About 10% of the intervals for downwind locations will produce exposures two to three times higher than the value estimated using the NAAQs form (Table 5). If VOC concentrations were averaged over a 1-h rather than a 6-h period, the discrepancy would be even greater.

The projected effect on indoor air

A house with one air change per hour would experience 75% of the outdoor ambient air after 3 h and 98% after 6 h. Further, even if the ambient air is reduced to the unlikely level of zero, it would require 3 h for the indoor concentration to fall to 25% of the maximum. Thus, for a significant portion of each month, residents downwind from pollution sources experience levels of pollution inside their houses that are higher than the monthly averages. These are potentially significant exposures from a physiological standpoint. The uptake of outdoor pollutant into house air is determined by assuming that the house has one air change per hour with instantaneous mixing, such that at the end of 1 h, the concentration inside of the house will be 1/2 the outside concentration. After 2 h, the concentration will be 75% of the outside and each hour the indoor-outdoor difference is reduced by one half. The clearing of the pollutant follows the same assumption.

Discussion

When evaluating acute responses to air toxics, it is important to understand the physiological and cellular responses to short-term exposures because inhalation or ingestion of a toxic agent can cause effects within minutes (35). The health sequelae seen near UNGD sites include respiratory, neurologic, and dermal responses as well as vascular bleeding, abdominal pain, nausea, and vomiting. Given the pathophysiologies of these acute toxic responses, it is apparent that current monitoring protocols at UNGD sites are inadequate to ensure safety.

When air emission levels are highly variable, the following typically collected measurements are not relevant to individual health impacts: periodic collection of 24-h samples, tons released per year, and hourly averages per day, per week, or per year. Instead, real-time measures of patterns of exposures are needed, and these must include peak levels, durations, and components of mixtures. The NAAQS compliance monitoring criteria (Table 1) do not provide sufficient information to assess human health risks from acute episodes of exposures. A relevant example of appropriate, real-time monitoring at industrial sites that abut residential areas is The Benzene and other Toxics Exposure (BEETEX) Study developed by the Houston Area Research Center (HARC) (36). The purpose of the study was to identify exposure to air toxics in nearby residential areas and to attribute air toxics to specific sources. The methodology for monitoring and data analysis are in development for the 2014 study, with the goal of identifying "cost-effective, state-of-the-art neighborhood scale monitoring networks .... the improvement of emissions inventories, the conduct of epidemiological studies for air toxics, and ultimately the enforcement of regulations" (36).

Others have demonstrated the mismatch between typical environmental compliance monitoring on the one hand, and health risk evaluation on the other. The Minnesota Department of Health (MDH), in particular, has addressed this problem with respect to ground water utilized for drinking. MDH has revised its Health Risk Limits (HRL) protocol as part of a concerted effort to provide conservative, health protective guidelines that respond to sensitive and highly exposed populations. The Minnesota HRLs respond to the relationship between the timing and duration of exposure as well as the potential adverse effects. The HRLs are intended to be protective for a range of adverse effects for a given duration of exposure. In addition, MDH's revised risk limits address the problem of multiple exposures – whether exposure from several pathways or from multiple chemicals – by using an exposure decision tree in conjunction with site-specific information. In the revised rules, MDH

includes methods that risk managers can use to sum up the risks from multiple chemicals that share a common health endpoint in order to assess the combined health risk at the site being evaluated. MDH typically utilizes this approach, but if specific data about a mixture are available, other more targeted approaches are likely to be preferable (37).

The form of current standards

The central problem identified in this paper is that at sites where it appears that health effects are produced by UNGD, toxic emissions are often not being measured or not detected at levels deemed dangerous. Our concern is that this may be an artifact of the sampling methodologies and analyses currently being used today. An example of how appropriate monitoring and sampling can reveal otherwise hard to capture variations can be found in a study of woodsmoke emissions in the Adirondack region of New York State (38). This rural region has a very limited air quality monitoring network, yet residents can experience multi-day and/or sub-daily pollution loading that can be intense. Given that monitoring sites are so widespread, and local hourly impacts cannot be captured, these populated areas have significant public health pollution threats that the regulatory system does not respond to or understand. However, when researchers used the appropriate equipment and methods, they instantaneously discovered serious air quality problems. In this example, a model that identified likely "hotspots" using geographic and demographic data was employed. Then mobile monitoring equipment and procedures as well as stationary monitoring sites were used to collect real-time data.

