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Residential proximity to hydraulically fractured oil and gas wells and adverse birth outcomes in urban and rural communities in California (2006–2015)

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Background: Prenatal exposure to hydraulic fracturing (HF), a chemically intensive oil and gas extraction method, may be associated with adverse birth outcomes, but no health studies have been conducted in California.

Methods: We conducted a retrospective cohort study of 979,961 births to mothers in eight California counties with HF between 2006 and 2015. Exposed individuals had at least 1 well hydraulically fractured within 1 km of their residence during pregnancy; the reference population had no wells within 1 km, but at least one oil/gas well within 10 km. We examined associations between HF and low birth weight (LBW), preterm birth (PTB), small for gestational age birth (SGA), and term birth weight (tBW) using generalized estimating equations and assessing urban-rural effect modification in stratified models.

Results: Fewer than 1% of mothers (N = 1,192) were exposed to HF during pregnancy. Among rural mothers, HF exposure was associated with increased odds of LBW (odds ratio [OR] = 1.74; 95% confidence interval [CI] = 1.10, 2.75), SGA (OR = 1.68; 95% CI = 1.42, 2.27) and PTB (OR = 1.17; 95% CI = 0.64, 2.12), and lower tBW (mean difference: –73 g; 95% CI = –131, –15). Among urban mothers, HF exposure was positively associated with SGA (OR = 1.23; 95% CI = 0.98, 1.55), inversely associated with LBW (OR = 0.83; 95% CI = 0.63, 1.07) and PTB (OR = 0.65; 95% CI = 0.48, 0.87), and not associated with tBW (mean difference: –2 g; 95% CI = –35, 31).

Conclusion: HF proximity was associated with adverse birth outcomes, particularly among rural Californians.

Keywords: Birth outcomes; Epidemiology; Oil and gas development; Hydraulic fracturing; Fracking; Pregnancy exposure; Reproductive health

California is among the top-10 oil and top-15 natural gas producing US states.[1] Hydraulic fracturing (HF) is a common well stimulation technique for enhanced oil and gas recovery[2] and accounts for about 20% of California's oil and gas production.[3] Uniquely, HF involves injecting water, proppants and chemicals into wells at high pressure to create cracks in rock formations, which maximizes extraction flow.[2,3] HF primarily occurs in California's Central Valley region, and compared with other states, most HF wells are shallower, more vertical, require less water per well, and use more concentrated chemical mixtures to recover primarily oil.[2–5] Although chemicals make up about 1% or less of the mixture, and HF usually takes less than a day, these chemicals may pose potential health hazards.[3]

One exposure pathway is via contamination of surface or groundwater with wastewater associated with HF (flowback) and oil and gas production (produced water).[3] Compared with conventional non-HF extraction, HF produces greater volumes of wastewater, which can include fugitive oil and gas, salts, organic and inorganic chemicals, radioactive material, and

What this study adds

This study addresses a critical knowledge gap regarding the health implications of hydraulic fracturing (HF) in California that can inform regional regulatory decision-making governing setback distances and emissions controls. Our retrospective cohort study evaluated associations between prenatal exposure to HF within 1 km of maternal residence and adverse birth outcomes for 2006–2015 births. Our results show that prenatal exposure to HF is associated with increased odds of adverse fetal growth outcomes, particularly for rural residents. Although HF is mostly confined to one region, and absolute risk is small, the relative risk is quite high for exposed pregnant women.

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Programming code for statistical analyses can be requested from the authors. Statistical models were developed using Proc Genmod. The analysis datasets were generated from the following repositories: CDPH Vital records:https://www.cdph.ca.gov/Programs/CHSI/Pages/Data-Applications.aspx#; CalGEM well records: https://www.conservation.ca.gov/calgem/maps/Pages/GISMapping2.aspx; CalGEM stimulation disclosure records: https://www.conservation.ca.gov/calgem/Pages/WSTDisclosureSearchDisclaimer.aspx; and CCST hydraulic fracturing data: ttps://ccst.us/wp-content/uploads/Appendix_M_cover.pdf; http://links.lww.com/EE/

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additives that can react with one another to generate byproducts–via flowback.[3] In California, between January 2011 and June 2014, nearly 60% (or 720,000 m^3) of wastewater generated from stimulated wells was disposed in unlined pits for evaporation and percolation although about a quarter of the wastewater was injected.[3] In the process of injecting wastewater into wells, accidental spills during transfer and transport, and leaks in storage wells can release contaminants into the environment. The highest number of wastewater-related spills across California were recorded in Kern County (Central Valley) between 2009 and 2014.[3] In Pennsylvania, trace metals related to HF (e.g., barium, strontium) have been found in private well-water.[6] In California, concerns about health and environmental impacts of water contamination associated with HF resulted in passage of Senate Bill 4 (SB4) in 2014[7] requiring oil and gas companies to expand monitoring and disclose chemicals used during fracking.

