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Occupational noise exposure and hearing assessment of hydraulic fracturing employees

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Abstract

Oil and gas extraction companies are exempt from implementing hearing conservation programs for their employees according to the Occupational Safety and Health Administration's (OSHA) noise standard. The occupational noise exposure and hearing status of these employees has not been published in scientific literature before the present study, presumably due to this exemption. In this study, area and personal noise exposures and employee hearing acuity were measured at both conventional and quiet hydraulic fracturing fleets, allowing a comparison between the fleets. Quiet fleets refer to the use of engineering controls to decrease noise levels of the pumps while conventional fleets do not employ these measures. In both fleets, the authors performed personal noise dosimetry, equipment noise measurements, and pure tone audiometry pre- and post-work shift to determine if there were temporary threshold shifts (TTS) in hearing. Based on the personal noise dosimetry results, 42/50 (84%) of the quiet fleet employees and 34/34 (100%) of the conventional fleet employees sampled were at or over 100% noise dose according to the American Conference of Governmental Industrial Hygienists' (ACGIH) noise Threshold Limit Value (TLV®). Based on the OSHA permissible exposure limit (PEL) noise criteria, 9/50 (18%) of the quiet fleet employees and 15/34 (44.1%) of the conventional fleet employees were at or over 100% noise dose. Employees in both fleets experienced TTS, but no significant difference was observed between the types of fleets in relation to TTS. Most equipment of both fleets exceeded 85 decibels, but the pumps of the quiet fleet were approximately 14 dB lower than those of the conventional fleet. Although the quiet fleet noise controls reduced personal noise exposure, a portion of the quiet fleet employees sampled still experienced noise levels that could increase the risk of hearing loss. The researchers suggest the initiation of a hearing conservation program despite OSHA exemption to safeguard employee health and recommend employees involved in certain job tasks employ dual hearing protection based on the exposure monitoring results.

Keywords fracking, fracturing, oil and gas extraction, conventional fleet, quiet fleet, hearing loss, noise dosimetry, pure-tone audiometry, temporary threshold shift

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What's Important About This Paper?

Oil and gas extraction companies are exempt from implementing hearing conversation programs for their employees according to the US OSHA noise standard. This study found, however, that personal noise dosimetry results frequently exceeded occupational exposure limits at oil and gas hydraulic fracturing sites using quiet and conventional technology. These results indicate the need for a hearing conservation program at hydraulic fracturing sites, and that some tasks require dual hearing protection.

Introduction

The National Institute for Occupational Safety and Health (NIOSH) estimates that 22 million employees in the United States are exposed to hazardous levels of noise and that these exposures can lead to permanent noise-induced hearing loss (NIHL) (Tak et al. 2009). Further, there is concern that employees in the oil and gas extraction (OGE) sector are at increased risk of NIHL, but alarmingly, OGE development companies are exempted from parts (c)–(n) of the Occupational Safety and Health Administration's (OSHA) Occupational Noise Exposure Standard—the same standard that mandates employees be protected from hazardous noise. Assumably, due to this partial noise-standard exemption, there is limited information available regarding occupational noise exposure and hearing loss in the OGE industry. There are limited studies on hearing loss or noise exposure in the OGE sector in the United States, and these employees are likely to suffer from work-related hearing loss (Lawson et al. 2019).

OSHA's Occupational Noise Exposure Standard (OSHA 29 CFR 1910.95) requires general industry employers to protect employee hearing by limiting employee noise exposure to an 8-h time-weighted average (TWA) of 90 decibels (dBA) as the permissible exposure limit (PEL) and to an 8-h TWA of 85 dBA (or 50% dose) as the action level (AL) for implementing a hearing conservation program (HCP). Because OGE employers are partially exempt from OSHA's noise standard, these employers are not required to implement HCPs, perform noise monitoring, or administer audiometric hearing tests. Given this partial exemption, the authors of the current study suspect, but do not have the requisite data, to determine if OGE employees are exposed to hazardous levels of noise and if they are suffering from work-related NIHL. Assessment of OGE employee noise exposures and hearing acuity is critical to determine if noise mitigation is required to protect employee hearing in the OGE sector.

Occupational noise exposure is a common workplace hazard. NIHL, a form of sensorineural hearing loss, is a form of permanent hearing loss that can result from hazardous noise exposure. Repeated exposure to noise can lead to the degradation of stereocilia and auditory nerve cells. In addition to hearing loss, exposure exceeding occupational exposure limits (OELs) to noise is associated with hypertension, high cholesterol, hearing difficulty, tinnitus, and reduced communication ability among employees (Kerns et al. 2018). The burden of occupational noise exposure has impacts beyond the employee level and can cause substantial societal health and financial burdens. The associated annual occupational NIHL-compensation costs in the United States alone are estimated to be more than $242 million and growing (Vos et al. 2012; Basner et al. 2014). To alleviate this burden, it is imperative to identify workplace hazardous noise exposures and employee temporary hearing loss, or repeated temporary threshold shifts (TTS), to prevent permanent or irreversible hearing loss (Dobie and Kopke 2020).

In 2022, there were an estimated 218,966 OGE employees employed in the United States and that number is expected to increase by 7,578 by 2027 (Ross 2022). In Canada, a bulletin published by WorkSafe BC writes that a majority of OGE drilling employees are exposed to hazardous levels of noise, (WorkSafeBC 2018a) and 45% of these employees showed signs of suffering from NIHL (WorkSafeBC 2018b). In the United States, NIOSH and the National Occupational Research Agenda (NORA) Oil and Gas Extraction Council have identified noise surveillance and characterization as a critical need in the OGE industry (NIOSH; NORA Oil and Gas Extraction Sector Council 2018). This study addresses, in part, NORA's request to evaluate noise exposure and hearing loss in the OGE industry by focusing on one phase of the OGE development process: hydraulic fracturing.

