Radiat Environ Biophys (2017) 56:111–120
DOI 10.1007/s00411-016-0673-2

ORIGINAL ARTICLE

Maternal residential proximity to nuclear facilities and low birth weight in offspring in Texas

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Received: 10 December 2015 / Accepted: 19 December 2016 / Published online: 29 December 2016

Abstract Health effects of close residential proximity to nuclear facilities have been a concern for both the general public and health professionals. Here, a study is reported examining the association between maternal residential proximity to nuclear facilities and low birth weight (LBW) in offspring using data from 1996 through 2008 in Texas, USA. A case–control study design was used together with a proximity-based model for exposure assessment. First, the LBW case/control births were categorized into multiple proximity groups based on distances between their maternal residences and nuclear facilities. Then, a binary logistic regression model was used to examine the association between maternal residential proximity to nuclear facilities and low birth weight in offspring. The odds ratios were adjusted for birth year, public health region of maternal residence, child's sex, gestational weeks, maternal age, education, and race/ethnicity. In addition, sensitivity analyses were conducted for the model. Compared with the reference group (more than 50 km from a nuclear facility), the exposed groups did not show a statistically significant increase in LBW risk [adjusted odds ratio (aOR) 0.91 (95% confidence interval (CI): 0.81, 1.03) for group 40–50 km; aOR 0.98 (CI 0.84, 1.13) for group 30–40 km; aOR 0.95 (CI 0.79, 1.15) for group 20–30 km; aOR 0.86 (CI 0.70, 1.04) for group 10–20 km; and aOR 0.98 (CI 0.59, 1.61) for group 0–10 km]. These results were also confirmed by results of the sensitivity analyses. The results suggest that maternal residential proximity to nuclear facilities is not a significant factor for LBW in offspring.

Keywords GIS · Health · Nuclear facilities · Low birth weight (LBW) · Ionizing radiation · Spatial modeling

Introduction

In the USA, around six million pregnancies occur each year (US CDC 2015). However, not all women have a safe term pregnancy and deliver a healthy infant (US CDC 2014). Low birth weight (LBW) is defined as a newborn with weight less than 2500 grams (or 5.5 lb) measured immediately after birth (WHO 1992).[1] LBW infants may have higher risks of many health problems than infants born with normal weight (US CDC 2012). The health problems not only include infant mortality and/or morbidity (Reynolds et al. 2004; Valero De Bernabé et al. 2004), but also involve adverse health outcomes in later life, such as coronary heart disease, hypertension and type II diabetes (Hales and Barker 1992; Osmond and Barker 2000), stroke (Lawlor et al. 2005), delayed motor and social development or learning disabilities (US CDC 2012), and other adult chronic diseases (Joseph and Kramer 1996). LBW has become an important predictor of infants' health (Ebisu et al. 2008). According to the data from the United States Centers for Disease Control and Prevention (CDC) (US CDC 2014), 2.6% of live term singleton births in the USA during 2000–2013 are LBW births. This rate varies between 1.3 and 4.8% in different states in the USA. Texas

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[1] Although g and kg are the unit of "mass", in this paper the term "weight" is preferred to keep consistency with the pertinent literature.

has a yearly LBW rate of 2.5–3.0% during 2000–2013, accounting for 7906–10,363 LBW infants per year.

LBW is associated with many risk factors, including genetics, maternal characteristics, and behaviors (e.g., younger than 15 years and older than 35 years, smoking, and drinking alcohol), socioeconomic factors (e.g., low income, low educational level, stress, domestic violence, and unmarried), and exposure to environmental risk factors (US CDC 2012; Valero De Bernabé et al. 2004). The potential environmental risk factors include air pollution (Glinianaia et al. 2004; Maisonet et al. 2004; Ritz and Wilhelm 2008; Srám et al. 2005), water contamination (Currie et al. 2013; Villanueva et al. 2005; Yang et al. 2002), lack of surrounding greenness (Dadvand et al. 2012; Laurent et al. 2013), among other factors.