HF chemicals could also affect public health via. air pollution emitted during well drilling, handling and mixing of chemicals for injection, HF, and management of recovered fluids and waste products.[8,9] Volatile organic compounds (VOCs), such as benzene, toluene, ethylbenzene, and xylene (BTEX) and formaldehyde, have been the most commonly measured pollutants in and near HF wells and may be associated with adverse birth outcomes.[10–13] Measured emissions during drilling, HF, flowback and production at 5–10 well pads showed that emission rates of benzene and most VOCs were highest during flowback.[14,15] In several regions with intense HF activity, higher concentrations of VOCs have also been measured in ambient air compared with regions without HF.[6]

Pregnancy is a vulnerable period of human development, and adverse birth outcomes are primary predictors of infant mortality and morbidity.[16–19] Studies indicate associations between prenatal exposure to oil and gas development (OGD) activities (HF [most studies] and conventional extraction methods) and reductions in birth weight (tBW),[6,20,21] increased odds or incidence of low birth weight (LBW),[20,22] preterm birth (PTB)[6,23–27] and small for gestational age birth (SGA).[20,21] Statistically insignificant[6,23,26] or inverse associations[21,28] for some birth outcomes have also been observed. Our previous California study found exposure to all OGD (mostly not involving HF) was associated with decreased tBW and increased odds of LBW and SGA in rural areas, and increased odds of SGA in urban areas.[29] Because unique elements of HF, including the use of additional chemicals and large volumes of wastewater generated, may pose additional health risks beyond risks from conventional extraction, which we previously analyzed,[29] we extend our work to examine associations between prenatal exposure to HF and four birth outcomes (tBW, LBW, PTB, and SGA) by focusing on those California regions where HF is prevalent.

Methods

Study population

The study population, previously described,[29] consisted of births between January 1, 2006, and December 31, 2015, derived from the California Department of Public Health (CDPH) birth records. The dataset included maternal and infant characteristics such as self-reported race/ethnicity and infant sex, and maternal residential addresses were geocoded with ArcGIS 10.6 (Esri, Redlands, CA). From all 2006–2015 births (5.2 million), we limited our analysis to births in four air basins (Sacramento Valley, San Joaquin Valley, South Central Coast and South Coast with 26 counties) where most of California's oil and gas extraction activities occur after excluding births with missing data and birth defects (eFigure 1; http://links.lww.com/EE/A155). Mothers also had to reside within 10 km of at least one well, a criterion applied to limit unmeasured confounding and enhance comparability of the exposed and unexposed populations.[29] For this analysis, we further limited our cohort to births from 8 counties (Colusa, Fresno, Glenn, Kern, Los Angeles, Orange, Santa Barbara, and Ventura) with at least one maternal residence within 1 km of at least one HF well during the study period. After removing births with missing data, the study population consisted of 979,961 live births. Ninety percent of HF wells were in Kern County (Figure 1) and 4% in Los Angeles County. Study protocols were approved by the Institutional Review Boards of the CDPH (#13-05-1231) and the University of California, Berkeley (# 2013-10-5693).

Birth outcomes

We assessed the relationship between HF and four birth outcomes: (1) continuous tBW (grams (g), among births at ≥37 completed weeks), (2) LBW (<2,500 g), (3) PTB (<37 completed wks), and SGA birth (birth weight less than the US sex-specific 10th percentile of weight for each week of gestation).[30] Gestational age was estimated by subtracting the last menstrual period (LMP) date from the date of birth.

Exposure assessment

We derived data on confirmed HF wells from two sources: (1) the California Council on Science and Technology's (CCST) well stimulation report (Vol 1, Appendix M; http://links.lww.com/EE/A155, hereafter CCST report)[31] and (2) California Division of Oil, Gas and Geothermal Resources' (DOGGR, now CalGEM) well stimulation treatment (i.e., HF, acid fracturing and matrix acidization) disclosure database.[32] Both datasets contain unique American Petroleum Institute (API) numbers for each well, latitude, longitude, and approximate HF dates. We compiled HF records from the CCST report for January 2005 to December 2013 and the remaining HF well records for January 2014 to December 2015 from DOGGR.

CCST's methodology for compiling Appendix M; http://links.lww.com/EE/A155 is described in detail elsewhere (Volume 1, Appendix I[2]; http://links.lww.com/EE/A155). Briefly, HF wells were identified by reviewing OGD permit records and scanning for "frac" for evidence of HF as there was no systematic reporting requirement before SB4 in 2014. Due to the large number of well records in Kern County, CCST randomly sampled and reviewed 20% of records while for Los Angeles County, they reviewed 80% of records that were made available by county officials; 100% of records were reviewed in all other counties. CCST extracted approximate HF dates from permits or other sources such as regional air or water districts.[31] The DOGGR stimulation disclosure database was initiated in January 2014 with the adoption of California SB4. We filtered on HF, the bulk of the permit records, among the three types of stimulation techniques. There was a sharp decrease in the number of HF wells in 2014 (reason unknown) while operators adjusted to SB4 implementation.[33]