Hydraulic fracturing, or fracking, is the process of injecting water, chemicals, and sand into the ground to fracture shale rock and extract petroleum. Researchers in the current study investigated the noise exposure from 2 forms of fracking: conventional and quiet fleet. Conventional fracking is hydraulic fracturing without the use of engineered noise controls for the fracking pumps and engines that power the pumps, while quiet fleet fracking uses engineering controls to reduce sound emissions by insulating the fracking pumps and engines that power the pumps. The authors compared quiet fleet and conventional fracking data to determine if these engineering controls were effective for reducing employee exposure to noise.

In the current study, hydraulic fracturing noise-exposure data and employee hearing status were assessed by (i) performing personal noise dosimetry on OGE employees who perform fracturing job tasks at quiet fleet and conventional fracturing sites; (ii) characterizing noise emissions from machinery for conventional and quiet fracturing processes; and (iii) administering pre- and post-shift pure tone audiometric hearing tests on quiet fleet and conventional fracking employees.

Methods

This study was performed at one quiet fleet fracking site in Colorado and one conventional fleet fracking site in Wyoming, both managed by the same oil and gas company. The quiet fleet sampling was performed from June to July 2022 while the conventional fleet sampling was performed over a 2-wk period during October 2022. Both fleets included 2 crews that were sampled during both day and night shifts. There was no overlap of employees between the quiet and conventional fleets. Twenty-nine men and one woman participated in the quiet fleet sampling campaign while 28 men participated in the conventional fleet sampling. Three to six employees were sampled during each work shift.

Employee recruitment

All aspects of this study were performed in accordance with the human subject research protocol approved by Colorado State University's Institutional Review Board (#3335). Subjects were recruited at the beginning of the work shift and were over the age of 18, English-speaking, and had no occlusion of the ear (eg perforated eardrum or excessive earwax) as this could have affected audiometric testing results. A nominal incentive was provided to each participating employee after the completion of the post-shift hearing test and noise dosimeter return.

Personal noise monitoring

Noise dosimetry was performed using Larson Davis Spark Dosimeters (Model 706 RC, Provo, UT, USA). Calibration occurred before and after sampling at 114 dB using a Larson Davis CAL 150 Precision Acoustic Calibrator (Provo, UT, USA). The noise exposure data were downloaded from the dosimeters using version 6.2.4 Blaze software (Larson Davis; Provo, UT, USA). To ensure accurate noise measurements, the dosimeters were set and used in accordance with the OSHA Technical Manual, Section III, Chapter 5 (OSHA 2022a). At the beginning of each employee's 12-h shift, a noise dosimeter was secured to the employee with the microphone attached in the hearing zone (ie, a 2-foot-wide [0.6 m]) sphere surrounding the head] on the employee's shoulder or lapel on their dominant hand side. The employees were instructed to perform their shifts normally and not to shout into the microphone or disturb it. The dosimeters were set to record continuously for the entire work shift since the employees took unscheduled, short breaks during the day and never left the frac pad, and the dosimeters were returned near the end of the work shift. The personal noise dosimetry samples were evaluated using the 8-h occupational noise exposure criteria for the OSHA action limit (AL) ([85 dBA, 5 dB exchange rate [ER]), OSHA permissible exposure limit (PEL) (90 dBA, 5 dB ER), and the American Conference of Industrial Hygienist (ACGIH) threshold limit value (TLV®) (85 dBA, 3 dB ER) in order to evaluate their work-shift time weighted average noise exposure.

Thirty employees were monitored for their personal noise exposures in the quiet fleet, 14 of whom were sampled more than once, resulting in 50 personal samples. For the conventional fleet, 27 employees were sampled, 5 of whom were sampled more than once, resulting in 34 personal samples.

Equipment noise measurement

Equipment sound pressure levels (SPLs) and frequency spectra in the A, C, and Z-weighted scales were measured using a sound level meter (SLM) and octave band analyzer (OBA) (Larson Davis, Model 831, Provo, UT, USA) and the distance between the measurement location and equipment was documented. When possible, noise measurements were taken at 3–4 cardinal points around the equipment during idling and fracking operations. Due to the presence of hazards at the conventional site, limited measurements were made. Before and after each sampling event, the SLM was pre- and post-calibrated with a CAL200 Precision Acoustic Calibrator (Larson Davis, Provo, UT, USA) at 94 and 114 dB.

Noise contour mapping

The company provided drawings of the frack pad site to the researchers, and the drawings were re-created using

Inkscape (The Inkscape Project, Version 1.4). The A-weighted sound pressure levels measured with the SLM were annotated on printed versions of these drawings. *NoiseAtWork* software (DGMR, Version 2022, Type D, Netherlands) was then used to generate noise contours superimposed onto the drawings.

Audiometry

A certified occupational hearing conservationist performed all audiometric testing and ear inspections. At the onset and conclusion of their work shifts, employees underwent pure-tone audiometric hearing tests to assess any changes in hearing acuity.

Prior to the pre-shift hearing test, an otoscope (Welch Allyn, Skaneateles Falls, NY, USA) was used to examine both ears of each employee for ear health. If an employee's eardrums were deemed healthy, they were then asked to provide details about their hearing history using an audiometric questionnaire. This questionnaire, developed by Adams and Brazile (2017), was derived from the US Public Health Service/Federal Occupational Health Audiogram History Report (Occupational Safety and Health Administration; Adams and Brazile 2017). The questionnaire captured information on previous noise exposure prior to the test, recreational noise exposures, types of hearing protection used at work, smoking habits, analgesic use, and any relevant medical history related to hearing loss.