When we examine the research summarized in Tables 2a–f, we find a common deficiency in the data collection, that is, the inability of commonly used methods to capture episodic or significant variability. Specifically, as we have already noted, many sampling methods fail to characterize and quantify peaks in emissions and potential exposures. Looking at Tables 3–5 as well as Figures 1 and 2, it becomes apparent that exposures do, in fact, become quite high relative to median or mean values. These spikes are inconsistent with the characterization of low to negligible risk.

Currently, compliance with NAAQS and state standards are the cornerstone of safety regulation of UNGD. These standards are designed to monitor compliance over a region, but not over individual sites. A review of the form of the application of the NAAQS illustrates the problem. The forms of the six criteria pollutant standards are similar to other air monitoring guidelines. Compliance with each is based on average findings typically collected at 3-day intervals. Performance criteria are based on the number of times the standard is exceeded each year.

These standards have been developed to reliably determine when a source is repeatedly out of compliance with permitted emissions. The regulatory assumption is that the variations in ambient air levels are negligible. The findings in this report show that the variability of emissions in UNGD is extreme and assessing this variability is critical to understanding health responses. Of the six studies evaluated here, only McCawley (27) measured in "real time" and reported finding high levels of fluctuation in emissions. McKenzie et al. reported health risks to short, subchronic but high emissions. However, they found that there were no appropriate measurements for assessing effects from acute exposures. In contrast, the Pennsylvania DEP report found nothing above NAAQS or other levels of concern. It should be noted that even if real-time equipment is deployed, given the high variability of emissions based on the stage of UNGD, care must be taken to use the appropriate equipment at the appropriate time to ensure accurate and meaningful data collection.

HI and PM – synergistic response

Underlying current standards is the assumption that each toxic agent in air emission mixtures acts independently when it is inhaled or ingested into the body. The ratios of the average ambient air level to the standards are summed in an HI (EPA.gov/airtoxics). At UNGD sites, this assumption is negated by the fact that PM is generally present at all sites; and it has been demonstrated that PM increases the amount of absorbed toxin by increasing transport into the deep lung. The surface area of the particle is what drives this synergistic response, producing greater than additive synergistic response (39).

EHP continuously measured particulate matter at 14 houses near UNGD in southwestern Pennsylvania. The monitoring periods ranged from 44 to 353 h. EHP found a range of 1 to 57 h (0.5% to 34.3%) with peak values over 150 cts/0.01 cubic feet. The findings in the literature and in EHP's PM monitoring indicated that episodes of high values were typical in gas fields. In the EHP data, peak values occurred at varying times of day and night. Figure 1 illustrates these results.

Meteorological impacts

Local weather conditions affect the dispersion of air pollutants from industrial sources (31). Figure 2 shows modeled

