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YALE SCHOOL OF PUBLIC HEALTH

MASTER’S DEGREE OF PUBLIC HEALTH THESIS

Unconventional Natural Gas Development and Self -Reported Heath Symptoms:

A Two-year Survey in Washington County, Pennsylvania

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Abstract

Introduction: Natural gas is a cleaner and more efficient energy type compared to coal and oil and could be vital to tackle the global energy crisis. The technical advance of unconventional natural gas development (UNGD) has permitted us to extract natural gas from shale formations, which were previously inaccessible for natural gas drilling. However, the new technology has shadows its environmental safety and impacts on human health. So far, no definitive conclusion about this issues has been reached.

Methods: In this cohort study in Washington County, Pennsylvania, we used an innovative exposure assessment model, integrating local wind flow direction and gas well production days, to assess residential exposure to gas well released air pollutants. We recorded the residents' respiratory and dermal symptoms in 2012 and 2014 and then used multi-level logistic regressions to estimate the risk of exposure to the pollutants and health outcomes.

Results: We found significantly elevated risk of having dermal symptoms in 2012 among people who were exposed to high level of pollutants at that time compared to those who were exposed to low level of pollutants in 2012 [odds ratio (OR) = 4.27; 95% confidence interval (CI): 1.06, 17.14]. There was no significant association detected of increase of exposure level over the two years and new health symptom occurrence in 2014.

Conclusions: Estimated exposure to high level of air pollutants released by unconventional gas wells could lead to significantly elevated risk of having dermal symptoms. However, we do not find that experiencing a rapid increase of exposures over two years could substantially increase the risk of having any dermal or respiratory symptoms. Future studies on this very topic are necessary to further investigate the association.

Introduction

Energy continues to be one of the major concerns in global development. While oil and coal remain the predominate energy sources worldwide, the environmental challenges such as air pollution and global climate change have driven the search and development of cleaner and safer alternatives (Finkel and Hays, 2013). Natural gas has a good reputation for being environmentally clean, economical and efficient. Very few byproducts are emitted as natural gas burns and less carbon-dioxide is produced during the process. Besides, it is easier to store and transport compared to oil and coal. Based on these advantages, natural gas has been a very popular choice as an energy source and is in great demand for civil and industrial uses.

The United States holds large deposits of on-shore natural gas (Adgate et al., 2014). The technical advance of unconventional natural gas development (UNGD) has made it possible to extract natural gas from shale formations, which is difficult to attain by conventional gas drilling methods (Ferrar et al., 2013). UNGD involves two major technologies: horizontal drilling and hydraulic fracturing (US Department of Energy, 2013; Werner et al., 2015). Horizontal drilling is a process where the well is positioned horizontally at depth. It is a common way of extracting natural gas from Marcellus Shale formations (Taylor at el., 2013). Hydraulic fracturing, or generally perceived by the public as “fracking”, is a process in which shale formations are injected with and fractured by a highly-pressurized liquid, known as “fracking fluid” (Kargbo et al., 2010; Slizovskiy et al., 2015).

In the US, the number of UNGD wells has been increasing dramatically (Vidas et al., 2008). The rapid expansion of UNGD wells nationwide has witnessed the “shale gas boost” and the economic transition from energy import to domestic production (US Energy Information Administration). However, the intensive embrace of the UNGD technology in the US has also raised growing concerns of its potential harm to the nearby environment and residents (Arthur et al., 2009; Entrekin et al., 2011). The process of UNGD involves the use of multiple chemicals in the fracking fluid, in which the exact ingredients remain unclear. Nevertheless, it is widely acknowledged that the fluid contains volatile organic compounds (VOCs), organic and inorganic acids, sulfates and heavy metals (Rozell et al., 2012; Vidic et al., 2013). Although the main procedure of hydraulic fracturing occurs underground, the waste water of the process, if not properly regulated, is likely to contaminate underground and ground water, soil and air (Jackson et al., 2013; Vengosh et al., 2013). Air pollution is also a significant route of environmental exposure of UNGD. Chemical hazards such as, and not limited to, diesel emissions, nitrogen oxides, methane and aromatic and aliphatic petroleum hydrocarbons would cause substantial health risks on neighboring residents (Adgate et al., 2014; Weinhold, 2012).

