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Review

Public health implications of environmental noise associated with unconventional oil and gas development

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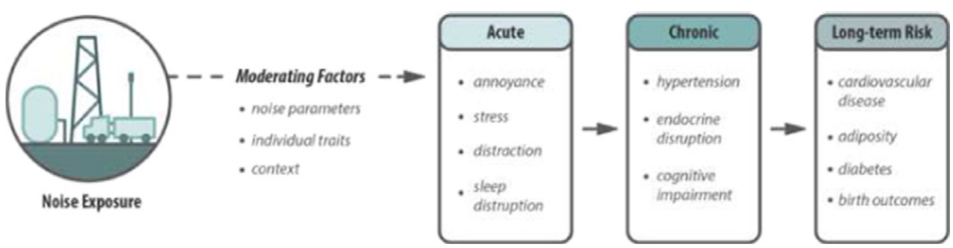
HIGHLIGHTS

- Reviewed non-auditory health outcomes from environmental noise exposure.
- Potential outcomes include annoyance, sleep disturbance, and cardiovascular disease.
- Oil and gas operations produce noises at levels that may increase health risks.
- Additional noise exposure research for oil and gas operations is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Modern oil and gas development frequently occurs in close proximity to human populations and increased levels of ambient noise have been documented throughout some phases of development. Numerous studies have evaluated air and water quality degradation and human exposure pathways, but few have evaluated potential health risks and impacts from environmental noise exposure. We reviewed the scientific literature on environmental noise exposure to determine the potential concerns, if any, that noise from oil and gas development activities present to public health. Data on noise levels associated with oil and gas development are limited, but measurements can be evaluated amidst the large body of epidemiology assessing the non-auditory effects of environmental noise exposure and established public health guidelines for community noise. There are a large number of noise dependent and subjective factors that make the determination of a dose response relationship between noise and health outcomes difficult. However, the literature indicates that oil and gas activities produce noise at levels that may increase the risk of adverse health outcomes, including annoyance, sleep disturbance, and cardiovascular disease. More studies that investigate the relationships between noise exposure and human health risks from unconventional oil and gas development are warranted. Finally, policies and mitigation techniques that limit human exposure to noise from oil and gas operations should be considered to reduce health risks.

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Contents

1. Introduction

Noise, or unwanted sound, is a biological stressor and potential public health hazard in a variety of contexts. Exposure to noise modifies the function of human organs and systems (Münzel et al., 2014) and can be a contributing factor to the development and aggravation of health conditions related to stress (e.g., high blood pressure) (Dratva et al., 2012). Numerous large-scale epidemiological studies have identified associations between environmental noise exposure and adverse health outcomes, such as cardiovascular disease (Babisch et al., 2013), diabetes (Sørensen et al., 2013), adiposity (Christensen et al., 2015), birth outcomes (Gehring et al., 2014), cognitive impairment in children (Lercher et al., 2002), depression (Orban et al., 2015), and sleep disturbance (Hume et al., 2012). Health outcomes due to environmental noise exposure may also carry economic consequences due to the size of populations exposed to hazardous levels of noise (Swinburn et al., 2015).

Recent combinations of technologies, including high-volume hydraulic fracturing and directional drilling, have unlocked oil and gas from low-permeability formations (e.g., shale, tight sands, etc.) that were previously not considered to be economically viable. As a result, oil and gas development activities are being cited in a wide array of new geographic locations, sometimes in urban areas and in close proximity to human populations (Adgate et al., 2014). Public concerns have advanced a large body of scientific research to assess various impacts of unconventional oil and gas development (UOGD). The term UOGD generally refers to oil and gas produced from atypical reservoir types that require techniques that are different than those required for conventional oil and gas production. However, in this paper, we use the term to refer specifically to onshore methods of oil and gas development enabled by hydraulic fracturing or “fracking” to produce oil or gas from shale and other tight formations.

Previous UOGD impact investigations have primarily focused on fugitive methane emissions, local and regional air quality degradation, surface and groundwater contamination, and the characterization of chemicals used in and produced by various processes (Jackson et al., 2014). Public health assessments have incorporated these data to assess the potential for human exposures to pollutants associated with UOGD through air and water pathways. Several reviews have identified health hazards and risks associated with UOGD and there is now an emerging body of epidemiology (Adgate et al., 2014; Shonkoff et al., 2014; Werner et al., 2015).

Air pollution and water contamination associated with UOGD are becoming increasingly well studied (Evans and Helmig, 2016; Hildenbrand et al., 2016). However, noise pollution related to UOGD remains understudied in the public health literature, even while the development of wind energy has generated a number of studies measuring potential health effects of noise exposure from wind turbines (Schmidt and Klokker, 2014; Van Renterghem et al., 2013). Many operations in various phases of oil and gas development produce transient and chronic noise (Maryland Institute for Applied Environmental Health, 2014). Although noise pollution has been cited as a primary concern among residents in areas of UOGD (Garfield County, Colorado, 2011), few researchers have evaluated noise levels and noise exposure associated with this industry. Measurements and estimates of noise levels are sometimes included in oil and gas environmental impact statements (Table 1), but to date there have been only a handful of reports that have evaluated noise associated with UOGD in the context of public health.

