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Manmade earthquakes and healthcare visits for anxiety disorders in Oklahoma, 2010–2019

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Background: Since 2010, seismicity in Oklahoma has increased from wastewater injection. It remains unknown if these earthquakes have resulted in increased treatment seeking for mental healthcare services.

Methods: Using data from a nationwide United States patient-level commercial and Medicare Advantage claims database from 2010 to 2019, we identified healthcare encounters for anxiety disorders using diagnostic codes and subclassified them as adjustment reaction; anxiety-related disorders; physical symptoms of anxiety; and stress disorders. With U.S. Geological Survey Advanced National Seismic System data, we generated county-level 6-month rolling counts of felt earthquakes ($\geq M$ 4) and linked them to patient residential county at the time of the healthcare visit. In this repeated measures, individual-level analysis we used generalized estimating equations to estimate the odds of monthly anxiety-related healthcare visits as a function of the frequency of $\geq M$ 4 earthquakes in the previous 6 months.

Results: We identified 4,594 individuals in Oklahoma observed from 2010 to 2019. For every additional five $\geq M$ 4 earthquakes in the preceding 6 months, the odds of healthcare visits for stress disorders increased (odds ratio [OR] = 1.27; 95% confidence interval [CI] = 1.03, 1.57). We found no evidence of an association with adjustment reaction (OR = 1.05; 95% CI = 0.89, 1.23), anxiety-related disorders (OR = 0.96; 95% CI = 0.90, 1.03), or physical symptoms of anxiety (OR = 1.03; 95% CI = 0.98, 1.09).

Conclusions: We report an association between increased frequency of felt earthquakes and treatment seeking for stress disorders. This finding should motivate ongoing study of the potential consequences of the oil and gas industry for mental health outcomes including anxiety disorders.

Keywords: Anxiety; Earthquakes; Fracking; Stress disorders

Introduction

Oil and gas production in the United States has intensified through technological advances such as horizontal drilling

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and high-volume hydraulic fracturing (known as "fracking"). These methods are known as unconventional oil and gas development (UOGD). Significant amounts of wastewater produced as an UOGD byproduct requires special disposal to minimize contamination of surface and drinking waters. In Oklahoma, operators often handle wastewater by reinjection into Class II Underground Injection Control disposal wells. Injection of wastewater in large volumes and at high rates can cause earthquakes via fluid pressure transients.[1–8]

By 2021, Oklahoma ranked sixth in crude oil and fifth in natural gas production and had become the most seismically active region in the United States.[9,10] From 2010 to 2017, over 2,500 earthquakes exceeding moment magnitude 3 (i.e., $\geq M$ 3) occurred in Oklahoma.[3,4] By 2015, injection wells were associated with over 98% of the $\geq M$ 3 earthquakes in the central and eastern United States.[3] An estimated 91 earthquakes $\geq M$ 4, a threshold typically felt by residents, occurred in Oklahoma from 2010 to 2019.[11]

Adverse consequences of UOGD include increased emission of methane; odor, noise, and air pollution from diesel trucks and equipment; secondary ozone formation; and contamination of surface and groundwater from spills and well-casing failures.[12–15] Consequences of UOGD may extend to the health

What this study adds

Intensification of unconventional oil and gas development requires reinjection of large amounts of wastewater into underlying shale formations, which leads to frequent manmade earthquakes. Using data from a nationwide claims database, we find an association between increased frequency of felt earthquakes and healthcare visits for stress disorders, but not other types of anxiety disorders. This finding should motivate ongoing study of the potential consequences of the oil and gas industry for mental health outcomes including anxiety disorders.

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of nearby residents.[16–19] In Oklahoma, studies report a relationship between felt earthquakes and increased frequency of both Google searches for anxiety and motor vehicle crashes, the latter perhaps reflecting increased distress and distraction. It is unknown whether increased frequency of felt earthquakes results in increased treatment seeking for mental healthcare services. The present study examines the association between the frequency of felt earthquakes and the odds of anxiety-related healthcare visits among privately insured individuals in Oklahoma from 2010 to 2019. We hypothesized that more frequent earthquakes would be associated with increased odds of anxiety-related healthcare visits.