Despite the phenomenal expansion of UNGD and the heated public health concerns, little peer-reviewed public health research exists as the new technology has just been employed in industries in recent years (Adgate et al., 2014). Fortunately, a handful of studies have been performed to investigate UNGD's environmental risks and drawn the attention of environmental health professionals, policy makers and the public. McKenzie performed a human health risk assessment of air emissions from UNGD and concluded that residents living within 1/2 mile from wells are at great risk of health effects (McKenzie et al., 2012). Hill in 2012 detected that exposure to UNGD before birth increased the prevalence of low birth weight by 25 percent (Hill, 2012). A health survey in southwest Pennsylvania suggests that people residing within 1 km from the nearest well have significant higher numbers of health symptoms compared to those who live further than 2 km, especially for dermal and upper respiratory symptoms (Rabinowitz et al., 2015). The health risk is not only among humans. Dogs also have elevated risk of having health symptoms when residing within 1 km from the nearest well (Slizovskiy et al., 2015). Not all studies report consistent conclusions as some are providing comforting messages. The Fryzek team found no significant childhood cancer risk associated with hydraulic fracturing industries in Pennsylvania counties in his study in 2013 (Fryzek et al., 2013). In 2014, a team of Australian researchers published a literature review on UNGD associated health risks and found no valid evidence to either definitively confirm or repudiate adverse health impacts (Werner et al., 2015). It is apparent that UNGD associated health risks are still controversial and more studies and investigations are essential.

In this paper, we report the results of a health risk analysis of a two-year neighborhood health survey in Washington County, Pennsylvania. By estimating residential exposures to UNGD air emissions in a more precise way, we can evaluate and display the human health risks associated with UNGD in a more accurate manner.

Methods

Description of study area

The target region in this study is Washington County, located in southwestern Pennsylvania. According to the census in 2010, the total population of Washington County is 207,820 (US Census Bureau, 2014). The ethnic diversity in Washington County is fairly low as nearly 94.1% people are Caucasians (US Census Bureau, 2010). The county has a high rural classification with nearly 40% of the land devoted to agriculture, possessing 2,023 farms sizing a total of 211,053 acres (US Department of Agriculture, 2007). Washington County consists of 32 spatially large rural townships and 34 spatially minor regions (32 boroughs and 2 cities). We randomly sampled households in a contiguous set of 38 rural townships within the center of Washington County to minimize the effects of environmental stressors from other heterogeneous regions, namely the metropolitan area of Pittsburgh and State of West Virginia (Rabinowitz et al., 2015).

The climate in Washington County shows a typical pattern of humid continental climate with a relatively warm, humid summer and cold, dry winter. According to the climate record by US Department of Commerce, wind is considerably frequent in this area. The prevailing wind direction in Washington County is from west to east in all twelve months annually, which matches the prevailing wind direction nationwide (US Department of Commerce, 1998).

Marcellus formation, the major source of UNGD, exists on a large scale in Washington County (Carter et al., 2011). Consequently, UNGD has been intensively performed in Washington County and the industry has also been supported by local authorities.

Survey questionnaire

A community environmental health assessment questionnaire was designed and adminstrated to residents in Washington County in the summer of 2012 and 2014. The questionnaire consisted of three parts. The first part of the questionnaire was aimed at collecting demographic data (sex, race, age etc.) and other basic information regarding each household (income, indoor smoking etc.). The second part of the questionnaire was designed to acquire personal health status. The participants were asked to report whether or not they had a list of symptoms in the past year. The symptoms we asked included but were not limited to respiratory symptoms, dermal symptoms and cardiac symptoms. The last part of the questionnaire was about household environmental qualities. Participants were asked about their satisfaction and awareness about their household and neighboring environments. The selection of households and participants was random and detailed recruiting methods were described in one previous study (Rabinowitz et al., 2015).