The types of noise associated with oil and gas operations can be complex in nature, owing to a wide variety of sources. Some of these noises are intermittent, some are continuous, and many vary in their intensity. Certain sources, such as compressor stations, produce low frequency noise (LFN), which is typically heard as a low rumble (Leventhall, 2003). There are also numerous source-dependent and subjective factors that may influence health outcomes, such as noise sensitivity (Hill et al., 2014; Schreckenberg et al., 2010), noise reduction technologies, and synergistic effects of noise and air pollution. Further, noise exposure, like other health threats, may disproportionately impact vulnerable populations, such as children, the elderly, and the chronically ill (van Kamp and Davies, 2013).

In this article, we explore the scientific literature on environmental noise to determine the potential hazards, exposures, and health outcomes that noise from UOGD may present. Many noise sources from UOGD are similar to those associated with conventional oil and gas development; however, some aspects can differ in important ways. For instance, drilling a horizontal well can take 4 to 5 weeks of 24 h per day drilling to complete whereas a traditional vertical well usually takes less than a week (Nagle, 2009). High-volume hydraulic fracturing also requires a greater volume of water and higher pressures to frac a horizontal well, resulting in more pump and fluid handling noise than traditional oil and gas development (Nagle, 2009). Nonetheless, because the data are limited we include noise measurements and estimates from some traditional oil and gas activities that are also relevant to UOGD.

This article expands on our initial findings presented in an appendix of the second volume of an independent scientific assessment of well stimulation treatments in California, commissioned by the California Natural Resources Agency pursuant to Senate Bill 4 and

Table 1
Noise levels associated with UOGD operations.

Category	Source	Distance (m/ft)		Average dBA[a]	dBA Range	Data type	Reference
Construction and preparation	General (unspecified)	<15	<50	–	70–90	Measurement	Bureau of Land Management, 2006
	Access road construction	15	50	89	–	Estimate	NYSDEC FSGEIS 2015
		76	250	75			
		152	500	69			
		305	1000	63			
		457	1500	59			
		610	2000	57			
	Site preparation	191	625	58–69	–	Measurement	McCawley, 2013
	Well pad preparation	15	50	84	–	Estimate	NYSDEC FSGEIS 2015
		76	250	70			
		152	500	64			
		305	1000	58			
		457	1500	55			
		610	2000	52			
	Truck traffic	<152	<500	–	65–85	Estimate	Garfield County, Colorado, 2011
		191	625	65	56–73	Measurement	McCawley, 2013
Production and completion	Horizontal drilling	15	50	76	–	Estimate	NYSDEC FSGEIS 2015
		76	250	62			
		152	500	56			
		305	1000	50			
		457	1500	47			
		610	2000	44			
	Vertical drilling	191	625	54	–	Measurement	McCawley, 2013
	Drilling (unspecified)	100	328	57.4–62	–	Estimate	Ambrose and Florian, 2014
		300	984	52.5		Measurement	
		1055	3461	36.9			
		2300	7546	30.4			
		191	625	75–80	–	Measurement	Witter 2011
		200	655				
		30	100	–	75–87	Measurement	Behrens and Associates, Inc., 2006
		61	200	–	71–79		
		91	300	–	65–74		
		122	400	–	60–71		
		152	500	–	56–68		
		183	600	–	54–59		
		213	700	–	51–55		
		244	800	–	51–54		
	Hydraulic fracturing	15	50	99–104	–	Estimate	NYSDEC FSGEIS 2015
		76	250	85–90			
		152	500	79–84			
		305	1000	73–78			
		457	1500	69–74			
		610	2000	67–72			
		191	625	52	47–60	Measurement	McCawley, 2013
	Hydraulic fracturing/flowback	191	625	58	55–61	Measurement	McCawley, 2013
	Flaring	On-site	On-site	97.9	–	Estimated	Bureau of Land Management, 2006
		161	528	66.3			
	Compressor station(s)	<305	<1000	63.15	35.3–94.8	Measurement	Maryland Institute for Applied Environmental Health, 2014
		305–610	1000–2000	55.48	35.3–77.6		
		610–762	2000–2500	54.09	35.3–80.3		
		>1067	>3500	51.50	35.3–74.1		
		On-site	On-site	69–86	–	Measurement	Bureau of Land Management, 2006
		1609	5280	58–75			
		2012	6600	54			
		100	328	53.8	–	Estimate	Ambrose and Florian, 2014
		140	459	50.9		Measurement	

[a] A-weighted decibel. This is a frequency dependent correction that is applied to a measurement to mimic the varying sensitivity of the ear to sound for different frequencies. dBA serves as an expression of a sound's relative loudness in the air as perceived by the human ear.

coordinated by the California Council on Science and Technology (Shonkoff et al., 2015). We highlight what is currently known and identify data gaps and research limitations. Additionally, we consider how these findings may inform discussions on the deployment of noise abatement techniques, such as the minimum surface setback distances between human populations and oil and gas infrastructure.