After compiling confirmed HF wells from the two data sources, we used the stimulation date to identify whether HF occurred during each pregnancy and the well location to identify proximity to residences. We then summed the number of HF events within 1 km of each mother's residence for each month of pregnancy using R version 3.3.1 (R Development Core Team, Auckland, New Zealand). HF wells that were not stimulated during a woman's pregnancy period did not contribute to exposure. We classified women who had at least one well stimulated within 1 km of their residential address at any point during pregnancy as exposed; prior literature found strongest associations with health indicators and exposure to OGD within this radius.[8,25,26,34,35] Women without any oil or gas wells within 1 km, but at least one well (whether HF or not during pregnancy) within 10 km, were classified as unexposed (Figure 2).

Covariates

To address potential confounding, our models controlled for several individual-level maternal characteristics and area-level

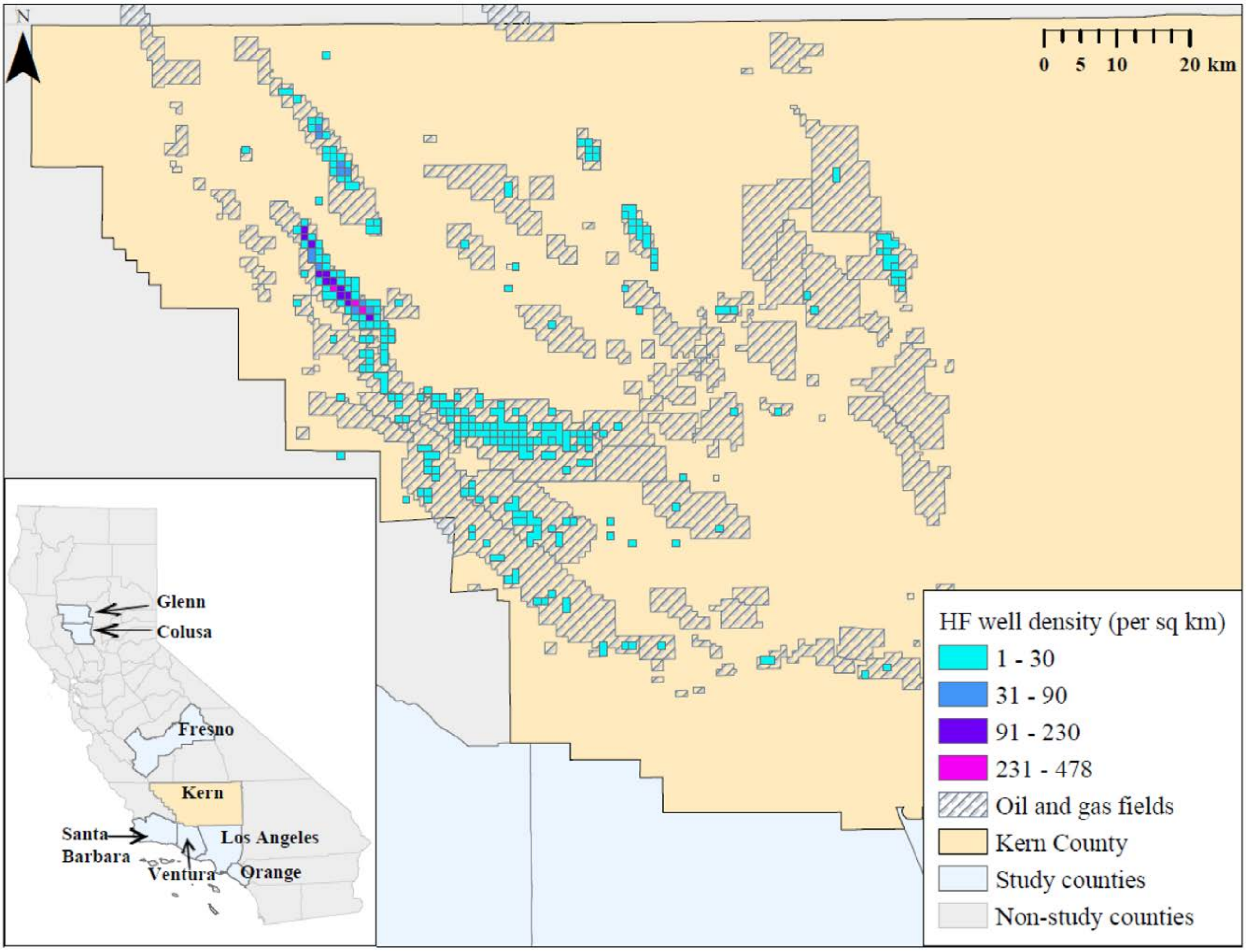

Figure 1. HF well density within Kern County (2005–2015), where 90% of HF in California occurred between 2005 and 2015. Seven other counties were included in this analysis but we zoomed into the county with the highest occurrence of hydraulic fracturing. The map was created in ArcGIS 10.6 (Esri, Redlands, CA). Well density was calculated via. the point density tool, based on the number of neighboring wells within a 1 km × 1 km cell around each well.