Methods

The Optum Clinformatics Data Mart (CDM, Optum, Inc. Eden Prairie, MN) is a large, de-identified commercial and Medicare Advantage claims database. Patient-level commercial claims data extend from 1 July 2010, to 31 December 2019, and each claim is linked to the patient's county of residence at the time of the encounter. Eligible individuals were age ≥18 years and resided in Oklahoma within the study period. We created an individual-level, repeated measures dataset in which each row corresponded to one person-month of follow-up. This study was approved by the Institutional Review Board at Stanford University (Protocol No. 45577).

Healthcare visits for anxiety disorders

Healthcare visits for anxiety disorders were identified using diagnostic codes from the *International Classification of Diseases, Ninth Revision* and *Tenth Revision* (*ICD-9* and *ICD-10*). We created a monthly indicator variable that equaled one if an individual had at least one outpatient, inpatient, or emergency department encounter for an anxiety disorder, and zero otherwise. We defined our outcome as an indicator variable because monthly counts of mental healthcare claims are often overdispersed due to both a point-mass at zero (i.e., most individuals have zero visits) and right skew (i.e., some individuals have many visits). To distinguish subtypes of anxiety, we further subdivided diagnostic codes into adjustment reaction; anxiety, dissociative, and somatoform disorders (hereafter, "anxiety-related disorders"); physical symptoms of anxiety, and stress disorder (Supplemental Table 1; http://links.lww.com/EE/A208).

Felt earthquakes

Data on location, date, and magnitude for earthquakes in Oklahoma were available through the U.S. Geological Survey Advanced National Seismic System. For each county, we specified the count of earthquakes of moment magnitude four or greater (≥M 4) within 100 km of the population-weighted centroid for each month during the study period. For our main analysis, we linked county-level 6-month rolling exposure to ≥M 4 earthquakes to each patient's county of residence at the time of their healthcare encounter. For example, for July 2010, we summed the number of earthquakes that occurred between January 2010 and June 2010. We selected ≥M 4 as the cutoff for magnitude because residents are likely to feel earthquakes of this magnitude (hereafter, "felt earthquakes"). We specified a 6-month exposure window because: (1) cumulative effects of earthquake exposure may be more salient for anxiety treatment seeking and (2) mental healthcare visits may be significantly delayed from symptom onset.[20,21] We created two alternative exposure metrics: a categorical variable (0, 1, 2–7, ≥8 earthquakes) with cutoffs selected based on the empiric distribution of monthly earthquakes within the study period, and an indicator for whether there was at least one ≥M 5 earthquake in the prior 6 months.

Statistical analysis

We used generalized estimating equations (GEE) to estimate the odds of monthly healthcare visits for anxiety disorders as a function of the frequency of felt earthquakes in the previous 6 months. In this study, there is potential nonindependence of repeated observations within individuals and within counties. We specified an exchangeable working correlation structure to account for the higher level of clustering (i.e., potential nonindependence of repeat observations within counties), as this has been previously demonstrated to yield improved coverage of resultant 95% confidence intervals (CIs) in simulation studies.[22] Models were adjusted for age (18–34; 35–44; 45–54; 55–64; ≥65), sex (male, female), and included indicators for calendar year and month to account for secular and seasonal trends, respectively. As sensitivity analyses, we repeated our main analysis with categorical number of earthquakes and an indicator for at least one ≥M 5 earthquakes in the previous 6 months, respectively, specified as the exposure of interest. All analyses were conducted using R version 4.0 (R Foundation for Statistical Computing, Vienna, Austria).

Results

We identified 4,594 individuals in Oklahoma (49.3% female) observed between 2010 and 2019. More than one-third were ages 18–34 (35.5%) and 26.9% resided in Oklahoma County (Table). Anxiety-related healthcare visits remained relatively constant over the study period and the frequency of felt earthquakes peaked near 2016 (Figure 1).