Exposure assessment

We employed a more detailed method of exposure assessment in this study, which is a major merit of it. Previous studies on this very topic used multiple different ways to measure the exposure level. Geological proximity was one of the most common approaches. The Rabinowitz team used the distance between household and the nearest well to estimate the residents' exposure to the pollutants (Rabinowitz et al., 2015). In a similar region, the Fryzek team used temporal cut points to determine exposure level (Fryzek et al., 2013). They compared the disease incidence rate before and after hydraulic fracturing began in that area. The McKenzie team have used a more complex method to estimate the environmental exposure. They integrated geological proximity with exposure duration to calculate a time-weighted exposure concentration (McKenzie et al., 2012).

However, there are some limitations in the previous studies. First, in those traditional Euclidean models the investigators assumed that wells in different directions affect the residents equally. In reality, the contributions of wells in different directions to residents' exposure vary dramatically as a result of the prevailing wind direction (Holford et al., 2010). In our study, we referenced the method of modelling residential exposure to traffic and used local wind flow data to adjust the exposure level (Skene et al., 2010). As stated before, the prevailing wind direction in Washington County is from west to east. Therefore, for each household, if a well is located in the western half of the household-centered coordinate, the airborne pollutants of the well would have an effect on the household residents. If the well is located in the eastern half of the household-centered coordinate, the airborne pollutants of the well will not impact the household residents. According to the wind flow direction data, we assigned the weight for the effect of wells in the west of the household a weight of 1 and the weight for the effect of wells east of a household a weight of 0.

Second, in previous studies the investigators assumed that each well produced the same amount of air pollutants. However, each well functions for different lengths of time annually, produces different amount of natural gas and, at the same time, pollutants. Since it's difficult to measure the exact amount of pollutants, we used annual days of production to estimate the level of pollutants. Number of drilling days for each well is recorded by the Pennsylvania Department of Environmental Protection. For those wells with a missing record of annual drilling days, we used the average annual drilling days for all wells with non-missing record as an estimate.

For each year, the final result of exposure assessment is expressed as parameters. There is a calculated parameter for each household and it is a combined effect of pollutant produced by every well in Washington County. The parameters are calculated according to the formula below:

$$E_j=\sum_{i=1}^{n}\frac{W_{ij}P_i}{D_{ij}*365}$$

In the formula, E_j refers to the exposure parameter for household j. D_{ij} refers to the distance between household j and well i. W_{ij} refers to the wind direction weight assigned for well i regarding the specific household j. P_i refers to the production days of well i and n refers to the total number of wells in that year. The environmental exposure level that each household was exposed to is an arithmetic summation of the effects of all active wells in Washington County on that house. In this calculation, we assumed that exposure level is linearly correlated with the reciprocal of the distance between the well and the household.

Another important improvement on the exposure assessment model is that we took the change of exposure over time into consideration. Previously, the investigators assessed the residential exposure to UNGD at one time point-usually at the start of the follow-up. In this study, we assessed the exposure in both 2012 and 2014. Both exposure levels were used in the statistical analysis. From 2012 to 2014, the number of wells in Washington County increased dramatically. Considering that many of our outcome symptoms are acute symptoms, we believed that assessing exposure levels in both years could lead to a more accurate association between exposure and outcomes.

In both years, the exposure scores are categorized into three levels. Residents with an exposure score lower than 10 are categorized into the low exposure group. Residents with an exposure score between 10 and 20 are categorized into the medium exposure group and residents with an exposure score higher than 20 are categorized into the high exposure group. To study the effect of a rapidly expanding UNGD industry in Washington County, we calculated the increase of exposure for each residents. An increase of exposure score smaller than 7, which is the average increase of exposure score for all residents, is classified into the group of “mild increase” and an increase of exposure score greater than 7 is classified into the group of large increase.