2. Health impacts of environmental noise exposure

Noise exposure can lead to adverse health outcomes through direct and indirect pathways (Fig. 1). Noise is an environmental stressor that activates the sympathetic nervous and endocrine systems (Ising and Braun, 2000). Acute noise effects are not limited to high decibel sound

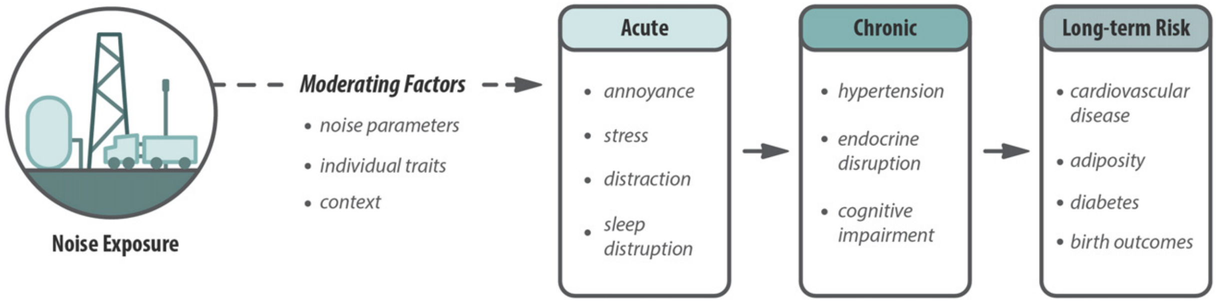

Fig. 1. Potential non-auditory health outcomes of environmental noise exposure. This figure is adapted from Shepherd et al. (2010) and depicts the relationships between exposure to noise and primary and secondary health effects. Non-physical effects of noise are also mediated by psychological and psychophysiological processes (Shepherd et al., 2010). The dashed lines indicate the physical effects of noise and the solid lines indicate the non-physical effects. Annoyance and sleep disturbance act as mediators between predisposing factors and secondary health effects, such as quality of life or cardiovascular disease.

levels such as those found in occupational settings, but also are evidenced at relatively low environmental sound levels when they cause disturbance of other activities (e.g., sleep, concentration, etc.) (Babisch, 2002). Both the sound level of the noise (objective noise exposure) and its subjective perception can influence the impact of noise on neuroendocrine homeostasis (Münzel et al., 2014). In other words, the way in which an individual perceives a particular sound can influence the impact of the noise.

Health outcomes associated with noise exposure have been studied for decades, although there has been an increasing body of literature on the non-auditory health effects of environmental noise exposure. Most of these studies analyze associations between adverse health outcomes and noise from airports, road traffic, and railways. Some of the more commonly identified non-auditory health endpoints for noise exposure are annoyance/perceived disturbance, sleep disturbance, and cardiovascular health outcomes (Basner et al., 2014). Although there are other health outcomes associated with noise exposure, here we focus on these three health endpoints. We also briefly discuss potential mechanisms and epidemiological evidence that considers threshold calculations and exposure-response relationships.

2.1. Annoyance

Annoyance appears to be one of the more common responses to general environmental noise exposure among communities. Noise annoyance may produce a host of negative responses, such as feeling of anger, displeasure, anxiety, helplessness, distraction, and exhaustion (World Health Organization, 2011). Annoyance affects both the wellbeing and quality of life among populations exposed to environmental noise. Noise sensitivity is a strong predictor of noise annoyance (Paunović et al., 2009; Stansfeld, 1992) and may also predict the risk of future psychological distress (Stansfeld and Shipley, 2015).

Annoyance is also source dependent, meaning that dBA (A-weighted decibel) readings alone are not always sufficient to gauge annoyance thresholds (Babisch et al., 2013). However, according to a 2010 report by the European Environment Agency (EEA), the thresholds are generally about the same for transport noises (European Environment Agency (EEA), 2010). Other agencies have slightly higher threshold averages for annoyance while differentiating between serious and moderate annoyance as well as outdoor and indoor activity interference (Table 2). Still, the results of studies that measure levels of annoyance vary and a number of uncertainties remain because of the noise dependent and subjective factors related to annoyance.

2.2. Sleep disturbance

Sleep disturbance is another common response among populations exposed to environmental noise (Muzet, 2007). Noise can impact sleep in a number of ways and can have immediate effects (e.g., arousal, sleep stage changes), after-effects (e.g., drowsiness, cognitive

Table 2
Noise level thresholds associated with various health outcomes.