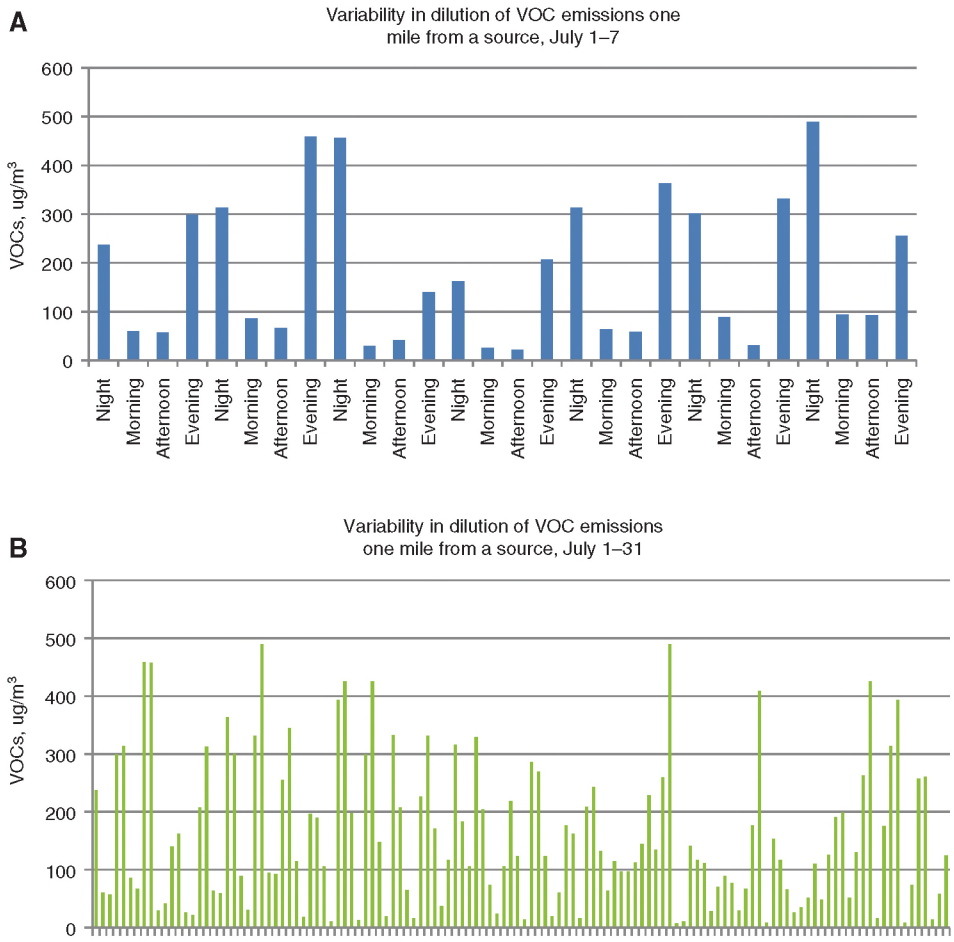

Figure 2 (A, B) Demonstration of the variability in dilution of 300 g/min VOC emissions from a source one mile away, in 6-h increments[a], modeled using Pittsburgh International Airport weather data.
[a]Calculations are based on July 2012 weather data from the Pittsburgh International Airport. The 6-h increments for the graphs above are broken down as follows: night: 12 midnight to 6:00 am; morning: 6:00 am to 12 noon; afternoon: 12 noon to 6:00 pm; evening: 6:00 pm to 12 midnight.

estimated exposures from a source of VOCs at 6-h intervals for 30 days. The chart reflects only the effects of weather conditions and illustrates that weather conditions alone can cause extreme variation in exposures at ground level. The 6-h exposures vary from 25 to over 200 μg/m^3. As expected, the monthly average 6-h exposure ranged from 43 to 89 μg/m^3, and the 90th percentile ranged from 123 to 206 μg/m^3. Both Figures 1 and 2 help make the argument that continuous measures, in conjunction with weather data, are needed to identify periods of extreme exposure.

Mixtures

The variety of point source types and the combinations of chemical gases present at UNGD sites complicate the assessment of health risk. The Commonwealth of Pennsylvania requires that certain permitted facilities report yearly emissions of 13 compounds to their oil and gas inventories. In 2012, there were 214 reporting sites in Washington County, PA. These included 196 well pads, 14 compressor stations, two gas processing plants, a booster station, and an interconnecting station. These installations are connected by pipelines that are under pressure and are vented as necessary. Table 6 shows a portion of the PA DEP emissions inventory data from the 214 reporting sites in Washington County (40).

Examining the discrepancy between the median and maximum values, it is easy to see that sites vary significantly in their emissions. The data show concurrent releases of multiple compounds (Table 6). Several of these have known interactions in the body, for example VOCs and particulates. The interactions with inhalable particulates, found at 110 of the 214 sites, are of concern because the doses increase synergistically when PM combines with air toxins. Thus, the commonly used HI is insufficient to

Table 6 Seven most prevalent chemicals emitted in 2012 across all reported sites in Washington County, PA (total, median and maximum by weight/tons per year).[a]

Chemical	Total tons/ year	Median	Maximum
Benzene	3.1	0.2	0.8
VOCs	501	0.8	30
$PM_{2.5}$	60	55	6
NO_x	1838	9.4	95
Formaldehyde	53	0.0008	4.2
Trimethyl pentene	0.13	0.004	0.12
Ethyl benzene	0.34	0.00003	0.07

[a]Other reported chemicals are carbon monoxide, sulfur dioxide, PM_{10}, n-hexane, toluene and xylene. Methane is not reported. Not every site reports every compound. As noted, these reports are for yearly emissions, but during well pad development, many stages occur for shorter time periods.

Table 7 Assessment of sampling methods for determining pathophysiological impacts from air pollution.