We identified 9,835 person-months with a healthcare encounter for anxiety disorders. Of these, 6,740 visits (68.5%) were for physical symptoms, 2,751 (28.0%) were for anxiety-related disorders, 731 (7.4%) were for adjustment reaction, and 273 (2.8%) were for stress disorders. For all anxiety disorders combined, we found no association with frequency of felt earthquakes in the preceding 6 months (odds ratio [OR] = 1.01; 95% CI = 0.96, 1.06). For every additional five felt earthquakes in the preceding 6 months, the odds of healthcare visits for stress

Table.

Demographic characteristics of Oklahoma residents in the Optum Clinformatics Data Mart Database with healthcare visits for anxiety disorders, 2005–2019

Characteristic	N (%)
Total, N (%)	4,594 (100.0)
Sex, N (%)	
Male	2,331 (50.7)
Female	2,263 (49.3)
Age group, N (%)	
18–34	1,633 (35.5)
34–44	799 (17.4)
45–54	811 (17.7)
55–64	622 (13.5)
65 and older	729 (15.9)
Years of follow-up, median (IQR)[a]	1.45 (0.56–3.47)
County, N (%)[b]	
Canadian County	220 (4.8)
Cleveland County	394 (8.6)
Creek County	94 (2.1)
McClain County	66 (1.4)
Oklahoma County	1,235 (26.9)
Pottawatomie County	100 (2.2)
Rogers County	150 (3.3)
Tulsa County	981 (21.4)
Wagoner County	109 (2.4)
Washington County	80 (1.7)

[a]Follow-up time reflects their total length of insurance eligibility in years between 2005 and 2019.
[b]Number of individuals residing only in the 10 most populous counties in the study population.
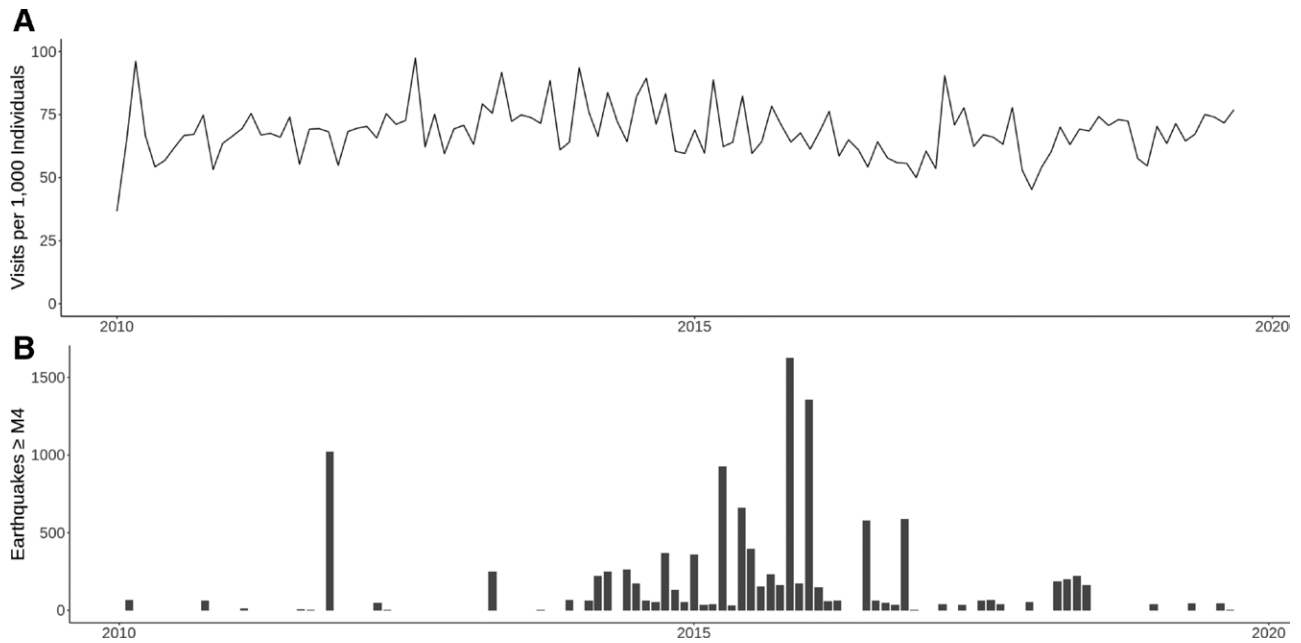IQR indicates interquartile range.