Outcome measurements

We used the presence of self-reported symptoms in the past year as the outcome. As we focus mainly on air pollutants released by UNGD wells, respiratory symptoms and dermal symptoms are our primary interests. To better understand the effects of UNGD-released air pollutants on nearby residents, we further divided the respiratory symptoms into two groups: upper respiratory symptoms and lower respiratory symptoms. Upper respiratory symptoms include allergies, cough and sore throat, itchy eyes, nose bleeds and stuffy nose and lower respiratory diseases include asthma and COPD, chronic bronchitis, chest wheeze, shortness of breath and chest tightness (Rabinowitz et al., 2015). Dermal symptoms include rashes and skin problems, dermatitis, irritation, burning, itching and hair loss. Our primary outcomes are the existence of any respiratory symptom, any upper respiratory symptom, any lower respiratory symptom, dermal symptom and any respiratory or dermal symptom at all. We decided to use the dichotomous symptom data rather than the total number or count of the symptoms. The reason is that the proportion of people who had symptoms, in both years, was not sufficiently high and the number of symptoms they had was relatively small. Therefore, although the results of analysis using total number of symptoms are mathematically valid and informative, they would be less meaningful to be interpreted in a public health context or to a general audience.

Statistical analysis

We used multi-level logistic regression model for analysis in order to account for the nesting variance among participants residing in the same household (Dai et al., 2006; Zhu, 2014). The statistical analyses were conducted using SAS 9.3. We used the exposure assessment results and health outcomes in 2012 to compute the odds ratio between exposure levels and presence of symptoms. Then we used increase of exposure from 2012 to 2014 and health outcomes in 2014 to estimate the effect of residents' increases of exposure to pollutants on their health status. We controlled for age, gender, household income, indoor smoking, pet and indoor pollution (fireplaces and woodstove). In the model estimating the effect of changing exposure, we also controlled for their baseline symptoms.

Results

There were 512 individuals from 180 households who participated in at least one survey. In

2012 there were 494 individuals in the survey and the number of individuals dropped to 392 as a result of loss to follow-up, rejection of participation and population mobility. We collected baseline information regarding individual demographics as well as environmental, social and economic conditions of the household. For the 18 individuals who participated in 2014 survey but not 2012 survey, they were asked about their individual demographics, namely age and sex, in 2012. Other questions were asked in respect to household. All baseline demographic conditions are displayed in Table 1.

Table 1: Participant demographics and household characteristics in 2012[a b]

Characters	**Individuals (N=494)**	**Households (N=180)**
Age (yrs)	43.66±23.09	NA
Gender		
Male	251 (50.8)	NA
Female	243 (49.2)	NA
Household income/year		
Under $40,000	86 (20.8)	43 (28.7)
$41,000-$100,000	218 (52.7)	70 (46.7)
More than $100,000	110 (26.6)	37 (24.7)
Indoor smoking		
Yes	117 (23.7)	33 (18.3)
No	377 (76.3)	147 (81.7)
Pets in the house		
Yes	426 (86.8)	150 (83.8)
No	65 (13.2)	29 (16.2)
Fireplace		
Yes	132 (27.0)	47 (26.3)
No	359 (73.1)	132 (73.7)
Woodstove		
Yes	152 (31.0)	56 (31.3)
No	339 (69.0)	123 (68.7)
Money from UNGD		
Yes	34 (8.2)	21 (14.0)
No	383 (91.9)	129 (86.0)

[a] The results are displayed as “mean ± SD” or “number (percentage)”

[b] Some results may not sum to 100 due to rounding.

The mean age of the participants in 2012 was 43.7 years old. The proportion by sex was nearly a half-half split. As we mentioned before, 94.4% of population in Washington County were Caucasian, so race is not an important factor in our study and we did not analyze it. 20.8% of individuals and 28.7% of households held an annual household income less than $40,000.