The hearing tests were performed inside a specially designed, sound-attenuating portable booth. This booth, constructed by the researchers, comprised 4 foamular NGX high-performance XPS insulation project panels arranged in an open-faced box configuration. Its interior was lined with 17 Berlai acoustic foam panels. The booth was positioned over a chair, and a blanket was draped over it, offering additional sound insulation, and minimizing distractions for the participant.

Before pre- or post-shift hearing tests were performed, the ambient noise was measured inside the booth for an average of 14.0 s (ranging from 10.4 to 24.3 s) and then uploaded to G4 LD Utility 4.6.2 software (Larson Davic, Depew, NY). The measured 500, 1,000, 2,000, 4,000, and 8,000 Hz octave bands were compared to the OSHA Table D1 for maximum allowable ambient sound levels for the quiet fleet because supra aural earphones were used (Occupational Safety and Health Administration). Insert earphones were used in the conventional fleet so the measured 500, 1,000, 2,000, 4,000, and 8,000 Hertz (Hz) octave bands were compared to ANSI S3.1-1999 (R2018) maximum permissible ambient noise levels (MPANLs), which OSHA permits (OSHA 2022b). For the quiet fleet, all measured sound levels at all average frequencies met the OSHA criteria except for 500 Hz, while all measured sound levels at all average frequencies for the conventional fleet were below the ANSI MPANLs thresholds.

Pure-tone audiometric hearing tests were manually performed with pulsed tone on each ear. A modified Hughson-Westlake Technique was used at the frequencies 500, 1,000, 2,000, 3,000, 4,000, 6,000, and 8,000 Hz, with 1,000 Hz being tested twice to ensure test reliability. The tone was recorded on an audiometric form when the employee heard the tone 2 ascending times. The order of the ears was standardized to right then left regardless of hearing deficit.

The quiet fleet subjects were tested using an Earscan 3 ES3S Pure Tone Audiometer (Micro Audiometrics Corporation, Murphy, NC, USA) calibrated to ANSI S3.6-1969 specification with supra-aural transducers attached. The Earscan 3 was biologically checked each day using a TSI Quest Bio-acoustic simulator (Quest Technologies, Model BA-202-25, Oconomowoc, WI, USA). The conventional fleet subjects were tested using a calibrated Inventis Piccolo Speech audiometer (Padova, Italy) with Etymotic Research 3C Insert Earphones (10 Ohm, Elk Grove Village, IL, USA) attached. E-A-RLink 3A Insert Ear tips were used and changed out between each hearing test. A bio-acoustic simulator was used to biologically check the Piccolo Speech audiometer (Model MI-300 Calibration Monitor, Monitor Instruments, Hillsborough, NC, USA) each day testing occurred.

Statistical analysis

Statistical analyses were performed using Microsoft Excel and RStudio, an interface for R (Boston, MA, version 2022.07.2). Personal noise dosimetry data were described using statistics by job titles, including mean, standard deviation (SD), and percentage exceeding the OEL. A linear mixed model was employed to compare dosimetry noise exposures between the conventional and quiet fleets based on 3 criteria: OSHA AL, OSHA PEL, and ACGIH TLV®. This mixed model was selected to account for random effects, given the study's repeated measures. The equipment noise data, as measured by the sound level meter, were benchmarked against the OSHA Action Level of 85 dBA using slow response. TTS was characterized by the proportion of employees showing a hearing acuity shift of ≥10 dB at any frequency. Hearing recovery was defined as shifts of ≤−10 dB at any frequency. A mixed logistic regression analysis was used to compare

Table 1 Fracking job titles for one quiet (Colorado) and one conventional (Wyoming) fleet (58 total employees in 2022).

Job title	Description of tasks
Chemical operator	Ensures proper chemical delivery from container to chemical pumps.
Crew lead	Supervisor; helps where needed and is all over the location.
Ground boss	Keeps horsepower pumps maintained; opening and closing the wellhead; keeping the iron safe and monitoring for leaking.
Ground walker	Assist in pump maintenance and general housekeeping .
Hydro operator	Running combo unit operates from the cab of unit; mixing water and chemicals.
Forklift/Sand Pusher	Loading and off-loading sandboxes; opening and closing sand boxes.
Sand operator	Mixing sand from enclosed unit.
Pump walker	Assists ground boss in day-to-day operations.
Pump down	Operates pumps to work directly with wireline company to perforate well.
Mechanic	Maintain and repair trucks and equipment on job site as needed.
Electrician operator	Works on computers, electrical, printers, and programming; keeps electronics of the pumps functioning.
Float	Performs a mix of job tasks as needed.
Blender operator	Operates equipment to blend the proper concentrations of water, chemical additives, and sand to pump into well.
Safety	Reviews written logs and ensures compliance with safety policies.

TTS and hearing recovery outcomes between the conventional and quiet fleets.

Results

Personal noise monitoring

Personal noise dosimetry sampling was performed on employees performing a variety of tasks. The job titles and their descriptions are provided in Table 1. The average noise dosimetry sampling duration was 8 h and 31 min for the quiet fleet employees, and 8 h and 48 min for the conventional fleet employees.

Results from the noise dosimetry, categorized by job titles s and criteria (OSHA AL, OSHA PEL, ACGIH TLV®), can be seen in Table 2. As detailed in Table 2, employees of the conventional fleet generally experienced a higher proportion of exposures exceeding OELs (noise doses of 100% or more) compared to those in the quiet fleet.

The linear mixed model statistical analysis revealed significant differences in noise measurements between the conventional and quiet fleets across all 3 criteria: OSHA AL (P-value = 0.0070), OSHA PEL (P-value = 0.0017), and ACGIH TLV® (P-value = 0.0011). These results indicate, with 95% confidence, that the conventional fleet employees faced considerably higher noise exposure compared to their quiet fleet counterparts across all evaluated criteria.