More and more nuclear facilities have been built to meet the increase in demand on electricity. A total of 100 commercial nuclear power reactors were in operation in the USA in 2015 (US NRC 2015a). Many studies found that nuclear facilities had negative influence on the living environment, including forest ecosystem (Wang et al. 2012), water (Ilyinskikh et al. 2000), and air (Dias et al. 2009). Nuclear power plant accidents [Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiichi (2011)] have also warned people the danger of nuclear power and brought the nuclear facilities into view (Huang et al. 2013). Ionizing radiation could act with the biochemical structure in tissue (including proteins, DNA, and other molecules), and cause the loss of organ or tissue functionality (Williams and Fletcher 2010). Although the ionizing radiation exposure level was found to be low (less than 0.2 µSv/h) in the surroundings of nuclear facilities, the general public and health professionals are still concerned about the potential health effects caused by nuclear facilities, especially for pregnant women (Wang et al. 2010). Therefore, many studies have attempted to investigate whether residential proximity to nuclear facilities was associated with adverse health outcomes, such as childhood leukemia (Kaatsch et al. 2008; Morris and Knorr 1996; Sharp et al. 1996; Spix et al. 2008), escalated sex odds (Scherb and Voigt 2011), chromosome aberrations (Ilyinskikh et al. 2000), birth defects (Queisser-Luft et al. 2011), and thyroid nodules (Mettler et al. 1992).

However, only few studies have examined the association between maternal residential proximity to nuclear facilities and LBW in offspring (“Nuclear Facilities-LBW association”). Mangones et al. (2013) and Wang et al. (2010) found that LBW was not related to residential proximity to nuclear facilities in their study areas. Slama et al. (2008) concluded that the LBW risk in the “canton” (electoral ward) with nuclear facilities was not increased when compared with reference areas in France. However, most of these studies were outside of the USA (Slama et al. 2008; Wang et al. 2010). The only US-based study (Mangones et al. 2013) focused on five Hudson Valley counties in New York State near a nuclear reactor. No study has investigated the “Nuclear Facilities-LBW association” in the southern USA. Moreover, previous studies had limited study areas and used much smaller study population sizes when compared with the present study. Most of the published studies investigating health outcomes near nuclear facilities used the “proximity-based model,” which categorizes people near nuclear facilities into different groups based on their residential distances to nuclear facilities using certain distance thresholds. However, these studies only used one set of predefined distance thresholds in the model and failed to investigate the influence of different distance thresholds on analysis results. In the present study, the association between maternal residential proximity to nuclear facilities and LBW in offspring in Texas is examined over a 13-year period and the sensitivity of “Nuclear Facilities-LBW association” to zones delineated by different distance thresholds is explored.

Materials and methods

The methodology framework consists of four steps as follows:

Data collection and GIS database development

The study area was the state of Texas, USA (Fig. 1). There are several reasons why Texas was chosen for this study. First, Texas has the largest area in the 48 contiguous United States. Second, Texas is the second most populous state in USA, with a total population of 25,145,561 in 2010 (US Census Bureau 2015). Third, it has a racially/ethnically diverse population, among which 45.3% were non-Hispanic whites, 11.5% were non-Hispanic blacks, 37.6% were Hispanics, 0.7% were Native Americans, and 3.8% were Asians (US Census Bureau 2010).

From the 100 operating commercial nuclear power reactors that generate electricity in the USA (US NRC 2015a), this study extracted the ones in operation during 1996–2008 in Texas (Fig. 1). There were two nuclear plants with four units selected (Table 1). The nuclear facilities were geocoded using ESRI ArcGIS 10.1. The output file was an ESRI shapefile containing both locations and corresponding non-spatial attributes of nuclear facilities.

Birth certificate data were obtained from the Center for Health Statistics in the Texas Department of State Health Services (TX DSHS) for all registered births in Texas from 1996 to 2008. Each birth certificate record included the

Fig. 1 Operating commercial nuclear power reactors that generate electricity in the USA in 2015 (study area Texas shaded)

Table 1 Information about nuclear power plants in Texas during 1996–2008

Plant name	Location	Unit number	Reactor type	Containment type	Licensee	Operating license issued	Operating license expires
South Texas Project	Bay City, TX (90 miles SW of Houston, TX)	South Texas Project, Unit 1	Pressurized Water Reactor	Dry, Ambient Pressure	STP Nuclear Operating Co	3/22/1988	8/20/2027
		South Texas Project, Unit 2	Pressurized Water Reactor	Dry, Ambient Pressure	STP Nuclear Operating Co	3/28/1989	12/15/2028
Comanche Peak Steam Electric Station	Glen Rose, TX (40 miles SW of Fort Worth, TX)	Comanche Peak Steam Electric Station, Unit 1	Pressurized Water Reactor	Dry, Ambient Pressure	Luminant Generation Co., LLC	4/17/1990	2/8/2030
		Comanche Peak Steam Electric Station, Unit 2	Pressurized Water Reactor	Dry, Ambient Pressure	Luminant Generation Co., LLC	4/6/1993	2/2/2033