52.7% of individuals and 46. 7% of households held an annual household income ranging from $41,000 to $100,000. The rest held an annual household income above $100,000. The majority of households (84.3%) had pets. Pet fur is a major source of allergies and could lead to several respiratory and dermal symptoms (Leaderer et al., 2002). We also investigated some sources of indoor air pollution. 23.7% of participants were exposed to indoor smoking, either a smoker themselves or a victim of secondhand smoke. 26.3% and 31.3% of households had, respectively, fireplaces and woodstoves. In addition, we collected some intriguing information. We asked about residents' detailed sources of income to determine whether or not they were compensated by local UNGD companies. We believe this might impact the validity of the self-report of their symptoms. Among 150 households that provided information about their income, 21 of them revealed the payment of compensation by gas companies.

Table 2: Exposure level and health outcomes of residents in 2012 and 2014[a b]

	2012	2014
Exposure	N=494	N=329
Number of wells	624	1018
Exposure score	10.32±6.17	17.83±6.53
Exposure group		
Low exposure (<10)	258 (52.2)	40 (12.2)
Medium exposure (10-20)	203 (41.1)	178 (54.1)
High exposure (>20)	33 (6.7)	111 (33.7)
Increase of exposure	N=311	
High increase (>7)	144 (46.3)	
Low increase (<7)	167 (53.7)	
Health outcomes	N=494	N=329
Respiratory	192 (38.9)	152 (46.2)
Upper	164 (33.2)	145 (44.1)
Lower	86 (17.4)	55 (15.5)
Dermal	33 (6.7)	66 (20.1)
Any symptoms	204 (41.3)	175 (53.2)

[a] The results are displayed as "mean ± SD" or "number (percentage)"

[b] Some results may not sum to 100 due to rounding.

In 2012, there were 624 active unconventional gas wells in Washington County. In 2014, the number boomed to 1018. As shown in Table 2, the average exposure score increased dramatically from 2012 to 2014. The large increase of exposure is more intuitive if displayed by exposure groups. In 2012, over half the people (52.2%) were exposed to low level of pollutants and only 6.7% people were highly exposed. However, in 2014, only 12.2% people were exposed to low level of pollutants and the proportion of highly exposed residents increased to 33.7%.

The proportion of residents who had any symptoms increased from 41.3% to 53.2% in 2012 to 2014. The proportion of residents having any respiratory symptoms and any upper respiratory symptoms also elevated, from 38.9% to 46.2% and 33.2% to 44.1%, respectively. The proportion of residents having any lower respiratory diseases decreased slightly from 17.4% to 15.5%. The proportion of residents having dermal symptoms increased dramatically, from 6.7% in 2012 to 20.1% in 2014.

Table 3: Association of exposure to air pollutants and symptom occurrence in 2012[a b]

	Medium exposure vs Low exposure		High exposure vs low exposure	
Symptoms	Odds ratio (95% CI)	p-Value	Odds ratio (95% CI)	p-Value
Respiratory	0.97 (0.62, 1.54)	0.9054	0.50 (0.20, 1.26)	0.1413
Upper	1.16 (0.64, 2.08)	0.6276	0.68 (0.22, 2.12)	0.5082
Lower	1.00 (0.49, 2.04)	0.9911	1.00 (0.25, 3.89)	0.9913
Dermal	1.91 (0.74, 4.93)	0.1776	4.27 (1.06, 17.14)*	0.0408*
Any symptom	1.05 (0.67, 1.65)	0.8445	0.78 (0.33, 1.86)	0.5731

[a] Results marked with * show a statistically significant association.

[b] All odds ratios above are results of adjusted regressions controlling for sex, age, income, pet in the house, fireplaces and woodstoves.