variables. Individual-level covariates from birth records were identified *a priori* as potential confounders based on prior studies. Infant covariates included sex (male/female), month and year of conception based on the date of LMP (both categorical) to control for seasonal and secular trends. Maternal covariates included age (<20, 20–24, 25–29, 30–34, 35+), self-reported race and ethnicity (non-Hispanic White, Black, Asian-Pacific Islander [API], Other and Hispanic), educational attainment (<high school, high school graduate/GED, some college, college+), Kotelchuck index of prenatal care,[36,37] and parity (nulliparous vs. multiparous). We aggregated Asian subgroups into the API category, and other racial/ethnic groups with small sample sizes into the other category to ensure adequate subgroup sample size. In the tBW model, we also added mean-centered and mean-centered squared gestational age (continuous) to allow for nonlinearity. Although mothers' smoking status during pregnancy and prepregnancy body mass index (BMI) are known predictors for adverse birth outcomes, they were not included because these variables were not available for 2006 births and our previous sensitivity analyses[29] indicated that including them when available did not substantially change effect estimates.

Area-level variables consisted of California Air Resources Board designated air basins, census-tract based urban-rural classification (urban tract if at least 60% of its area overlapped with an urbanized or urban area as defined by the US Census Bureau,[38] rural otherwise), modeled annual average nitrogen dioxide (NO_2) concentrations[39] as a proxy for traffic-related air pollution,[40,41] and Index of Concentration at the Extremes (ICE) (quartiles), a measure of neighborhood-level relative deprivation or affluence based on household income by census tract.[42] ICE for income was categorized into quartiles and ranged between 1 (concentration of affluence) and −1 (concentration of deprivation). The variable reflects the difference between the number of people with median household income in the top 80th percentile and the number of people with median household income in the lower 20th percentile within census tracts (urban tracts) or county (rural tracts), adjusted by the total tract/county population. These covariates were included to account for neighborhood and regional differences in air quality, economic activity, and sources of emissions.[43–47]

Statistical analyses

Statistical analyses were conducted in SAS 9.4 (SAS Institute, Cary, NC). We constructed separate models for each of our four birth outcomes to assess the association between prenatal exposure to HF and odds of PTB, LBW or SGA, or mean tBW. We used generalized estimating equations to account for clustering within census tracts. For the primary analysis, we compared births to mothers who were exposed to HF to those who were not exposed to any OGD during pregnancy within 1 km. As our previous study revealed significant effect modification (EM) by urbanicity,[29] we stratified models by urban and rural tracts (model 1). We then tested for significant heterogeneity between strata-specific estimates by modeling urbanicity as an interaction term to derive *P* values for two-sample z-tests using