Figure 1. Frequency of ≥ *M4* earthquakes and anxiety-related healthcare visits in Oklahoma, 2005–2019. A, Depicts the rate of unique anxiety-related diagnoses per 1,000 individuals for each month of the study period. Monthly rates were calculated using the number of unique individuals eligible for insurance as the denominator and the number of unique diagnoses as the numerator. B, Depicts the number of felt earthquakes (≥ *M4*) across the state of Oklahoma throughout the study period.

disorders increased (OR = 1.27; 95% CI = 1.03, 1.57). We found no evidence of an association with adjustment reaction (OR = 1.05; 95% CI = 0.89, 1.23), anxiety-related disorders (OR = 0.96; 95% CI = 0.90, 1.03), or physical symptoms of anxiety (OR = 1.03; 95% CI = 0.98, 1.09) (Figure 2 and Supplemental Table 2; http://links.lww.com/EE/A208). Sensitivity analyses with frequency of felt earthquakes defined as a categorical exposure showed some evidence of an association for adjustment reaction and stress disorders, although they were relatively imprecise as evidenced by wide CIs (Supplemental Table 3; http://links.lww.com/EE/A208). Only four ≥*M 5* earthquakes occurred within 100 km of the population centroid of an Oklahoma County during our study period, and we observed

no evidence of associations between these earthquakes and any anxiety disorder diagnostic subgroups (Supplemental Table 4; http://links.lww.com/EE/A208).

Discussion

We draw upon longitudinal mental health claims data in Oklahoma during a time of considerable manmade seismic activity. We report an association between the frequency of felt earthquakes and odds of stress disorders, but not other types of anxiety disorders. Stress disorders are psychiatric diagnoses that occur within weeks of a traumatic event. Features include anxiety, intense fear or helplessness, dissociative symptoms, reexperiencing the event,
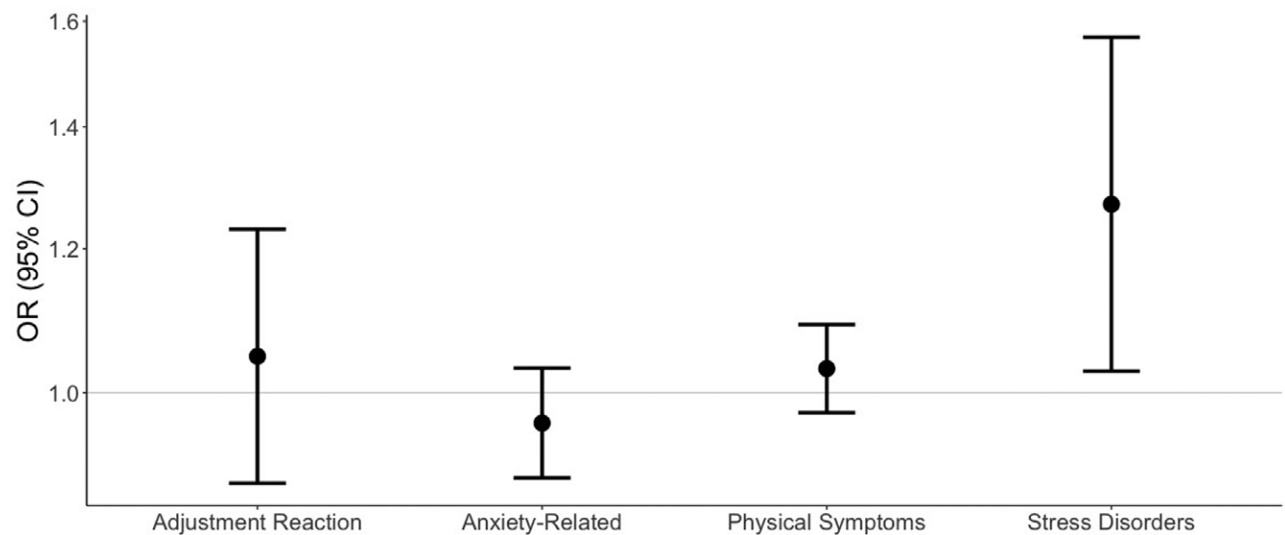