following variables: maternal residential address at delivery; birth weight; child's sex; mother's age at delivery; mother's race/ethnicity; mother's education; gestational age in weeks; date for last menstrual period (LMP); year of birth, among others. This study excluded births with incomplete location information (10.9%), plural delivery (2.7%), births with weight less than 1000 grams or greater than 5500 grams (0.1%), or births with gestational age greater than 44 weeks or less than 37 weeks (17.8%). The study also omitted births that occurred outside of Texas or those given by non-Texas residents (0.2%). Then, LBW cases were selected if they had a birth weight less than 2500 grams at birth, and were delivered between 1996 and 2008 ($n = 94{,}106$); controls were births with weight greater than or equal to 2500 grams during the same period ($n = 3{,}386{,}971$). ESRI ArcGIS 10.1 was used to geocode maternal addresses of all cases and controls. Then, this study constructed a LBW geodatabase containing both the georeferenced locations of LBW cases and controls, as well as non-spatial variables obtained from the birth certificates.

Categorization of cases/controls into proximity groups

This study first selected distance thresholds, which defined multiple groups of proximity to nuclear facilities. Then, the LBW cases and controls were categorized into these proximity groups based on distances between their maternal residence locations and nuclear facilities. In most studies on health effect near nuclear facilities, cases and controls that lived more than 50 km away from any nuclear facilities were categorized into the reference group. Accordingly, this study also used 50 km as the distance threshold for the reference group. Distance within 50 km was further divided into five equal interval groups (0–10, 10–20, 20–30, 30–40, and 40–50 km) using thresholds 10, 20, 30, and 40 km. These five proximity groups were considered as exposed groups in the following analysis.

Epidemiological analysis

This study applied a binary logistic regression model to examine the association between maternal residential proximity to nuclear facilities and LBW case/control status. In the analyses of odds ratios (ORs) associated with different proximity groups, the study used the Wald statistic to test the significance of linear trends among ORs. The ORs were adjusted for several potential confounding variables that might be associated with the LBW.

These potential confounding variables were first chosen based on the LBW-related literature, including child's sex, gestational weeks, maternal age, education, race/ethnicity, public health regions (11 regions in Texas; each region consists of 16–41 counties), and others. Then, this study applied a linear regression model with birth weight as a continuous dependent variable and all potential confounding variables (excluding residential proximity variable) as independent variables to explore whether expected associations were observed (e.g., maternal age associated with lower birth weight). Variables exhibiting statistically significant associations with birth weight were incorporated into the binary logistic regression model to calculate the adjusted odds ratios (aORs) of "Nuclear Facilities-LBW association."

Sensitivity analysis

Sensitivity analyses on model parameters (distance thresholds) were conducted to validate the results. Based on the original analysis group, this study created three groups of sensitivity analysis by changing both the distance threshold of reference group and the distance intervals of exposed groups as shown in Table 2. For each sensitivity analysis group, the study used the same epidemiological analysis procedure to examine the "Nuclear Facilities-LBW association." Results were compared with the original analysis group to examine how model parameters may affect the results. This study also conducted sensitivity analyses for the model restricting the dataset to frequency-matched LBW cases and controls only. To investigate whether the "Nuclear Facilities-LBW association" differs by using different data types, this study conducted one additional analysis considering birth weight and maternal residential distance to nuclear facilities as continuous variables. Rather than considering birth weight directly, another additional analysis was conducted using sex- and gestational age-adjusted z-scores of birth weight as the dependent variable in the regression analysis.

Results

Table 3 shows a comparison between cases and controls by child's sex, mother's age at delivery, mother's race/ethnicity, gestational length, year of birth, public health region of maternal residence at the time of delivery, and mother's education. The LBW cases accounted for 2.7% of the total births, 2.3% of the male births, and 3.2% of the female births. Compared with control-mothers, case-mothers were more likely to be non-Hispanic black, or have younger delivery age, shorter gestational length, or less education.