Category	Effect	Threshold (average dBA)	Acoustic indicator	Time domain	Reference
Annoyance	Unspecified	42	L_{den}	Chronic	EEA, 2010
	Serious	55	LA_{eq}	Chronic	WHO 1999
	Moderate	50	LA_{eq}	Chronic	WHO 1999
	Outdoor activity interference	55	$L_{dn}/L_{eq(24)}$	Chronic	US EPA 1974
	Indoor activity interference	45	$L_{dn}/L_{eq(24)}$	Chronic	US EPA 1974
Sleep	Sleep disturbance	30	LA_{eq}	Chronic	WHO 1999
		45	LA_{max}	Acute	WHO 1999
	Sleep (polysomographic)	32	$L_{max,indoors}$	Acute, Chronic	EEA, 2010
	Self-reported sleep disturbance	42	L_{night}	Chronic	EEA, 2010
	Reported awakening	53	$SEL_{indoors}$	Acute	EEA, 2010
Cardiovascular	Hypertension	50	L_{den}	Chronic	EEA, 2010
	Ischaemic heart disease	65–70	LA_{eq}	Chronic	WHO 1999
		60	L_{den}	Chronic	EEA, 2010
General	Reported health/wellbeing	50	L_{den}	Chronic	EEA, 2010
	Health/welfare	55	L_{dn}	Chronic	US EPA 1974

L = sound level.
LA = A-weighted sound level.
L_{den} = Day-evening-night equivalent level.
LA_{eq} = A-weighted, equivalent sound level (dBA L_{eq}).
L_{dn} = Day-night equivalent level (A-weighted, L_{eq}).
LA_{max} = A-weighted, maximum sound pressure level occurring in an interval.
$L_{max\ indoors}$ = Maximum sound pressure occurring indoors.
L_{night} = Night equivalent level (L_{eq}, A-weighted, sound level).
$SEL_{indoors}$ = Sound exposure level (logarithmic measure of the A-weighted), indoors.

impairment), and long-term effects (e.g., chronic sleep disturbance) (World Health Organization, 2011). The body continues to respond to stimuli coming from the environment during sleep. Similar to annoyance, noise sensitivity plays a significant role in sleep disturbance as well, and is influenced by both noise dependent factors (e.g., noise type, intensity, frequency) and other subjective factors (e.g., age, personality, self-estimated sensitivity) (Muzet, 2007).

There is a large body of research on sleep and health with variable and controversial results. Because the effects of noise exposure on sleep are dependent on a number of objective and subjective factors, it is difficult to determine a clear dose-response relationship. However, reviews of evidence produced by epidemiological and experimental studies have identified relationships between noise exposure at night and adverse health outcomes (Ristovska and Lekaviciute, 2013). It is generally accepted that no effects on sleep tend to be observed below the level of 30 dBA L_{night} (average sound pressure level over one night) and there is no sufficient evidence to indicate that the biological effects that have been observed below 40 dBA L_{night} are harmful to health (World Health Organization, 2009). Adverse health effects such as self-reported sleep disturbance, insomnia, and increased use of drugs are observed at levels above 40 dBA L_{night} and levels above 55 dBA present a major public health concern (World Health Organization, 2009).

2.3. Cardiovascular health

Reactions to noise can occur at both a conscious and non-conscious level. Specifically, noise can trigger emotional stress reactions from perceived discomfort as well as physiological stress from interactions between the auditory system and other regions of the central nervous system (Basner et al., 2014). Exposure to noise can increase systolic and diastolic blood pressure, create changes in heart rate, and cause the release of stress hormones (e.g., catecholamines and glucocorticoids) (Basner et al., 2014). Studies have found positive correlations between chronic noise exposure and elevated blood pressure, hyptertension, ischaemic heart disease, and stroke (Halonen et al., 2015; Münzel et al., 2014; Vienneau et al., 2015). Systematic and quantitative reviews have collated and synthesized evidence of the relationship between noise exposure and cardiovascular disease (Babisch, 2000, 2006; Stansfeld and Matheson, 2003; van Kempen et al., 2002) and some meta-analyses have developed exposure-response curves that are used to quantify human health risks in health impact assessments (Argalášová-Sobotová et al., 2013). Table 2 provides EEA, World Health Organization (WHO), and United States Environmental Protection Agency (US EPA) threshold levels for increased cardiovascular risk.

3. Noise sources and levels during oil and gas development

There is currently no peer-reviewed literature on the noise levels and potential health impacts from noise exposure related to oil and gas development. However, measurements and estimates of noise levels for oil and gas development can be found in a number of government reports and independent analyses in the grey literature. These sources are subject to limitations and can vary significantly in terms of methodology and the type of oil or gas development for which the measurements were taken.

The main sources of noise from oil and natural gas operational activities can be grouped into the following two categories: (1) construction and preparation (e.g., road construction, site and well pad preparation, truck traffic) and (2) production and completion (e.g., flaring operations, drilling, hydraulic fracturing, compressor stations). Table 1 summarizes noise measurements and estimates from environmental impacts statements, reviews, and other reports. These findings are not necessarily commensurable, however, because of the heterogeneity of approaches and study systems across the reports (e.g., source of noise, measurement distance, type of oil or gas operations, etc.). Furthermore, some of the data contained in these reports are industry/consultant predictions and do not necessarily reflect actual field monitoring results. Nonetheless, these are the best available data for determining expected noise levels from various aspects of UOGD.