Figure 2. Association of frequency of ≥ *M4* earthquakes in previous 6 months with anxiety-related diagnoses in Oklahoma, 2005–2019. We used generalized estimating equations to estimate ORs for the association of the frequency of ≥ *M4* earthquakes in the previous 6 months with adjustment reaction, anxiety-related disorders, physical symptoms, and stress disorders. We specified an exchangeable working correlation structure to account for potential nonindependence of individuals residing within the same county. Models were adjusted for sex, age group, and included a set of fixed effects for calendar year and season.

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and avoidant behaviors.[23] One interpretation of our study results is therefore that the cumulative experience manmade earthquakes constitutes an experienced trauma that leads to treatment seeking specifically for stress disorders—but not other types of anxiety disorders—in some subset of individuals.

Our analysis extends a limited number of prior studies that consistently identified increased psychiatric distress in populations experiencing earthquakes.[24,25] Earthquakes that are directly attributable to human activity may further elicit feelings of anger and frustration.[26] Few studies have specifically examined the mental health effects of manmade earthquakes. We previously found that Google searches for anxiety approximately 3 weeks after an $\geq M$ 4 earthquake in Oklahoma.[27] Further, we estimated an excess of 39.2 vehicle crashes for every additional $\geq M$ 4 earthquake in most highly exposed Oklahoma counties (i.e., those with most high-magnitude earthquake epicenters), presumably because of increased driver distress and distraction.[17] In Texas, where UOGD has also recently intensified, exposure to manmade earthquakes was associated with increases in residents' perceived threat of environmental issues.[18] Finally, mixed methods analysis of earthquake preparedness among Oklahoma residents indicates an overall sense of resentment towards induced earthquakes and that damages should not be the responsibility of impacted residents.[28]

It must be stated that anxiety-related healthcare visits are rare, and consequently, many of our estimates are imprecise. Lack of statistical power further precluded our ability to examine subgroup differences, yet prior research demonstrates that women may be more likely to experience psychiatric distress in response to environmental threats.[18,29] Our estimates are subject to residual confounding by sociodemographic characteristics such as income and employment that were not available in these data. Healthcare encounters only capture the subset of individuals experiencing anxiety-related symptoms who receive treatment, which reflects some combination of disease severity, norms and perceptions surrounding mental illness, and access to care. Our outcome measure may be subject to misclassification as some prior research has found that administrative healthcare diagnoses of anxiety disorders have relatively poor agreement with the reference standard,[30] although we have no reason to suspect this misclassification is differential with respect to earthquake exposure. Selection bias may arise as there is evidence that administrative healthcare diagnoses likely capture a different population than those who would receive an anxiety disorder diagnosis through structured interview.[31] We anticipate that our results may underestimate the magnitude of the relationship between manmade earthquakes and anxiety, especially given that as of 2021, an estimated 71.6% of mental healthcare needs went unmet in Oklahoma.[32] Finally, we focused analyses on $\geq M$ 4 earthquakes, in line with our prior epidemiologic studies.[27,33] Future work may wish to evaluate a lower threshold, such as $\geq M$ 3, because these quakes are more common and because quakes in Oklahoma tend to be shallower than other tectonic zones,[34] meaning residents could exhibit a psychological response at lower magnitudes than elsewhere. We also assigned exposure at the county-level; future studies could use individual addresses and surveys or publicly available data such as the United States Geological Survey (USGS) "Did You Feel It?" dataset to better determine which people or locations felt earthquakes.[35]

Overall, our results motivate future research that aims to characterize the relationship between manmade earthquakes and anxiety, particularly when differences in population subgroups can be examined and wherever precise measures of symptom frequency and severity are available.

Conflicts of interest statement

Acknowledgments

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