Table 4 shows results for the linear regression model using birth weight as a continuous dependent variable and all potential confounding variables as independent variables. All variables in Table 4 demonstrated statistically significant associations with birth weights. Specifically, female infants tended to have lower birth weights; mothers with less education or younger age had lower birth weights in offspring; the shorter gestational lengths were also associated with lower birth weights. Moreover, when compared to Non-Hispanic white mothers, mothers from other races/ethnicity groups were more likely to have had infants with lower birth weights. Therefore, the ORs for the association between maternal residential proximity and LBW need to be adjusted for child's sex, maternal race/ethnicity, age, education, and gestational length. Because of the uneven distribution of births in both time and space (Table 3), the ORs were also adjusted for the year of birth and public health region of maternal residence.

Table 5 displays the association between proximity groups and LBW in the original analysis group. The aORs for the five exposed groups were not statistically significant, which means that LBW risks in the exposed groups are not significantly different from those in the reference group. In proximity groups 40–50, 30–40, and 10–20 km, the unadjusted ORs were statistically significant and smaller than one. However, after adjusting for the

Table 2 Distance thresholds for original analysis and sensitivity analyses

Group ID	Reference group (km)	Exposed groups (km)	Description
Original analysis	>50	0–10, 10–20, 20–30, 30–40, 40–50	Proximity groups of original analysis
Sensitive analysis I	>100	0–10, 10–20, 20–30, 30–40, 40–50	Increase the distance threshold of reference group
Sensitive analysis II	>50	0–5, 5–10, 10–15, 15–20, 20–25	Decrease the distance interval of exposed groups
Sensitive analysis III	>50	0–20, 20–40	Increase the distance interval of exposed groups

confounding variables, none of the three proximity groups showed statistically significant aORs. Moreover, there was no statistically significant linear trend for these aORs ($p = 0.066$). The results of the original analysis indicate that maternal residential proximity to nuclear facilities was not associated with LBW in offspring.

Table 6 shows results of sensitivity analyses on model parameters (distance thresholds). The pattern of results is very similar to those of the original analysis. Although some unadjusted ORs are statistically significant, none of the aORs are statistically significant. The trends are not monotonic in any of the three sensitivity analysis groups. Consequently, the “Nuclear Facilities-LBW association” did not change significantly when different distance thresholds were used.

In the sensitivity analysis using frequency-matched LBW cases and controls, four controls were selected for each case to ensure enough study power. The control births were frequency matched to cases by year of delivery (1996–2008) and public health service region (11 regions) in which the case-mothers resided at the time of delivery. This sensitivity analysis ($n = 470{,}530$) for the logistic regression model provided similar results to those based on all data ($n = 3{,}481{,}077$). No statistically significant aORs were found in any of the proximity groups.

When both birth weight and maternal residential distance to nuclear facilities were considered as continuous variables, this study used a linear regression model to test the association between the two variables. After adjusting for confounding variables, estimated coefficients from the linear regression model indicated a change in mean infant birth weight of −0.056 g (95% CI −0.163 to 0.050 g) for each 10-km decrease. The difference in mean birth weight is not statistically significant, so no relationship with birth weight was identified for maternal residential distance to nuclear facilities.

In the additional analysis of birth weight z-scores, birth weights were adjusted for child’s sex and gestational age based on a US birth weight reference population (Talge et al. 2014). Then, this study used a linear regression model to test the association between the birth weight z-scores and maternal residential distance to nuclear facilities. The model was adjusted for all confounding variables except for the child’s sex and gestational age. The estimated coefficients from the linear regression model indicated a change in mean birth weight z-score of −0.000121 (95% CI −0.000367 to 0.000126, p value 0.336) for each 10-km decrease in maternal residential distance. Therefore, no statistically significant association was observed in this analysis.

Discussions

The insignificant “Nuclear Facilities-LBW association” found in the present study corroborates results from previous studies. In a study conducted in New York State over a 10-year period, the authors used four zones of 5-mile increments to categorize the proximity to a nuclear reactor. They concluded that LBW was not related to the proximity to the nuclear power plants (Mangones et al. 2013). The second group of sensitivity analyses in the present study (exposed groups: 0–5, 5–10, 10–15, 15–20, 20–25 km) utilized similar distance thresholds and found similar results as the New York State study.