In a report prepared for the West Virginia Department of Environmental Protection, McCawley (2013) monitored noise levels associated with various stages of natural gas development from 2 to 4 sampling sites located 190.5 m (625 ft) from the center of five different well pads. McCawley (2013) provided actual monitoring results from a number of different sites and for a variety of stages in the development process, including site preparation, drilling, hydraulic fracturing, and truck traffic. Analysis of these data yields the percent of time particular noise levels were exceeded in minutes (Table 3 and Table 4). In all cases, for the five major operations the study surveyed, noise levels exceeded 55 dBA for >24 h, though not necessarily continuously. Pad Preparation in Wetzel County, WV was more frequently louder (on both the basis of total time and percent of time sampled) than was Hydraulic Fracturing in either Marion County, WV or Wetzel County, WV. As all sound levels were measured at least 190.5 m from the center of the pad it may not be

Table 4
Traffic noise levels, Wetzel County, West Virginia.[a]

Site 2A (next to road/construction)			Site 2C (far side of pad away from traffic)		
Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)
1	0.01	90	13	0.18	90
254	3.48	80	134	1.84	80
5213	71.32	70	499	6.84	70
7304	99.93	60	927	12.71	60
7309	100.00	50	6363	87.22	50
7309	100.00	40	7295	100.00	40
7309	100.00	30	7295	100.00	30

[a] These data come from a report prepared for the West Virginia Department of Environmental Protection (McCawley, 2013). Samples were continuous over the total time duration listed in the bottom row. The total sampling time for Site 2A was 7309 min (~122 h) and Site 2C was 7295 min (~122 h).

Table 3
Hydraulic fracturing noise levels, Marion County, West Virginia.[a]

Site A (near impoundment above pad)			Site C (near road)			Site D (1200 ft. from pad)		
Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)
53	0.357023	90	6	0.04	90	3	0.02	90
191	1.286628	80	52	0.35	80	19	0.13	80
644	4.338161	70	930	6.26	70	138	0.93	70
2277	15.3385	60	4949	33.32	60	658	4.44	60
4261	28.70327	50	11,331	76.30	50	2760	18.63	50
7353	49.53183	40	12,048	81.13	40	10,028	67.68	40
14,845	100	30	14,851	100.00	30	14,817	100.00	30

[a] These data come from a report prepared for the West Virginia Department of Environmental Protection (McCawley, 2013). Samples were continuous over the total time duration listed in the bottom row. The total sampling time for Site A was 14,845 min (~247 h), Site B was 14,851 min (~248 h), and Site C was 14,817 (~247 h).

surprising that Pad Preparation was more frequently loud. The heavy earth moving equipment was observed to frequently pass directly next to the sound monitoring equipment.

McCawley (2013) found that other operations also exhibited similar, apparently anomalous results – such as the vertical drilling operation in Wetzel County, WV, where no drilling took place during the time period of sampling. On the far side of the pad, away from the road and out on its own solitary point of land, but the same distance from the center of the pad as the second sampling site, sound levels exceeded 60 dBA far less frequently than did the sampling site next to roadway on the other side (approximately 180 degrees opposite) of the pad. The sampling site next to the roadway had sound levels exceed 70 dBA far more frequently than did the Hydraulic Fracturing site in Marion or Wetzel County. Again, heavy-duty traffic and construction equipment were frequently observed around the second sampling site and not around the first.

McCawley (2013) also concluded that air emissions should not be assumed to necessarily be coming from the center of the pad based on trends similar to the sound levels but for volatile organic compounds (hypothesized to emanate from the heavy duty diesel equipment). Since the sound levels appear to follow the same pattern, the sound levels could be hypothesized to also be coming from the heavy-duty equipment. Additional research is required here and the cautionary lesson is that site setbacks do not necessarily provide the expected attenuation if the source is not located solely at the center of the pad. One might therefore expect to see results for noise similar to the levels and frequencies in Table 4 along the roadways near the operations mentioned in the McCawley (2013) report due to traffic flow and ancillary pad site operations.

A 2014 pilot study conducted as part of a report prepared for the Maryland Department of the Environment and the Maryland Department of Health and Mental Hygiene monitored resident exposures to noise associated with natural gas compressor stations in West Virginia (Maryland Institute for Applied Environmental Health, 2014). The study found an average L_{eq} (equivalent continuous sound pressure level) for the combined compressor stations of 60.2 dBA (range 35.3 to 94.8 dBA) and an average short term L_{eq} of 61.4 (range 45.3 to 76.1 dBA), both of which decreased with distance from the compressor stations. For instance, for 24-h measurements the recorded average of 63.15 dBA at <305 m (1000 ft) decreased to 54.09 dBA at 610 to 762 m (2000 to 2500 ft). The average L_{eq} at control homes located >1067 m (3500 ft) from a compressor station was 51.40 dBA.