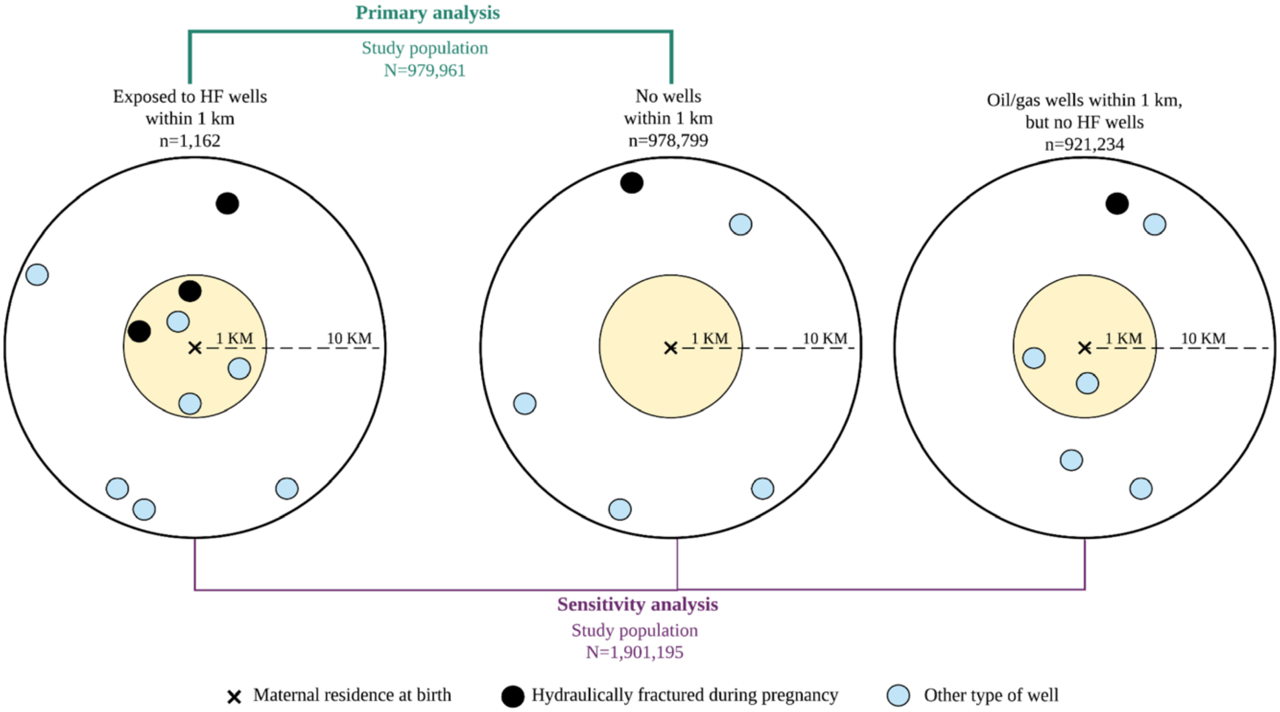

Figure 2. Schematic of exposed and reference groups for the primary and sensitivity analyses. For both primary and secondary analyses, exposed mothers had at least one well that was hydraulically fractured during pregnancy within 1 km of maternal residence. For the primary analysis, reference mothers had no oil or gas wells of any kind within 1 km of maternal residence during pregnancy. For the sensitivity analysis, the reference group consisted of mothers without HF within 1 km of maternal residence during pregnancy, including women who lived within 1 km of no wells and women who lived within 1 km of at least one oil or gas well that was not recorded as being hydraulically fractured during their pregnancy.

model-estimated beta coefficients and variances.[48,49] Due to the small exposed sample size, we evaluated model overadjustment by adjusting for one maternal covariate at a time and comparing the effect estimates between the fully adjusted models and single-covariate adjusted models.

Sensitivity analysis

We conducted a sensitivity analysis including broader exposure reference groups: mothers with no wells of any type and mothers with active or inactive wells that were not identified as HF wells within 1 km (Figure 2). Because HF and conventional wells are often clustered, which may confound associations between HF exposure and adverse birth outcomes, the sensitivity analysis adjusted for exposure to non-HF active and inactive wells (model 2). The number of inactive wells was categorized as 0, 1, 2–5, ≥6 following Tran et al.[29] Production volume was calculated as the sum of total monthly barrels of oil equivalent (BOE) from oil and gas wells during pregnancy (normalized by length of pregnancy and categorized as 0, 1–100, or >100 BOE/day).[29]

Results

The study population consisted of 979,961 births to mothers residing within 10 km of an oil or gas well between January 2006 and December 2015 in the eight California counties (eFigure 1; http://links.lww.com/EE/A155). Of these, 0.1% (n = 1,162) were exposed to HF *in utero* (Figure 2). Mean birth weight was 3,310 g (standard deviation = 523) (Table 1). Five percent (n = 52,378) of all births were LBW, 7% (n = 70,772) preterm, and 12% (n = 120,590) SGA. PTB was 2% higher among the reference group compared with the HF exposed, while SGA was 4% higher among the exposed group. HF exposed mothers, on average, were exposed to 2 HF wells within 1 km and a maximum of 20 HF wells (Table 1). Exposed mothers were also more educated (31% vs. 24% college or more educated), older (29% vs. 26% ages 30–34), more often non-Hispanic Black (16% vs. 4%), more likely to have inadequate prenatal care (13% vs. 10%), and more likely to not have previously given birth (42% vs. 39% nulliparous). Relative to unexposed mothers, exposed mothers were more likely to reside in Kern (17% vs. 3%), Los Angeles (65% vs. 57%), and Ventura counties (10% vs. 3%), rural areas (20% vs. 7%), and economically segregated areas (e.g., 35% vs. 25% in neighborhoods with concentrated poverty and 37% vs. 25% with concentrated affluence).

In overall unstratified models, effect estimates showed positive associations between prenatal exposure to HF wells and SGA and reduced tBW as well as inverse associations between exposure and LBW and PTB (eTable 1; http://links.lww.com/EE/A155). Table 2 shows our models stratified by urbanicity. When fully adjusted, the associations differed by urban and rural tracts (Table 2); EM *P* values were 0.007, 0.09, 0.10, and 0.05 for LBW, PTB, SGA, and tBW, respectively. Among rural mothers, exposure to HF wells was associated with increased odds for LBW (OR = 1.74, 95% CI = 1.10, 2.75), PTB (OR = 1.17, 95% CI = 0.64, 2.12), and SGA (OR = 1.68, 95% CI = 1.42, 2.27) and decreased tBW (mean difference = –73 g, 95% CI = –131, –15) (Table 2). Among urban mothers, HF exposure was associated with increased odds of SGA (OR =1.23, 95% CI = 0.98, 1.55), but not with tBW (mean difference = –2, 95% CI = –35, 31), as well as reduced odds of PTB (OR = 0.65, 95% CI = 0.48, 0.87) and LBW (OR = 0.83, 95% CI = 0.63, 1.07). Compared with the single maternal covariate adjusted models (eTable 2; http://links.lww.com/EE/A155), results were qualitatively similar, albeit attenuated.