Sampling method	Does it measure quantities of mixed compounds?	Does it measure frequency of peaks?	Does it measure intensity of peaks?	Does it measure duration of peaks?
Summa Canister	Yes	No	No	No
Ambient air monitors	No	Some yes, some no	No	No
DNPH-coated cartridges	No	No	No	No
OP-FTR open path sampler[a]	No	Yes	Yes	Yes

[a]OP-FTR does have sensitivity and specificity limitations.

evaluate the health impact of the mixtures because it uses average exposures and reference doses based on a single exposure to an agent. In this case, HI is also insufficient because the duration of the typical averaging time used to evaluate exposure is longer than the duration of concern. These findings show that the current protocols used to evaluate safety are not sufficient and that a change is needed.

Conclusion

Several factors should be included in all measures. First, based on the analysis presented in this paper, it is clear that the use of current standards is not appropriate for good pathophysiological evaluation, and consequently for good public health protection. The currently used methods of data collection also cannot provide the necessary data for determining an exposure's composition, intensity, duration, or frequency.

In sum, our findings indicate the presence of peak emissions occurring near UNGD, which may lead to extreme exposures among people in close proximity to these sites. Furthermore these exposures can be exacerbated by local weather conditions and by the presence of particulate matter. Exposures are highly variable and can be difficult to monitor. Moreover, current monitoring efforts and health standards do not adequately track these events, though health reports from persons living near these sites are consistent with episodic exposure (EHP, Earthworks). The risk of developing chronic diseases due to exposures, especially by vulnerable populations, has yet to be determined. Revisions to health standards are necessary to protect public health in regions of UNGD. Toxicity values must be developed for shorter durations for residents in other than emergency situations. Research is also needed to evaluate the health effects of short, repeated, higher than background exposures (Table 7).

In order to overcome limitations of sampling methodologies commonly used to gauge risks, we suggest that a combination of strategies be adopted because no single sampling method can accurately capture all of the essential data. Finally, realistic reference values that focus on the potential pathophysiologic effects caused by exposures are needed. In the re-examination of reference values for water pollutants, Minnesota's Department of Health provides a good example to emulate.

In order to properly evaluate and respond to the public health problem posed by UNGD activities, we suggest a new strategy for collecting air data and interpreting findings. The following three components ought to be at the center of this new strategy:

- continuous measures of a surrogate compound to show periods of extreme exposure;
- a continuous screening model based on local weather conditions to warn of periodic high exposures; and
- comprehensive detection of chemical mixtures using canisters or other devices that capture the major components of the mixtures.

Acknowledgments: We wish to thank Norman Anderson MPH; Sandra Baird D.Sc.; Phillip Johnson MES, MPH, PhD; Michael Kelly PhD; and Tyler Rubright for their assistance in the development of this article.

Received January 6, 2014; accepted February 14, 2014; previously published online March 29, 2014

Appendix A Glossary of abbreviations

AEGL	acute exposure guideline level
AERR	air emissions reporting requirement
AMCV	air monitoring comparison values
ATSDR	Agency for Toxic Substances and Disease Registry
BEETEX	benzene and other toxics exposure study
BTEX	benzene, toluene, ethylbenzene, and xylene
DEP	Department of Environmental Protection
DNPH	2.4. dinitrophenylhydrazene
DOH	Department of Health
EC	elemental carbon
EHP	Environmental Health Project
EPA	U.S. Environmental Protection Agency
ERPG	Emergency Response Planning Guidelines
ESL	effects screening levels
FLIR	forward-looking infrared camera
GC/MS	gas chromatography-mass spectrometry
HAP	hazardous air pollutant
HARC	Houston Area Research Center
HI	hazard index
HQ	hazard quotient
HRL	health risk limits
IRIS	EPA integrated risk information system
IUR	Inhalation unit risk
LCL	lowest comparison level
UNGD	unconventional natural gas development
MDH	Minnesota Department of Health
MDL	method detection limit
NAAQS	National Ambient Air Quality Standards
NATA values	National-Scale Air Toxics Assessment
NEI	National Emissions Inventory
OC	organic carbon
OP-FTR	Fourier transform infrared spectrometer
PA	Pennsylvania
PID	photo-ionsitization detector
PNC	particle number concentration
PM	particulate matter
REL	reference exposure level
RfC	reference concentrations
SNMOC	speciated non-methane organic compounds
TCEQ	Texas Commission on Environmental Quality
TEOM	tapered element oscillating micro-balance, a particulate monitor
VOC	volatile organic compounds

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