Equipment noise

The equipment noise measurement results are presented in Table 3, including the measurement distance to the noise source (meters) and if taken at the worker location (WL). Noise measurements of equipment increased during fracturing and decreased while idling. Idling equipment noise in the quiet fleet (excluding employee enclosures) ranged from 52.0 to 89.0 dBA and during fracturing operations the equipment noise ranged from 81.7 to 99.2 dBA. Idling equipment noise in the conventional fleet (excluding employee enclosures) ranged from 84.1 to 101.4 dBA while during fracturing operations the equipment noise ranged from 93.9 to 113.1 dBA.

Both the quiet and conventional fleets registered the highest noise measurements at the horsepower pumps (99.2 dBA, 113.1 dBA), T-belt (91.9 dBA, 98.9 dBA), manifold (92.2 dBA, 101.8 dBA), blender (92.1 dBA, 103 dBA), and outside the sand box (88.4, 99.3 dBA). The most prominent octave frequency band, using OBA, of both fleets was 31.5 Hz, or low frequency noise.

Noise contour mapping

The noise contour map for the quiet and conventional fleets is displayed in Fig. 1. The loudest areas for both fleets were around and between the pumps (ie horsepowers). Of particular note is that the quiet fleet noise

Table 2 Noise exposure among frackers for one quiet (Colorado) and one conventional (Wyoming) fleet in 2022 (58 total employees).

Task	Number of employees assessed per task	OSHA AL			OSHA PEL			ACGIH TLV®		
		Mean noise dose percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-h shift Number (%)	Mean noise dose Percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-hr shift Number (%)	Mean noise dose Percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-hr shift Number (%)
Quiet Fleet										
Blender operator	1	97.0	90.9	1 (100)	71.1	88.7	0 (0)	353.2	91.2	1 (100)
Chemical operator	2	76.1 (33.7)	88.8 (3.2)	2 (100)	56.9 (36.1)	86.2 (4.8)	1 (50.0)	336.9 (153.8)	90.7 (2.0)	2 (100)
Crew lead	8	67.0 (36.4)	87.6 (4.3)	5 (62.5)	49.2 (36.7)	83.1 (6.4)	1 (12.5)	535.2 (474.8)	90.9 (4.0)	7 (87.5)
Electrician technician	1	12.5	74.3	0 (0)	5.5	68.3	0 (0)	45.0	81.1	0 (0)
Float	5	77.7 (24.2)	88.1 (2.0)	5 (100)	58.6 (22.9)	86.0 (2.5)	0 (0)	381.5 (160.5)	90.7 (1.5)	5 (100)
Ground boss	7	69.2 (43.8)	86.9 (4.9)	5 (71.4)	51.5 (44.0)	83.4 (7.5)	1 (14.3)	377.7 (385.8)	89.8 (4.1)	6 (85.7)
Ground walker	3	62.5 (10.3)	87.2 (2.6)	3 (100)	44.1 (13.6)	84.5 (3.2)	0 (0)	375.1 (167.4)	90.9 (2.5)	3 (100)
Hydro operator	6	30.5 (19.4)	80.8 (4.6)	2 (33.3)	13.9 (18.5)	72.5 (7.4)	0 (0)	133.3 (138.5)	85.0 (3.8)	4 (66.7)
Mechanic	3	180.2 (161.9)	92.6 (5.8)	3 (100)	172.3 (166.6)	91.9 (6.3)	1 (33.3)	5,504.0 (4,404.8)	100.0 (6.9)	3 (100)
Pump walker	10	158.1 (263.1)	89.7 (7.1)	9 (90.0)	142.5 (265.7)	87.6 (8.3)	4 (40.0)	3,042.4 (7,362.5)	94.1 (6.7)	10 (100)
Pump down	2	11.0 (0.6)	73.4 (2.5)	0 (0)	5.0 (0.1)	67.8 (2.3)	0 (0)	37.5 (4.6)	80.4 (1.8)	0 (0)
Sand operator	1	18.2	77.1	0 (0)	12.0	74.1	0 (0)	79.8	83.6	0 (0)
Sand pusher	1	128.3	93.2	1 (100)	104.0	91.7	1 (100)	1,033.2	96	1 (100)
All tasks	50	86.6 (130.1)	86.6 (6.4)	36 (72.0)	70.4 (131.4)	83.0 (8.7)	9 (18.0)	1,199.1 (3,633.2)	90.5 (6.0)	42 (84.0)
Conventional Fleet										
Blender operator	2	154.7 (102.0)	91.3 (6.0)	2 (100)	133.1 (112.4)	89.5 (7.9)	1 (50)	1,096.0 (1,000.5)	93.6 (5.2)	2 (100)
Chemical operator	6	271.3 (401.0)	92.6 (7.7)	5 (83.3)	258.0 (403.1)	91.6 (8.4)	3 (50)	6,757.7 (13,798.4)	97.5 (6.5)	6 (100)
Crew leader	2	45.1 (12.5)	85.4 (1.5)	1 (50)	36.0 (8.0)	84.0 (0.8)	0 (0)	442.5 (32.2)	92.2 (0)	2 (100)
Electrician technician	1	16.6	78.1	0 (0)	12.4	76.0	0 (0)	260.3	89.8	1 (100)
Float	6	100.1 (27.4)	90.1 (2.5)	6 (100)	79.8 (30.2)	88.3 (3.5)	2 (33.3)	684.4 (249.2)	93.3 (2.2)	6 (100)
Frac operator	1	74.8	88.7	1 (100)	35.0	83.2	0 (0)	282.2	90.0	1 (100)
Ground Boss	2	359.9 (232.4)	99.3 (4.4)	2 (100)	349.3 (230.8)	99.0 (4.5)	2 (100)	9,026.0 (9,187.6)	103.5 (5.2)	2 (100)
Mechanic	1	193	96.1	1 (100)	185.3	95.8	1 (100)	7,435.9	104.5	1 (100)
Pump walker	8	133.7 (84.3)	92.0 (4.8)	8 (100)	121.2 (84.5)	90.9 (5.4)	4 (50)	1,575.0 (1,165.7)	96.5 (3.5)	8 (100)
Safety	1	102.4	90.7	1 (100)	91.3	89.8	0 (0)	1,535.0	97.2	1 (100)
Sand operator	3	102.2 (5.0)	90.7 (0.5)	3 (100)	80.3 (8.3)	89.0 (0.8)	1 (33.3)	567.5 (102.8)	92.8 (0.7)	3 (100)