In our sensitivity analysis with an expanded reference population (no wells of any type within 1 km as well as non-HF OGD wells within 1km), results were qualitatively similar to those from the primary analysis for all four birth outcomes (eTables 1 and 3; http://links.lww.com/EE/A155). However, evidence of urban-rural effect modification was weaker in the sensitivity analysis. Except for LBW and tBW among the rural population, most effect estimates did not change by >10%.

Table 1.

Neonate, maternal, and area-level characteristics of 2006–2015 births by binary HF exposure category in eight California counties with HF wells

Variable	N (%) 1,005,755	No HF wells (%) n = 1,004,563	HF wells (%) N = 1,192	*P*[a]
Neonate characteristics				
Mean birth weight (g) (SD)	3,310 (523)	3,310 (523)	3,304 (545)	0.54
Mean gestational age (weeks) (SD)	39.1 (2.0)	39.2 (2.0)	39.3 (1.9)	0.008
Low birth weight	52,378 (5)	5	5	0.90
Preterm birth	70,772 (7)	7	5	0.01
Small for gestational age	120,590 (12)	12	16	<0.0001
Missing	4 (<0.01)	<0.01	0	
Conception year				
2005	81,081(8)	8	8	<0.0001
2006	109,838 (11)	11	21	
2007	108,906 (10)	11	24	
2008	103,191 (10)	10	3	
2009	97,253 (10)	10	1	
2010	96,915 (10)	10	8	
2011	95,498 (9)	9	9	
2012	96,446 (10)	10	12	
2013	97,472 (10)	10	9	
2014	95,526 (10)	9	4	
2015	23,629 (2)	2	1	
Maternal Characteristics (%)				
Education				
<High school	278,658 (28)	28	23	<0.0001
High school diploma/GED	241,528 (24)	24	20	
Some college	221,485(22)	22	24	
College+	238,535 (24)	24	31	
Missing	25,549 (2)	2	2	
Age at delivery				
< 20	84,400 (8)	8	8	0.04
20–24	208,964 (21)	21	18	
25–29	261,529 (26)	26	25	
30–34	259,815 (26)	26	29	
35+	191,042 (19)	19	20	
Missing	5 (<0.01)	<0.01	0	
Race/ethnicity				
Asian/Pacific Islander	128,273 (13)	13	12	<0.0001
Black	43,829 (4)	4	16	
Hispanic	602,738 (60)	60	50	
Other	23,048 (2)	2	4	
White	207,867 (21)	21	18	
Kotelchuck index				
Inadequate	101,192 (10)	10	13	0.0004
Intermediate	97,007 (10)	10	11	
Adequate+	337,530 (33)	33	31	
Adequate	470,026 (47)	47	45	
Parity				
Nulliparous	392,327 (39)	39	42	0.03
Multiparous	612,989 (61)	61	58	
Missing	439 (<0.01)	<0.01	<0.01	
Area-level characteristics (%)				
County				
Colusa	1,755 (0.2)	0.2	0.3	<0.0001
Fresno	131,406 (13)	13	0.3	
Glenn	1,730 (0.2)	0.2	0.2	
Kern	34,305 (3)	3	17	
Los Angeles	573,911 (57)	57	65	
Orange	198,259 (20)	20	7	
Santa Barbara	33,157 (3)	3	0.1	
Ventura	31,232 (3)	3	10	
Mean annual NO_2 (ppb) (SD)	18 (7)	18 (7)	18 (8)	0.37
Missing	2 (<0.01)	<0.01	0	
Urban	936,724 (93)	93	80	<0.0001
ICE for income				
Quartile 1—poverty	251,667 (25)	25	35	<0.0001
Quartile 2	250,933 (25)	25	12	
Quartile 3	252,021 (25)	25	16	
Quartile 4—wealth	251,092 (25)	25	37	
Missing	42 (<0.01)	<0.01	0	
Wells				
Mean active+inactive well count (SD)[b,c]	0.2 (7)	0 (0)	143 (148)	
Mean inactive well count (SD)[b]	0.1 (5)	0 (0)	98 (104)	
Mean active well count (SD)[c]	0.1 (2)	0 (0)	45 (51)	
Mean BOE/day of gestation (SD)	1 (66)	0 (0)	1,089 (1,583)	

The percentage is provided unless otherwise indicated in the variable column. Note that active wells include all wells that produced oil or gas during our study period while inactive wells did not produce anything. Only wells within 1 km of residences were counted.

[a] ANOVA or chi-square test

[b] Well count within 1 km of residences across pregnancy and derived by taking the difference between total well count and active well count within 1 km.

[c] Well count within 1 km of residences across pregnancy and based on whether a well had monthly production volume.

BOE indicates barrels of oil equivalent (gas cubic feet converted to BOE to sum to barrels of oil); G, grams; HF, hydraulic fracturing; ICE, Index of Concentration at the Extremes; ppb, parts per billion; SD, standard deviation.