A 2006 Bureau of Land Management Environmental Impact Statement for the Jonah Infill Drilling Project (JIDPA) in Sublette County, Wyoming incorporated measurements from previous investigations to assess typical noise levels near gas field operations (Bureau of Land Management, 2006). Noise levels from one compressor station just south of the JIDPA were recorded between 58 and 75 dBA about 1.6 km (1 mi) and 54 dBA about 2 km (1.25 mi) to the southeast, while another station provided readings of about 65 dBA about 1.6 km (1 mi) east (Bureau of Land Management, 2006). Readings from construction activities ranged from 70 dBA to 90 dBA within 15 m (50 ft) from the source.

In 2006, the Fort Worth Gas Well Task Force commissioned Behrens and Associates, Inc. to produce a gas well drilling noise impact and mitigation report for drilling rigs operating within and near the City of Fort Worth, Texas (Behrens and Associates, Inc., 2006). Drilling noise levels for three different rigs were measured at various times from four directions (e.g., generator side of rig, rear side of rig, etc.) up to 800 ft away. Average drilling sound levels were 75–87 dBA at 30 m (100 ft), 71–79 dBA at 61 m (200 ft), 65–74 dBA at 91 m (300 ft), 60–71 dBA at 122 m (400 ft), 56–68 dBA at 152 m (500 ft), 54–59 dBA at 183 m (600 ft), 51–55 dBA at 213 m (700 ft), and 51–54 dBA at 244 m (800 ft).

In 2014, the Wyoming Game and Fish Department had sound levels recorded in order to measure the threat from noise to greater sage grouse (a species reliant on vocal communication for its propagation) in the Pinedale Anticline Project Area (PAPA) (Ambrose and Florian, 2014). The report provided estimates of sound levels at 100 m (328 ft) based on measurements taken at further distances for a number of common PAPA gas field activities (median (L_{50}) over a 24-h period). For instance, a reading of 53.8 dBA was estimated at 100 m based on an actual measurement of 50.9 dBA at 140 m (459 ft). Various sources produced median sound levels at least 50 dBA at 100 m, including an active drill rig (62 dBA), an injection well complex (56 dBA), a compressor station (54 dBA), and a well pad with 21 well heads and a generator (50 dBA) (Ambrose and Florian, 2014).

The New York State Department of Environmental Conservation's Final Supplemental Generic Environmental Impact Statement On The Oil, Gas and Solution Mining Regulatory Program provided the greatest number of estimates for noise levels associated with various aspects of UOGD. Composite noise levels at 15 to 610 m (50 to 2000 ft) ranged from 57 dBA to 89 dBA for access road construction, 52 dBA to 84 dBA for well pad preparation, 44 dBA to 76 dBA for horizontal drilling, and 52 dBA to 104 dBA for hydraulic fracturing (New York State Department of Environmental Conservation, 2015).

A 2011 Health Impact Assessment (HIA) conducted by the Colorado School of Public Health (CSPH) considered the health impacts of noise, vibration, and light pollution on health in the Battlement Mesa community in Garfield County, Colorado. CSPH obtained well pad noise monitoring data from Antero Resources, an oil and gas exploration and production company. Unmitigated noise levels during drilling operations were measured below industrial noise limits at 191 m (625 ft) to the northwest and 165 m (540 ft) to the southeast (75 and 80 dBA during night and day, respectively) (Garfield County, Colorado, 2011). According to Antero's models, however, mitigation could reduce noise from drilling to the 50–63 dBA range at 107 m (350 ft). The CSPH HIA found that heavy truck traffic, construction equipment, and diesel engines used throughout drilling and hydraulic fracturing would likely account for the most significant sources of noise.

4. Potential health outcomes from UOGD noise exposure

To determine the potential for health outcomes, thresholds and guidelines from Table 2 can be compared with data from Table 1. The health literature on noise exposure considered with dBA levels associated with oil and gas operations suggest that noise from UOGD present a number of potential adverse health outcomes. This finding is consistent with other studies and reports that consider potential health threats of noise exposure in the context of oil and gas development (Maryland Institute for Applied Environmental Health, 2014; McCawley, 2013; Witter et al., 2013). In particular, oil and gas operations have produced sound level measurements and estimates that could lead to all three of the non-auditory health outcomes considered in this review.

Of the potential health outcomes discussed above, there is a more significant risk for annoyance and sleep disturbance because these generally occur at lower noise thresholds. Although hypertension and cardiovascular diseases are associated with higher average dBAs than annoyance and sleep disturbance, many sources of noise from UOGD have produced noise at levels that are known to be associated with these outcomes. Most UOGD activities are not permanent, so there may be less of a risk for cardiovascular health outcomes, which are associated with chronic and continuous noise exposure (e.g., living next to a busy highway). However, some sources do produce chronic noise once drilling and other production processes are complete (e.g., compressor stations) and may contribute to the types of exposures associated with cardiovascular health outcomes. Further, these sources can produce LFN, which may considerably increase the adverse effects of noise exposure (Berglund et al., 1999).