A French study also concluded that there was no evidence of decreased mean birth weight when compared a “canton” (electoral ward) with nuclear facilities against a reference area without nuclear facilities (Slama et al. 2008). This French study used two separated regions as the study area and reference area, which was different from the proximity group design of the present study. However, if the present study only took into account the reference group (e.g., >50 km) and the proximity group that was closest to the nuclear facilities (e.g., 0–10 km), the design would be comparable to the French study. Both studies support the conclusion of insignificant “Nuclear Facilities-LBW association.”

Wang et al. (2010) also summarized that residence in the vicinity of a nuclear power plant was not a significant factor of LBW (OR 1.04; 95% CI 0.79, 1.37) based on a study conducted in Taiwan over four years. This Taiwan study used distance threshold of 20 km to categorize the study population into “Plant-vicinity” and “Non-plant-vicinity” groups, which matched the parameter setting of sensitivity analysis III of the present study (exposed

Table 3 Selected characteristics of low-birth-weight cases and controls, Texas, 1996–2008

Characteristic	Cases ($n = 94{,}106$)		Controls ($n = 3{,}386{,}971$)		Total ($n = 3{,}481{,}077$)	
	n	%	*n*	%	*n*	%
Child's sex						
Male	39,787	42.3	1,728,516	51.0	1,768,303	50.8
Female	54,319	57.7	1,658,455	49.0	1,712,774	49.2
Mother's age at delivery (years)						
11–19	18,791	20.0	465,020	13.7	483,811	13.9
20–24	28,850	30.7	938,984	27.7	967,834	27.8
25–29	22,139	23.5	928,873	27.4	951,012	27.3
30–34	14,898	15.8	692,733	20.5	707,631	20.3
35–39	7470	7.9	303,232	9.0	310,702	8.9
>40	1957	2.1	58,079	1.7	60,036	1.7
Unknown	1	<0.1	50	<0.1	51	<0.1
Mother's race/ethnicity						
Non-Hispanic white	27,642	29.4	1,287,870	38.0	1,315,512	37.8
Non-Hispanic black	18,344	19.5	359,367	10.6	377,711	10.9
Hispanic	43,366	46.1	1,602,992	47.3	1,646,358	47.3
Others, non-Hispanic	4754	5.1	136,742	4.0	141,496	4.1
Gestational length (weeks)						
37	29,089	30.9	350,204	10.3	379,293	10.9
38	25,426	27.0	748,946	22.1	774,372	22.2
39	18,488	19.6	969,056	28.6	987,544	28.4
40	10,578	11.2	730,301	21.6	740,879	21.3
41	5307	5.6	351,559	10.4	356,866	10.3
42	2830	3.0	132,644	3.9	135,474	3.9
43	1634	1.7	71,204	2.1	72,838	2.1
44	754	0.8	33,057	1.0	33,811	1.0
Year of birth						
1996	5739	6.1	221,212	6.5	226,951	6.5
1997	5750	6.1	224,665	6.6	230,415	6.6
1998	5910	6.3	228,012	6.7	233,922	6.7
1999	5974	6.3	234,588	6.9	240,562	6.9
2000	6333	6.7	241,921	7.1	248,254	7.1
2001	6433	6.8	244,912	7.2	251,345	7.2
2002	7023	7.5	259,662	7.7	266,685	7.7
2003	7166	7.6	259,517	7.7	266,683	7.7
2004	7535	8.0	266,609	7.9	274,144	7.9
2005	8451	9.0	286,653	8.5	295,104	8.5
2006	9071	9.6	301,555	8.9	310,626	8.9
2007	9236	9.8	309,295	9.1	318,531	9.2
2008	9485	10.1	308,370	9.1	317,855	9.1
*Public health region**						
1	3855	4.1	109,923	3.2	113,778	3.3
2	1992	2.1	68,861	2.0	70,853	2.0
3	24,253	25.8	960,736	28.4	984,989	28.3
4	3230	3.4	104,574	3.1	107,804	3.1
5	2561	2.7	75,028	2.2	77,589	2.2
6	23,094	24.5	847,952	25.0	871,046	25.0
7	9236	9.8	365,936	10.8	375,172	10.8
8	10,324	11.0	339,109	10.0	349,433	10.0