Table 2.

Adjusted odds ratios and mean difference for adverse birth outcomes associated with exposure to HF during pregnancy by urban and rural census tract for the primary analysis using a reference group of 2006–2015 births to mothers who were not exposed to *any* oil or gas wells within 1 km across the eight California counties (N = 979,961) (model 1)

	No wells (ref)		1+ HF wells			
	n	Cases (%)	*n*	Cases (%)	EE (95% CI)	EM p-value[c]
Low birth weight[a]						
Rural	66,822	3,183 (5)	225	15 (7)	1.74 (1.10, 2.75)	0.007
Urban	911,977	47,761 (5)	937	45 (5)	0.83 (0.63, 1.07)	
Preterm birth[a]						
Rural	66,822	4,903 (7)	225	13 (6)	1.17 (0.64, 2.12)	0.09
Urban	911,977	64,048 (7)	937	48 (5)	0.65 (0.48, 0.87)	
Small for gestational age[a]						
Rural	66,822	7,237 (11)	225	40 (18)	1.68 (1.42, 2.27)	0.10
Urban	911,977	110,146 (12)	937	144 (15)	1.23 (0.98, 1.55)	
Term birth weight (g)[b]						
Rural	61,919	--	212	--	–73 (–131, –15)	0.05
Urban	847,929	--	889	--	—2 (–35, 31)	

Eight counties included: Colusa, Fresno, Glenn, Kern, Los Angeles, Orange, Santa Barbara and Ventura

[a] Logistic regression models (odds ratio) with generalized estimating equations adjusted for child's sex, conception month and birth year; maternal education, age, race/ethnicity, Kotelchuck prenatal care index, parity; urban indicator, NO_2 concentration, air basin, and ICE for income.

[b] Linear regression model (mean difference) with generalized estimating equations also adjusted for gestational age in addition to those in footnote a.

[c] Test for difference in strata-specific effect estimates between rural and urban populations. Effect modification p-values were derived from two-sample z-tests using strata-specific estimates and variances. CI indicates confidence interval; EE, effect estimate; EM, effect modification; g, grams.

Discussion

To our knowledge, this study is the first to examine the association between prenatal exposures to HF and adverse birth outcomes in California. We found that prenatal exposure to HF was associated with all four adverse birth outcomes among rural residents, with the strongest associations observed for LBW, SGA, and tBW. Although the direction of the urban effect estimate was consistent with the rural communities for SGA, we observed inverse associations for PTB and LBW and no association with tBW. In our evaluation of overadjustment, the effect estimates remained stable.

Results remained consistent, with slightly weaker associations, in both rural and urban tracts in our sensitivity analysis including a larger reference population. With a broader definition for the unexposed group, there is a higher likelihood of exposure misclassification as 80% of Kern–where the majority of HF occurs–well records were not reviewed to confirm HF status; this may have led to the observed weaker associations. Nevertheless, the consistency of results between the primary and sensitivity analyses suggests that HF exposure may influence birth outcomes independent of the presence of conventional wells.

Similar to our previous analysis of exposure to all OGD,[29] we observed differences in effect estimates between rural and urban areas. The significant EM *P* values for LBW and tBW suggest that urbanicity modifies the association between HF exposure and birth weight. This may occur because urban regions tend to have more diverse mobile and stationary sources of ambient air pollution, and OGD likely contributes relatively less to urban ambient air pollution, making detection of the unique effects from OGD, and HF in particular, more challenging. Rural residents are also more likely to rely on groundwater sources for their drinking water, which may more likely be untreated if contaminated by OGD-related chemicals.[50] Most HF wells in Kern County are located in relatively shallow reservoirs, where groundwater protected for drinking water might be found within a few hundred feet.[33]

Our findings were consistent with those of previous studies that examined exposure to HF in rural and urban Pennsylvania and urban Texas. Evidence of a relationship between HF and LBW has been sparse; two studies observed increased risk of LBW associated with HF exposure in Pennsylvania.[20,22] Evidence of associations between HF exposure and tBW has been mixed; among five studies, two found no relationship (Pennsylvania, Texas),[23,26] and three found decreased tBW in Pennsylvania.[20–22] Cohort studies in Pennsylvania and Texas suggested that prenatal exposure to HF significantly increased odds of PTB by 14% to 100%.[23,25,26] We observed a PTB estimate similar in magnitude and direction to those findings among the rural population, while the association was inverse in urban areas. Among the three studies that evaluated SGA, two studies (Pennsylvania, Texas) found no association[23,26] while the other Pennsylvania study observed a similar magnitude of increased odds of SGA as in our study.[21] The observed differences across studies may be partially explained by differences in exposure sources, setting, and OGD infrastructure. Ambient air pollution levels and pollution sources in rural California may be more similar to those of rural Pennsylvania than those observed in urban Californian communities. New well pad development, drilling of new wells and horizontal or directional drilling also occur less frequently in California compared with Pennsylvania and Texas where infrastructure is less mature and wells are deeper, meaning higher volumes of water are pumped into wells and collected as flowback.[3] Additionally, California primarily produces oil[2] while Pennsylvania mainly produces gas and Texas produces mainly gas in the northern region. The constituents of fracking fluid vary by region based on hydrocarbon properties (e.g., oil is more viscous than gas) and local geology,[2] meaning the type and concentration of chemicals that may contaminate air and waterways likely also vary by region.