In the hierarchical model that adjusted for age, sex, household income level, indoor smoking, pets in the household, fireplace in the household and woodstove in the household, we found a limited number of statistically significant associations between exposure to air pollutants and health symptoms in 2012. The results are shown in Table 3. However, we did find that compared to low exposure group residents, high exposure group residents had a significantly higher risk of having dermal symptoms [odds ratio (OR) = 4.27; 95% confidence interval (CI): 1.06, 17.14]. Medium exposure group residents also had an elevated risk of having dermal symptoms, but the result is not statistically significant (OR = 1.91; CI: 0.74, 4.93). No significant or meaningful results were found among people from higher exposure groups, compared to people from low exposure group, that they may have substantially higher risk of having respiratory symptoms, or having any symptom at all. The results of the hierarchical model that estimated the association between the increase of exposure and symptoms in 2014 showed no significant results (Table 4). Controlled for symptoms in 2012, people who live in households that experienced a dramatic increase of exposure to pollutants, compared to those who live in households that experienced a mild increase of exposure to pollutants, were 1.37 times more likely to develop lower respiratory symptoms in 2014 (OR = 1.37; 95% CI: 0.62, 3.03). However, this association was not statistically significant (p-value=0.4324)

Discussions

This study is a large, systematically enrolled and on-going cohort study from a high-UNGD-density area. To our knowledge, it is the largest study to date of the association of exposure to UNGD pollutants and reported symptoms. Using a more detailed model, we found a significant elevated risk of having dermal symptoms among people who were highly exposed to air pollutants in 2012 compared to those who were exposed to low level air pollutants. Apart from that, no significant health risks were detected associated with exposure to air pollutants. The result of the significant adverse health effect of UNGD pollutants on dermal symptoms was consistent with Peter Rabinowitz's study in 2015, in which the same cohort was analyzed (Rabinowitz et al., 2015). In that study, they also found an increased frequency of reported dermal symptoms among people who lived within 1 km of the nearest fracking well, compared to those who lived further than 2 km. Rabinowitz also found similar health effects on upper respiratory symptoms. However, in this study, the result failed to be statistically significant. We also examined the cohort longitudinally to see whether people exposed to a large change in exposure to pollutants would have a higher risk of having new symptoms in 2014. The results provided no convincing evidence that being exposed to dramatically increasing level of pollutant would induce new symptoms.

Table 4: Association of increase in exposure level and symptom occurrence in 2014[a] [b]

Symptoms	Odds ratio (95% CI)	p-Value
Respiratory	0.89 (0.45, 1.77)	0.7427
Upper	0.84 (0.41, 1.71)	0.6243
Lower	1.37 (0.62, 3.03)	0.4324
Dermal	0.90 (0.45, 1.82)	0.7674
Any symptom	1.02 (0.56, 1.87)	0.9528

[a] The odds ratios represent the risk of having symptoms among people exposed to large increase of exposure compared to those exposed to mild increase of exposure from 2012 to 2014

[b] All odds ratios above are results of adjusted regressions controlling for sex, age, income, pet in the house, fireplaces and woodstoves.

We analyzed several potential sources of bias in this study that might discredit our result. We first examined potential information bias. An important uncertainty factor in the survey was that many of the households received financial compensation from gas companies and this may hugely bias their reports on symptoms. We implicitly asked about whether they received such financial supports from gas companies and 14% of the households admitted it. We calculated adjusted models further controlling for this factor and found a negligible difference with the previous results. After adjusting for the financial compensation receipt, the odds ratios for any symptom occurrence in 2012 are 1.04 and 0.80, respectively, for people in medium and high exposure groups and the odds ratio for any symptom occurrence in 2014 remains unchanged. Consequently, we can conclude that whether the household received financial supports or not did not differentiate their reports of symptoms and there was no significant.