When considering the health impacts of noise from a given source, the volume and intensity of the noise, whether it is prolonged and/or continuous, how it contrasts with the ambient noise levels, and the time of day must be taken into account. Noise levels depend not only on the type of source, but also on other factors such as distance from the source, air temperature, humidity, wind gradient, and the topography. The specific environment should also be taken into account, such as whether or not the dBA level is indoor/outdoor or whether it is heard in a hospital, school, daycare center or other facility.

4.1. Co-exposures

There are a number of health damaging air pollutants associated with UOGD that have been measured in high concentrations, including volatile organic compounds (VOCs), aromatic hydrocarbons, particulate matter (PM), and ground level ozone (Helmig et al., 2014; Oltmans et al., 2014; Pétron et al., 2014). Some of these pollutants have been shown to increase risk factors associated with heart disease and other adverse health outcomes. Numerous epidemiological studies have observed exposure to noise and air pollution simultaneously, since both often accompany transportation sources (e.g., busy roadways). It can be difficult to link one or the other to increased cardiovascular risks, and correlated exposures may lead to confounding in some epidemiological studies. It is not entirely clear from the available body of science whether air pollution is independent, additive, or synergistic to impacts from noise exposure.

Several papers have also acknowledged that light pollution resulting from nighttime UOGD operations may constitute an additional stressor and potential health hazard (Ferrar et al., 2013; Perry, 2013; Witter et al., 2013). Evidence suggests that light at night may impact health by disrupting normal circadian rhythms and altering melatonin and other hormone releases (Chepesiuk, 2009; Pauley, 2004). There has also been some epidemiological links of light at night to breast cancer (Hurley et al., 2014) and obesity (McFadden et al., 2014), although the research is still preliminary.

4.2. Low frequency noise

LFN is produced by some oil and gas operations (e.g., compressor stations), yet, there are few data available and concerns about LFN tend to focus more on wind turbines (Møller and Pedersen, 2011). LFN is not clearly defined and presents challenges for regulation based on conventional methods of assessing noise (based on A-weighted equivalent level) (Leventhall, 2004). LFN generally occurs below a frequency of 100 to 150 Hz (Hertz is a unit of frequency defined as one sound vibration or cycle per second) and at very low frequencies referred to as infrasound (20 Hz) people may complain about "pressure sensations" or describe an experience of "feeling the noise" (Department of the Environment, Nothern Ireland, 2001).

The association between exposure to LFN and adverse health outcomes has not received as much attention in the scientific literature as compared to higher frequency noise measured by traditional A-weighted bands (Murphy and King, 2014). However, the WHO has suggested that LFN may considerably increase the adverse effects of noise exposure (Berglund et al., 1999). Exposure to LFN has been associated with sleep disturbance (Leventhall, 2003), annoyance (Persson and Björkman, 1988), and other secondary health effects (Berglund et al., 1999). Residential exposure to LFN may even be a greater problem than noise measured in the normal frequency range given that most walls in buildings and homes are not able to attenuate LFN (Leventhall, 2003). Some evidence suggests that dBA may underestimate the level of annoyance experienced by exposed populations (Persson and Björkman, 1988).

4.3. Vulnerable populations

As with other environmental stressors, noise exposure may disproportionately impact vulnerable populations, including children, the elderly, and the chronically ill. In addition to these groups, the literature also considers those who are sensitive to noise, of a low socioeconomic status, suffering from tinnitus, mentally ill, and foetus or neonates (van Kamp and Davies, 2013). Overall, there is very little epidemiological literature on the effects of environmental noise exposure on vulnerable groups and so determining dose-response curves and setting specific limit values is difficult.

4.4. UOGD public health literature

There is an emerging body of epidemiology that suggests an association between UOGD and adverse health outcomes (Hays and Shonkoff, 2016). In a study using over 95,000 inpatient records from three counties in northeast Pennsylvania, Jemielita et al. (2015) noted an association between density of unconventional natural gas wells and increased inpatient prevalence rates for a number of medical categories, including cardiology and neurology. The authors hypothesized that this association could be due in part to potential toxicant exposure and stress responses (Jemielita et al., 2015), the latter of which may bear particular relevance to noise exposure. Several other studies have found associations between UOGD and some adverse birth outcomes (Casey et al., 2015; McKenzie et al., 2014; Stacy et al., 2015), which have also been associated with noise exposure. In light of these findings and our understanding of noise as a potential health risk factor for stress and adverse cardiovascular outcomes, additional research on noise levels and noise exposure associated with UOGD is warranted.