(*continued*)

Table 2 Continued

Task	Number of employees assessed per task	OSHA AL			OSHA PEL			ACGIH TLV®		
		Mean noise dose percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-h shift Number (%)	Mean noise dose Percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-hr shift Number (%)	Mean noise dose Percent (SD)	Mean 8-hr TWA dBA (SD)	Employees over-exposed 8-hr shift Number (%)
Sand pusher	1	82.6	92.0	1 (100)	53.9	88.9	0 (0)	462.5	93.7	1 (100)
All tasks	34	152.7 (188.8)	91.2 (5.4)	31 (91.2)	136.8 (190.7)	89.8 (6.2)	15 (44.1)	2,648.8 (6,348.6)	95.6 (4.8)	34 (100)

OSHA AL, Action level of 85 dBA; OSHA PEL, Permissible exposure limit of 90 dBA; ACGIH TLV®, Threshold limit value of 85 dBA; SD, Standard deviation; TWA, Time weighted average; dBA, decibel in A-weighted scale; %, percent

did not exceed 110 dBA, whereas the conventional fleet noise did exceed 110 dBA. The acoustical barrier wall used in the quiet fleet appeared to be effective at attenuating noise levels.

Audiometry

TTS (ie decrease in hearing acuity) occurred in both fleets as well as recovery (ie increase in hearing acuity). Proportions of TTS and recovery are displayed in Table S1, and the results of analysis are shown in Table S2. The highest proportion of TTS was in the quiet fleet at 6,000 and 8,000 Hz in the right ear (20.0%) and 6000 Hz in the left ear (22.9%). The largest proportion of recovery was in the left ear of the quiet fleet at 6,000 Hz (17.1%). Though TTS and recovery occurred in both fleets in both ears in most frequencies, a higher proportion of TTS occurred than recovery.

Pre-shift audiograms were used as a baseline to compare pre-existing hearing acuity to post-shift hearing acuity. This allowed the researchers to determine how noise exposure that occurred during the shift affected hearing acuity. The pre-shift audiograms were also used to characterize the percentage of hearing loss categorized by ear, frequency, and fleet type. Repeated pre-shift audiograms for the same employee were excluded. This analysis excluded the frequency 500 Hz for the quiet fleet as this was above OSHA Table D1 maximum allowable ambient sound levels; the conventional fleet maximum sound levels were below the threshold. Non-recordable decibels recorded at any frequency were excluded.

Audiometric questionnaire

Results for the audiometric questionnaire are presented in Table 4. For medical history, the history of hearing loss was marginally higher in the conventional fleet a (17.9%) than in the quiet fleet at (10%). Ototoxicant use recorded in the survey included analgesics and current smoking. More employees in the conventional fleet reported taking analgesics in the past 7 d (53.6%) compared to the quiet fleet (35.0%), which current smoking was similar (conventional = 17.9%, quiet = 10%). A relatively large difference was observed in the history of ringing ears (39.3% of the conventional fleet employees versus 0% in the quiet fleet). HPD reported use at work was comparable, with 100% of the quiet fleet and conventional fleet at 96.4%. When examining social noise exposure and the use of HPD, a sizeable proportion of both fleets' employees reported usage of firearms (quiet = 65.0%, conventional = 89.2%). However, reported HPD

Table 3 Equipment area noise measurements while fracturing (*9 pumps running each side) or idling for one quiet (Colorado) and one conventional (Wyoming) fleet in 2022.

Equipment/Location	Idle/ Fracturing	SPL A (dBA)	SPL C (dBC)	OBA range	Predom-inant frequency band (Hz)	Distance (meters or worker location (WL))	Over 85 dBA?
Quiet Fleet							
Horsepower—front of cab	Idle	71.8	87.0	Low	63	1 m	No
	Fracturing	87.4	97.4	Normal	125	1 m	Yes
Horsepower—between 2 pumps	Idle	81.1	89.3	Low	31.5	0.3 m	No
	Fracturing	99.2	106.6	Normal	125	0.3 m	Yes
Horsepower—one pump	Idle	74.1	—	—	—	1 m	No
	Fracturing	90.2	98.1	Normal	125	1 m	Yes
Blender—inside unit	Idle	71.1	84.7	Low	31.5	WL	No
	Fracturing	80.3	91.7	Normal	63	WL	No
Blender—outside unit	Idle	85.0	91.5	Low	31.5, 63	1 m	Yes
	Fracturing	92.1	98.9	Normal	125	1 m	Yes
Blender—door of unit open	Idle	—	—	—	—	—	—
	Fracturing	87.9	97.3	Normal	31.5	WL	Yes
T-belt	Idle	89.0	94.3	Low	63	1 m	Yes
	Fracturing	91.9	99.3	Normal	63	1 m	Yes
Sand box—inside unit	Idle	70.4	83.3	Low	31.5	WL	No
	Fracturing	70.8	87.1	Normal	63	1 m	No
Sand box—outside unit	Idle	—	—	—	—	—	—
	Fracturing	88.4	93.8	Normal	500	1 m	Yes
Manifold	Idle	74.5	—	—	—	—	No
	Fracturing	92.2	99.6	Normal	250	WL	Yes
Hydro inside	Fracturing	70.8	83.9	Normal	31.5	WL	No
Hydro outside	Fracturing	84.2	95.0	Normal	31.5	1 m	No
Pump down—front of cab	Idle	52.0	—	—	—	—	No
	Fracturing	81.7	90.8	Normal	31.5	1 m	No
Pump down—side	Idle	57.0	—	—	—	—	No
	Fracturing	87.1	93.2	Normal	31.5	1 m	Yes
Conventional fleet							
Loud horsepower—front of cab	Idle	88.8	94.6	Normal	31.5	1 m	Yes
	Fracturing	93.9	105.4	Normal	125	1 m	Yes