Table 5: Comparison of drop-out participants and all participants in 2012[a b]

Symptom Category	Proportion of people having symptoms	
	Drop-out population (N=183)	Overall population in 2012 (N=494)
Respiratory	63 (34.4)	192 (38.9)
Upper	50 (27.3)	164 (33.2)
Lower	35 (19.1)	86 (17.4)
Dermal	10 (5.5)	33 (6.7)
Any	65 (35.5)	204 (41.3)

[a] Data records in the tables are displayed as number (percentage)

[b] Some results may not sum to 100 due to rounding.

We also analyzed potential attrition bias occurred during the two-year survey. There were altogether 183 people who participated in the 2012 survey but did not participated in the 2014 survey due to refusal, moving or death. We found that the proportion of these people having health symptoms were very similar with that in the overall population (Table 5). Similarly, among the 52 households that participated in the 2012 survey but not the 2014 survey, their levels of exposure to air pollutant were fairly similar with those among all 180 households (Table 6). Therefore, we could conclude that there was no notable attrition bias due to either participant or household drop-outs during the survey period.

The merits of this study include a large sample size, high-quality follow-up and good questionnaire design. And more importantly, we have employed a more detailed exposure assessment metric. In 2012, 494 participants were enrolled in the study. They were from 180 different households, distributed all across the county. The large sample size allows us to estimate the association of exposure to UNGD pollutants and health outcomes more accurately. The high-quality questionnaire design ensures that we have better understanding towards participants' demographics and household features. Also, it ensures that we could control for a variety of confounders in our analysis to avoid their distortion of the main results.

Table 6: Comparison of drop-out households and all households [a] [b]

Exposure Category	Drop-out households (N=52)		All households (N=180)	
	Exposure level 2012	Exposure level 2014	Exposure level 2012	Exposure level 2014
Low Exposure	25 (48.1)	7 (13.5)	86 (47.78)	19 (10.56)
Medium exposure	24 (46.2)	29 (55.8)	80 (44.44)	97 (53.89)
High exposure	3 (5.8)	16 (30.8)	14 (7.78)	64 (35.56)

[a] Data records in the tables are displayed as number (percentage)

[b] Some results may not sum to 100 due to rounding.

There are also some inevitable limitations in this study. First, though the exposure assessment method is more detailed compared to proximity or temporal cut points, it is still not precise enough and based on some key assumptions. We used the well's annual production days to represent the intensity of its production. However, this is based on the assumption that all wells were producing the same amount of air pollutants daily, which in reality could hardly be real. Also, we categorized the prevailing wind direction dichotomously, assuming that wells east of a household would not carry pollutants to the household. It is a generally correct but coarse classification. There exists a very small proportion of days in which wind is coming from the east.

The second limitation is that the reliance on self-report of health outcomes. During the survey, we only asked one respondent in a household questions and the respondent reported individual demographics and health symptoms on behalf of everyone in the household. While the individual demographics were likely to be precise, the reports of health symptoms may be questionable. On the one hand, the respondent may underreport the symptoms of others in the household due to unawareness; on the other hand, the respondent may also overreport the symptoms if he/she were concerned about the presence of environmental health hazards.

The reason that exposure to air pollutants affect only dermal outcomes is unclear. Possible explanations include that dermal symptoms are relatively more acute hence more likely to occur in response to heavy exposure in short periods of time. Besides, the occurrence of dermal symptoms could attribute to not only air pollutants, but also waterborne pollutants. The insignificant association of increase in exposure and occurrence of symptoms in 2014 could be comforting news for the local community. However, since most of the gas wells in the study area had been drilled only for 5-6 years, we would not expect to see associations with diseases with having a relatively long latency period.

Conclusion

The results of this study suggest that residential exposure to air pollutants released by unconventional natural gas wells were associated with the occurrence of dermal symptoms in 2012. No association was found of the increase in exposure during 2012 to 2014 and the incidence of symptoms in 2014. Further studies with more precise exposure assessments and outcome measurements are warranted in order to estimate the human health risks and environmental safety of UNGD industries.

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