Table 3 continued

Characteristic	Cases (n = 94,106)		Controls (n = 3,386,971)		Total (n = 3,481,077)	
	n	%	n	%	n	%
9	2565	2.7	74,400	2.2	76,965	2.2
10	4183	4.4	134,086	4.0	138,269	4.0
11	8813	9.4	306,366	9.0	315,179	9.1
Education						
<High school	33,963	36.1	1,021,964	30.2	1,055,927	30.3
High school	30,200	32.1	978,790	28.9	1,008,990	29.0
>High school	29,082	30.9	1,359,124	40.1	1,388,206	39.9
Unknown	861	0.9	27,093	0.8	27,954	0.8

* 11 regions in Texas; each region consists of 16–41 counties; areas of the regions range from 12,060 to 61,456 square miles

Table 4 Difference in birth weight associated with selected non-proximity variables (95% confidence interval) for cases and controls combined, Texas, 1996–2008

Variable	Difference in birth weight (g)
Child's sex	
Male (reference)	
Female	−123.7 (−124.7, −122.8)
Mother's race/ethnicity	
Non-Hispanic white (reference)	
Non-Hispanic black	−160.6 (−162.2, −159.0)
Hispanic	−41.7 (−42.8, −40.6)
Others, non-Hispanic	−183.2 (−185.6, −180.7)
Mother's education	
High school (reference)	
<High school	−7.7 (−9.0, −6.5)
>High school	22.1 (20.9, 23.3)
Mother's age (years)	
30–34 (reference)	
11–19	−157.4 (−159.1, −155.6)
20–24	−96.0 (−97.4, −94.6)
25–29	−35.4 (−36.8, −34.1)
35–39	12.5 (10.6, 14.3)
>39	−1.7 (−5.4, 2.0)
Gestational length (weeks)	
40 (reference)	
37	−325.4 (−327.1, −323.7)
38	−184.9 (−186.3, −183.5)
39	−79.9 (−81.2, −78.6)
41	36.4 (34.6, 38.2)
42	−8.1 (−10.7, −5.6)
43	−32.0 (−35.4, −28.7)
44	−15.0 (−19.9, −10.2)

groups: 0–20, 20–40 km). The odds ratio in the Taiwan study was 1.04 (95% CI 0.79, 1.37), which is also comparable to the ones in the present study (Table 6c).

The sensitivity analyses on model parameters (distance thresholds) indicated that the proximity-based model in the present study was not sensitive to the choice of distance thresholds. However, if distance thresholds were too small, there would be very few cases/controls in some proximity groups. For example, the 0–5 km group in the sensitivity analysis II only had two LBW cases available. Under this circumstance, the uncertainty of the OR would increase. Practically, the recommended distance thresholds should be relatively large in order to keep the number of cases and controls in each proximity group greater than five.

Although results from the present study do not identify any associations between maternal residential proximity to nuclear facilities and LBW in offspring, one should not conclude that there is no association at all. The reason is that the absence of evidence does not simply mean no information exists (evidence of absence) (Altman and Bland 1995). Therefore, although no evidence of "Nuclear Facilities-LBW association" was found, one should not further infer that living closer to nuclear facilities would be risk-free. Considering the serious effect of nuclear power plant accidents and widespread radiation exposure in population, studies searching for evidence of "Nuclear Facilities-LBW association" have become very important; while existing studies did not prove such association, further studies should still be carried out when necessary (Altman and Bland 1995).

This study is not without limitations. First, there were only two nuclear power plants with four reactors in Texas, which limited the sample sizes in the exposed groups when calculating odds ratios. Three other operating research reactors in Texas were not included in this study because the power levels and fuel quantities at these facilities were very small when compared to large electrical power generation plants (US NRC 2015b). Future studies may consider using larger research areas (e.g., the 48 continental United States) to include more nuclear facilities and LBW cases/controls in the exposed groups. Second, because no

Table 5 Maternal residential proximity to nuclear facilities and LBW in offspring (Original analysis)