(continued)

Table 3 Continued

Equipment/Location	Idle/ Fracturing	SPL A (dBA)	SPL C (dBC)	OBA range	Predom-inant frequency band (Hz)	Distance (meters or worker location (WL))	Over 85 dBA?
Loud horsepower—between 2 pumps	Idle	101.4	103.8	Normal	63	0.3 m	Yes
	Fracturing	113.1	116.1	Normal	125	0.3 m	Yes
Loud horsepower—pump	Idle	94.2	97.5	Normal	31.5	1 m	Yes
	Fracturing	104.6	108.9	Normal	125	1 m	Yes
Blender—inside unit	Idle	76.3	90.8	Normal	31.5	WL	No
	Fracturing	89.3	101.4	Normal	125	WL	Yes
Blender—outside unit	Idle	86.6	96.2	Normal	31.5	1 m	Yes
	Fracturing	103.0	110.0	Normal	125	1 m	Yes
Blender—door of unit open	Idle	—	—	—	—	—	—
	Fracturing	96.1	105.2	Normal	31.5	WL	Yes
T-belt	Idle	98.8	102.2	Normal	31.5	1 m	Yes
	Fracturing	98.9	107.3	Normal	250	1 m	Yes
Sand box—inside unit	Idle	66.3	85.2	Normal	31.5	WL	No
	Fracturing	81.0	93.7	Normal	125	1 m	No
Sand box—outside unit	Idle	96.0	101.5	Normal	31.5	1 m	Yes
	Fracturing	99.3	106.5	Normal	250	1 m	Yes
Manifold	Idle	84.1	98.7	Normal	31.5	WL	No
	Fracturing	101.8	111.1	Normal	125	WL	Yes

*Measurements were taken with 9 running pumps per side for 18 pumps running total. Predominant frequency is based on (1/1) octave band frequency spectrum.
SPL, Sound Pressure Level; OBA, Octave Band Analysis; dBA, decibels in A-weighting scale; dBC, decibels in C-weighting scale; Hz, Hertz; "—", data not collected for this category

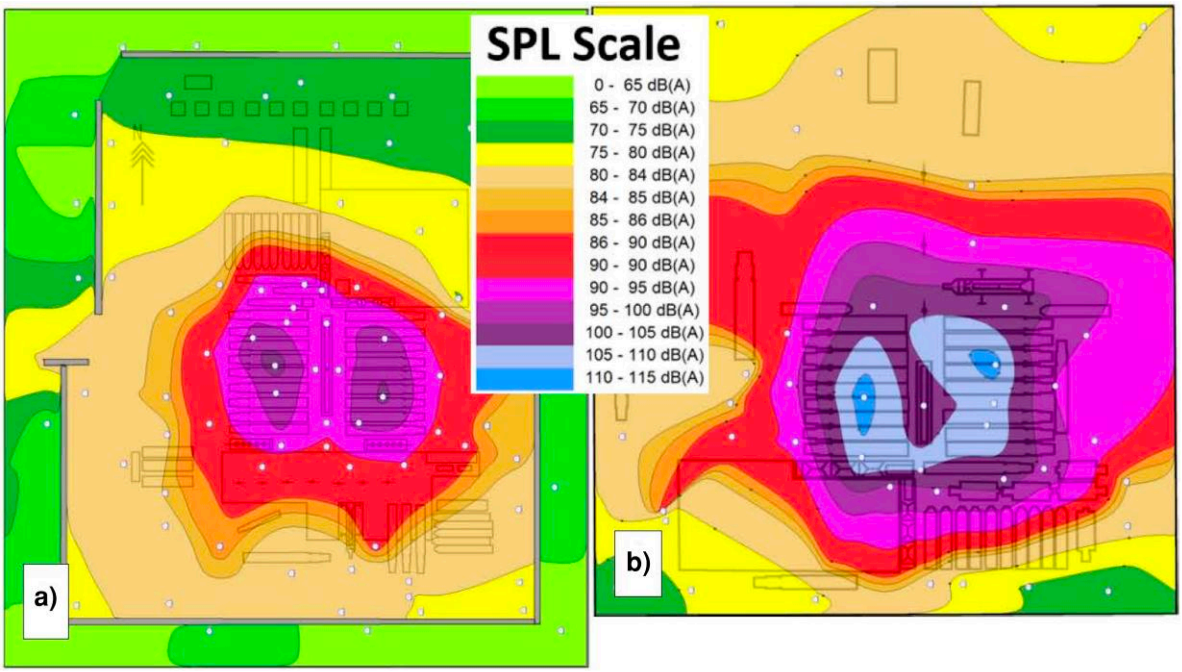

Figure 1 Quiet (a) and conventional (b) fleet noise maps. Areas where noise measurements were taken are marked with dots. The straight lines in (a) indicate where the acoustical barrier wall was erected for. The OSHA action criterion level is reached and exceeded in dark orange (85 to 86 dBA) and red (86 to 90 dBA) areas and above. The OSHA PEL criterion level is reached at 90 dBA (dark red) and exceeded at 90 to 95 dBA (light purple), 95 to 100 dBA (purple), 100 to 105 dBA (dark purple), 105 to 110 dBA (light blue), and 110 to 115 dBA (dark blue).

use of the employees who shot firearms was higher among the quiet fleet (92.3%) than the conventional fleet (80.0%).