4.5. Limitations

Noise data from actual oil and gas operations are very limited and most are based on estimations rather than actual field measurements. Some of the oil and gas noise data from traditional operations may underestimate average noise levels from unconventional oil and gas operations, which may be more intense in terms of infrastructure, truck traffic, duration, etc. It may be difficult to assess the potential health outcomes associated with LFN from oil and gas operations due to a lack of data and because traditional dBA may underestimate particular health outcomes (e.g., annoyance) from LFN. Additionally, many of the noises from UOGD are transient in nature, making them challenging to capture. Further, some noise level thresholds included in this review (Table 2) may not adequately reflect the current science on health outcomes associated with environmental noise exposure. For instance, US EPA guidelines are now over 40 years out of date and do not incorporate the large body of epidemiology that has been published since 1974.

Due to the psychological dimension of noise exposure, the relationship between the source and the exposed individual can vary dramatically. While most of the epidemiology on noise exposure involves aircraft, road traffic, and railways, the dBAs associated with these sources are not necessarily transferable to oil and gas development for all health outcomes. Depending on the individual, levels of annoyance from noise exposure to oil and gas activities may be greater or less than levels of annoyance associated with road traffic. For instance, a landowner who has permitted oil or gas development to obtain production royalties may have a higher threshold for noise and/or annoyance than a landowner nearby without any economic incentive. Relatedly, some evidence suggests that annoyance felt by residents living in the vicinity of wind turbines occurs at significantly lower noise levels than noise from other environmental sources (Janssen et al., 2011). It is unclear whether or not UOGD will follow a similar pattern. Regardless, individual variation presents a high degree of uncertainty for most potential health outcomes associated with noise exposure.

5. Research and policy considerations

There are a number of factors that should be taken into account when assessing health risks from UOGD noise. These include the distance of populations to oil and gas operations, mitigation techniques, and differences in noise sensitivity among individuals, which are sometimes driven by age and pre-existing health conditions. The majority of populations living in communities with active oil and gas development may not experience many of the dBA readings and estimates mentioned in this report, depending on the siting of oil and gas operations, topography, and infrastructure. Likewise, some communities may already take preventive measures with policies and practices designed to limit exposure. Nonetheless, there is some evidence that oil and gas operations can, and do, produce noise levels that may adversely impact population and community health.

Policies aimed to protect the health and wellbeing of human populations should consider noise levels when determining minimum surface distances between residents and sensitive receptors (e.g., schools, hospitals, etc.), as noise measurements typically decrease with distance from the source. Setback ordinances for UOGD activities have ultimately been the result of political compromise since they have lacked a sufficient technical or empirical basis given the heterogeneity of factors that influence environmental hazards from UOGD (Fry, 2013). Profits and other economic considerations are weighed against environmental and health protection and other community concerns (e.g., nuisance, aesthetics, etc.). However, some evidence suggests that setback distances may not be adequate to reduce public health threats (Haley et al., 2016). Setback distances based on noise may offer a more empirical foundation than methods that have been used to date.

Policies should also require noise mitigation techniques, which are well known and already used by many oil and gas operators. These may include perimeter sound walls, sound control systems, acoustical enclosures and buildings, and the use of sound absorbing materials. Natural terrain can also play a role in mitigation and where possible pads may be sited to make use of hills, trees, and other natural objects to reduce exposure. Significant restrictions on nighttime operations should be put into place in order to minimize sleep disruption. Maximum allowable noise levels should take into account location and sensitivities of surrounding populations, which may be more vulnerable to noise exposure from UOGD. For instance, the data suggest that maximum allowable noise levels should be lower for schools and hospitals than for industrial or commercial areas.

As previously discussed, both the nature and duration of noise are relevant to potential health outcomes. Many of the noise levels associated with UOGD are transient in nature and only occur during certain development activities. For instance, some activities, such as well pad preparation, drilling, and hydraulic fracturing will only be encountered prior to the completion of a well. Certain adverse health outcomes usually only result from long-term noise exposure and may be less of a concern with most development activities. On the other hand, some sources, such as compressor stations, produce chronic noise that will continue for years after wells are put out of production. Although noise levels may fall under municipal and industrial noise limits, data indicate these limits may not be low enough to protect public health.

More research is needed to clarify noise exposure from UOGD as a potential health risk. Field campaigns to measure noise levels from UOGD activities should be undertaken to inform policies and to protect public health. Cohort or longitudinal studies should be developed to address the question about causal links between UOGD noise and adverse health outcomes. In particular, studies should be designed and implemented to investigate the following in the context of UOGD:

- the effectiveness of noise mitigation measures as well as the adequacy of setback distances;
- the implications of noise exposure on vulnerable populations, including children, the elderly, and communities with multiple and cumulative socioeconomic and environmental burdens;
- potential co-exposures of noise, air, and light pollution;
- LFN levels and associations between exposure to LFN and adverse health outcomes;
- relationships between noise exposure and stress related health outcomes associated with UOGD, such as cardiology inpatient prevalence.

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