Associations between exposure to HF and SGA were stronger than those we previously observed in California for exposure to high production volume from mostly conventional wells in both rural [OR = 1.22 (95% CI = 1.02, 1.45)] and urban [OR = 1.04 (95% CI = 1.01, 1.07)] areas.[29] This suggests that HF treatment may present additional hazards or enhanced health risks compared with conventional OGD operations. However, because only a small proportion of births were exposed to HF (<0.01% of births to mothers residing within 10 km of any well in the 8 counties), the risk difference between the exposed and unexposed is smaller compared with that for exposure to all types of actively producing wells (which affected a larger population, 4% of California births to mothers residing within 10 km of any well in 23 counties). Within 1 km, HF wells likely contribute a sizeable proportion of OGD-related air pollution. Truck traffic required to transport materials and equipment to and from the well pad for HF[2] is likely a primary source. HF in California typically requires about 100–200 diesel truck trips per vertical well, and 200–400 trips per horizontal well.[3] Ambient $PM_{2.5}$, a component of diesel particulates, has been associated with higher odds of SGA.[51–53] Air samples collected in five states (Arizona, Ohio, Wyoming, Colorado, and Pennsylvania) near stimulated well sites and wastewater impoundments from distances as close as 27–320 m of unconventional OGD sites revealed elevated levels of VOCs, including BTEX.[54] Benzene from unconventional wells has been measured at elevated levels within 1 km from oil and gas fields in several states.[8,54–59] This indicates that OGD equipment and volatized chemicals from percolation pits can contribute to OGD emissions. VOCs and BTEX may be associated with decreased birth weight[10,12] and substantial decreases in birth weight can result in SGA. BTEX is not only found in emissions but also in groundwater samples after spills at HF sites.[60] As water contamination risks are not well understood, current water treatment practices may not prevent exposure to HF-related chemicals.

Besides significant associations with SGA, exposure to HF was also unexpectedly inversely associated with PTB and LBW within urban areas. Among studies that evaluated birth outcomes and unconventional OGD, one revealed an inverse association with exposure to HF and PTB in Pennsylvania.[21] Decreased odds of PTB have also been observed with increasing levels of ambient air pollution.[61,62] The inverse association between HF and PTB observed in our study may be due to residual confounding from area-level SES characteristics or environmental factors that we could not account for in our analyses. Additionally, live birth bias can result from the depletion of susceptibles, which may occur if exposed compared with unexposed mothers were more likely to experience fetal loss.[63–65] Miscarriage has been associated with exposure to OGD; women residing in Ecuadorian communities within 5 km downstream of an oil field had greater odds of spontaneous abortions relative to those living at least 30 km upstream of an oil field.[66] Because we were not able to examine fetal loss in our analysis, we cannot rule out the possible role of live birth bias in our analysis.

This study had limitations. To assign exposure to each pregnancy period, we used data on verified HF well status. Most HF occurs in Kern County, but only 20% of Kern County well records were randomly sampled to verify HF status before 2014; we underestimated the number of HF wells and women exposed, likely biasing effect estimates toward the null. We could not fully evaluate the impact of missingness on our results without an accurate probability of HF for births with missing data. Although missingness could have biased our effect estimates in any direction, the impact is likely to be minimal as only 5% of study county births in our 8 county study area would have occurred in Kern where stimulation is most likely to occur compared with the 7 other counties. With a limited number of exposed births, we were also unable to assess trimester-specific effects. Additionally, the HF well data did not include specific dates for phases of preproduction (i.e., pad development, drilling, and stimulation) which precluded assessment of hazards at each phase of well creation or stimulation. Another limitation was our reliance on distance to HF wells as a proxy for exposure to diverse HF hazards that have yet to be fully characterized. However, distance allows evaluation of associations for large populations and serves as an aggregate measure for potential physical, chemical and social stressors associated with HF, and can inform regulations such as minimum allowable distances to well sites.[67] Finally, we did not have access to data on maternal occupation, BMI, smoking status, or maternal mobility during pregnancy, which likely modestly biased results toward the null.[68–72]

Our retrospective birth cohort study, the first study of HF in California, adds to the evidence that prenatal exposure to HF is associated with adverse birth outcomes. Relative risk is high although absolute risk may be low across the state. Although findings from this study may not be generalizable and additional studies are needed to verify these findings, results from this and our previous work can inform regulatory strategies in California and motivate research to better characterize potential HF-specific hazards and the adequacy of current setback distances to OGD, and HF in particular, especially in rural areas.

Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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