Discussion

Personal noise monitoring

Based on the personal noise dosimetry results, the quiet fleet controls were effective at decreasing personal noise exposures. For example, 18% of quiet fleet employees were at or exceeded the OSHA PEL, yet 44% of conventional employees were at or exceeded the OSHA PEL. In the quiet fleet, the mechanic and sand pusher exceeded the OSHA PEL while all other job titles were under 90 dBA TWA. For the conventional fleet, several job titles were at or exceeded the OSHA PEL: the blender, chemical, ground boss, mechanic, pump walkers, and safety. The mechanic job title overlapped these 2 fleets as being exceeding the OSHA PEL. Given these exposures exceeding OELs, additional discussion on adequate hearing protection is found in the Recommendations section of this paper.

Not all job titles were monitored for each fleet as monitoring was based on available employee volunteers and also the equipment being used at the time of monitoring. The job titles that were measured in the quiet fleet included the blender operator, chemical operator, crew lead, electrician technician, float, ground boss, ground walker, hydro operator, mechanic, pump walker, pump down, sand operator, and s sand pusher. The job titles that were measured in the conventional fleet included the blender operator, chemical operator, crew lead, electrician technician, float, frac operator, ground boss, mechanic, pump walker, sand operator, sand pusher, and safety. The pump down and hydro operator were job titles only in the quiet fleet for this sampling period as the conventional fleet did not have sump pumps or hydro equipment.

Equipment noise

Overall, the conventional fleet was louder than the quiet fleet during both idling and fracturing operations. The quiet fleet attenuated pump design decreased employee and area noise exposure when compared to conventional

Table 4 Audiogram questionnaire results for 48 employees from one quiet (Colorado) and one conventional (Wyoming) fleet in 2022.

Category	Source	Quiet fleet ($n = 20$) Number (%)	Conventional fleet ($n = 28$) Number (%)
Social noise exposure and HPD use	Loud music	15 (75.0)	22 (78.6)
	Loud music—wear HPD	3/15 (20.0)	1/22 (4.5)
	Firearms	13 (65.0)	25 (89.2)
	Firearms—wear HPD	12/13 (92.3)	20/25 (80.0)
	Power tools	16 (80.0)	21 (75.0)
	Power tools—wear HPD	4/16 (25.0)	6/21 (28.6)
	Heavy machinery	11 (55.0))	19 (67.9)
	Heavy machinery—wear HPD	8/11 (72.7)	11/19 (57.9)
	Motorcycles	7 (35.0)	10 (35.7)
Medical	Analgesics in past 7 d	7 (35.0)	15 (53.6)
	Prior military	2 (10.0)	6 (21.4)
	History of hearing loss	2 (10.0)	5 (17.9)
	Family history of hearing loss	1 (5.0)	3 (10.7)
	History of ear infections	0	1 (3.6)
	Current cold, flu, or allergy	2 (10.0)	2 (7.1)
	Current smoking	2 (10.0)	5 (17.9)
	History of hearing aid	0	2 (7.1)
	History of ringing ears	0	11 (39.3)
	History of recurring impacted ear wax	0	3 (10.7)
	History of head injury	0	5 (17.9)
	Wear HPD at work	20 (100.0)	27 (96.4)

HPD, hearing protection device.

fleet equipment. The engineering controls used to reduce the pump noise should be used whenever possible.

Several work areas were inside enclosures, isolating the workers from exterior equipment noise; and included the blender, sand box, and hydro cabins in which the noise measurements were taken. In general, noise measurements taken inside these enclosed spaces had relatively lower noise measurements when compared to outside noise measurements taken within 1 m of the exterior of the enclosure; thus, these enclosures offered noise protection to the employees who performed operations within the enclosures.

During quiet fleet fracturing, the noise measurements (one measurement taken per location) outside of the blender cabin was measured at 92.1 dBA, whereas the noise measurement inside the blender cabin at the employee location with the door closed was at 80.3 dBA; and inside with the door open was 87.9 dBA. While the cabin offered approximately 4 dBA noise attenuation with the door open, having the door closed decreased the noise measurement to less than 85 dBA. The same noise measurements were taken at the conventional fleet during fracturing: 103 dBA outside of the blender cabin, 89.3 dBA inside the blender cabin at the employee location, and 96.1 dBA inside the blender cabin at the employee location with the door open. Based on these results, it is expected that employees working in the cabin with the door closed would be exposed to noise levels below the OSHA PEL, however while working with the cabin door open or being outside of the blender could result in employee exceedance of noise OELs.

In addition, the sand box enclosure provided substantial noise protection to the sand operator during fracturing operations for both the quiet and conventional fleets. The quiet fleet outside measurement was 88.4 dBA vs. 70.8 dBA inside the enclosure; and the conventional fleet outside measurement was 99.3 dBA vs. 81.0 dBA inside the enclosure.

Likewise, the hydro enclosure interior noise measurement at the quiet fleet was at 70.8 dBA vs. an exterior noise measurement of 84.2 dBA, approaching the OSHA AL if the equivalent noise level were present for 8 h (note: the hydro was not in operation at the conventional fleet during sampling). In general, all of the enclosures that were measured (blender, sand box, hydro) provided excellent noise protection for employees inside the enclosures during fracturing operations.

When compared to the Canadian WorkSafe BC bulletin, the equipment noise had similar values (WorkSafeBC 2018a, 2018b). This bulletin listed noise measurements for "fracturing" and "pump trucks" but did not include distances from equipment or locations. The noise measurements for fracturing ranged from 104 to 107 dBA, while pump trucks ranged from 112 to116 dBA; for this study, pumps of the conventional fleet were measured up to 113.1 dBA, which falls within this range.

Temporary threshold shift (TTS)

Even though the conventional fleet site had higher levels of measured noise demonstrated by the personal dosimetry results and equipment measurements, there was no significant difference of TTS (hearing acuity decrease) between the employees in the 2 fleets. In the right ear, the most affected frequencies were 6,000 and 8,000 Hz, with 7 employees experiencing decreased hearing acuity in both of these frequencies. In the left ear, eight employees (22.9%) experienced a decrease in hearing acuity at 6,000 Hz. For the conventional fleet, the most hearing acuity decrease experienced by the workers was demonstrated in the workers' left ears at 500 Hz, where 6 employees (17.1%) had a measurable decrease in hearing.

It was noted that employees associated with the quiet fleet had a higher proportion of TTS when compared to those in the conventional fleet. This may be attributed to a misinterpretation of the term "quiet" fleet. Although 100% of employees in the quiet fleet reported HPD use, those employees may have been less vigilant in the proper use of HPD. Despite this name, quiet fleet sites still presented hazardous noise measurements and the consistent use of HPD remains vital. Further, it is important to note that the term "quiet fleet" is often intended by manufacturers as a control for community noise exposure concerns and less for occupational noise exposure concerns.

Hearing protection devices

During the sampling campaign, employees were observed wearing HPDs incorrectly, which could be attributable to a lack of knowledge of proper HPD use. For example, employees were observed wearing hooded sweatshirt hoods or balaclavas under the HPD which would impair the seal of the earpiece, reducing protection from noise. Also, employees were observed shifting earmuffs to the sides of their heads in hazardous noise areas to communicate, which may have increased hazardous noise exposures. These types of inappropriate HPD usage should be addressed by providing proper HPD use training to reduce potential hazardous noise exposures.

Limitations

Noise maps and personal dosimetry results represent the days the measurements were taken. Different operations, number of pumps running, equipment, and site layout could result in different noise measurements.

The PEL, AL, and TLV® personal noise measurements account for an 8-h TWA exposure to compare to 8-h TWA regulatory exposure limits and not the actual length of the employees' 12-h shifts. It was assumed by the researchers that the remaining 4 h of shift time would result in similar exposures as the previous 8-h.

Employees were not hearing tested immediately before and after shifts but instead were tested within the first 2 to 3 h of the 12-h shift start time and within 2 h of the end of the shift due to requisite employee tasks. As such, a TTS could have already occurred before the first hearing test. Many of the employees, especially those that participated in the study multiple days, were already exposed to loud noise during the past 48 h, as the employees in both fleets work in 2-wk rotations. Only 3 of 35 (8.5%) of the audiograms for the quiet fleet had no loud exposures within 48 h and 8 of 35 (22.9%) of the conventional fleet; this previous loud noise exposure could affect TTS results, or TTS that have previously occurred for a former workday may still be recovering.

Another limitation is that the employees were not tested within a commercially available audiometric booth. Despite this limitation, all ambient noise measurements were appropriate for hearing tests except for 500 Hz for the quiet fleet due to supra-aural earphone use. Further, as reported in the current study, the most prominent measured octave frequency band measured from the equipment was 31.5 Hz, which could have impacted the ambient noise levels in the hearing test location. Though the fleets were tested using different audiometers and earphone types, test results are still comparable.

Further, hearing test data are not static and employee familiarity with audiometric exams, motivation, and other factors can influence exam accuracy (Chan 1998). While a larger TTS cannot predict a larger increase in permanent hearing loss, the very presence of a TTS is a risk of developing permanent hearing loss.

An aspect not considered or measured in this study that could affect hearing levels is chemical ototoxicants (OSHA and NIOSH 2018). Ototoxicants, or "ear poisons," are chemicals that can harm hearing through exposure to the chemical alone or in combination with noise. It is suspected that oil and gas extraction employees are exposed to ototoxicants (AIHA 2023). Ototoxicants and their effects on hearing were not accounted for in this study, so the effect of noise on hearing could potentially be worse. Personal sampling of employees for chemicals such as n-hexane, toluene, xylene, and ethylbenzene, all of which can be found in vapors and gases in oil and gas operations, could provide more information on if these employees are at hearing damage risk (Morata et al. 1994; Lawson et al. 2019).

Conclusions

This study addresses a significant gap in research pertaining to noise and hearing status in the OGE sector, specifically hydraulic fracturing. This study compared the noise measurements and the presence of TTS between the quiet and conventional fleets to evaluate the effectiveness of the engineering controls of the quiet fleet in protecting employee health. While these controls reduced the occupational exposure levels of the quiet fleet employees significantly more than the conventional fleet (OSHA AL P-value = 0.0070, OSHA PEL P-value = 0.0017, ACGIH TLV® P-value = 0.0011), hazardous noise levels still remained present in the "quiet" fleet. As both fleets experience hazardous noise, the proper use and training for HPDs are necessary but are not currently mandated by the OSHA noise standard due to exemptions. Based on the results in the current study, employers may consider implementing a hearing loss prevention program based on NIOSH recommendations to prevent future hearing loss in OGE sector employees.

Although this study offers foundational information, further research is needed. The suspected exposure of these employees to ototoxicants presents an added layer of concern; the synergistic effects of such chemicals, in conjunction with noise, could amplify hearing damage. A comprehensive approach to address these combined potential risks is crucial for ensuring employee safety.

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Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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Conflicts of interest

The authors declare no conflict of interest relating to the material presented in this Article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article cannot be shared publicly for the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

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