Proximity (km)	Cases		Control		Unadjusted OR (95% CI)	Adjusted OR (95% CI)[a]	*p* value for trend
	n	%	*n*	%			
>50	92,526	99.23	3,327,655	99.04	1.00 (referent)	1.00 (referent)	0.066
40–50	297	0.32	14,112	0.42	0.76 (0.68, 0.85)	0.91 (0.81, 1.03)	
30–40	188	0.20	7946	0.24	0.85 (0.74, 0.98)	0.98 (0.84, 1.13)	
20–30	111	0.12	4351	0.13	0.92 (0.76, 1.11)	0.95 (0.79, 1.15)	
10–20	106	0.11	5047	0.15	0.76 (0.62, 0.92)	0.86 (0.70, 1.04)	
0–10	16	0.02	721	0.02	0.80 (0.49, 1.31)	0.98 (0.59, 1.61)	

[a] Adjusted for birth year, public health region, child's sex, maternal race/ethnicity, age, education, and gestational length

Table 6 Maternal residential proximity to nuclear facilities and LBW in offspring (sensitivity analyses on distance thresholds) (a) Sensitivity analysis I; (b) Sensitivity analysis II; (c) Sensitivity analysis III

Proximity (km)	Cases		Control		Unadjusted OR (95% CI)	Adjusted OR (95% CI)[a]	*p* value for trend
	n	%	*n*	%			
(*a*)							
>100	79,570	99.11	2,838,585	98.88	1.00 (referent)	1.00 (referent)	0.077
40–50	297	0.37	14,112	0.49	0.75 (0.67, 0.84)	0.92 (0.82, 1.03)	
30–40	188	0.23	7946	0.28	0.84 (0.73, 0.98)	0.98 (0.85, 1.14)	
20–30	111	0.14	4351	0.15	0.91 (0.75, 1.10)	0.95 (0.79, 1.15)	
10–20	106	0.13	5047	0.18	0.75 (0.62, 0.91)	0.86 (0.71, 1.04)	
0–10	16	0.02	721	0.03	0.79 (0.48, 1.30)	0.98 (0.59, 1.61)	
(*b*)							
>50	92,526	99.77	3,327,655	99.72	1.00 (referent)	1.00 (referent)	0.172
20–25	91	0.10	3597	0.11	0.91 (0.74, 1.12)	0.93 (0.75, 1.14)	
15–20	72	0.08	3430	0.10	0.76 (0.60, 0.95)	0.80 (0.63, 1.01)	
10–15	34	0.04	1617	0.05	0.76 (0.54, 1.06)	1.00 (0.71, 1.41)	
5–10	14	0.02	605	0.02	0.83 (0.49, 1.41)	1.03 (0.60, 1.75)	
0–5	2	0.00	116	0.00	0.62 (0.15, 2.51)	0.72 (0.18, 2.94)	
(*c*)							
>50	92,526	99.55	3,327,655	99.46	1.00 (referent)	1.00 (referent)	0.122
20–40	299	0.32	12,297	0.37	0.87 (0.78, 0.98)	0.97 (0.86, 1.09)	
0–20	122	0.13	5768	0.17	0.76 (0.64, 0.91)	0.87 (0.73, 1.04)	

[a] Adjusted for birth year, public health region, child's sex, maternal race/ethnicity, age, education, and gestational length

directly measured data on radiation exposure were available, the study applied a proximity-based model that used a non-continuous function of distance as a proxy of ionizing radiation exposure to categorize the LBW cases/controls. To improve the accuracy of exposure assessment, future research may consider using biomarker testing or portable radiation measurement instruments to measure directly and/or using a Gaussian dispersion model to simulate the dispersion of ionizing radiation including dependence on preferred wind direction. Third, this study categorized cases/controls into proximity groups using maternal residential addresses at delivery, assuming that maternal residential addresses were unchanged from conception to delivery. While it was true for most mothers, some mothers might have changed their residential locations during pregnancy (Canfield et al. 2006; Lupo et al. 2010), and the movement may have caused proximity group misclassifications for those mothers. However, since the movement tended to involve short distances, its effect on the proximity-based model might be minimal (Lupo et al. 2010).

This study has several strengths. First, its study area and study population were much larger than those in the previous studies. This study is also the first attempt to investigate the "Nuclear Facilities-LBW association" in the southern USA. Second, the study also tested the sensitivity of proximity-based model to the distance thresholds, which was missing in most of existing studies. Last but not least, this study summarized and modified the methods used in the literature and proposed a complete methodology framework for study "Nuclear Facilities-LBW association" which covered the whole analyzing process from data collection to sensitivity analysis. The framework can be conveniently applied to other study areas and health outcomes and therefore can be used as a standardized protocol for the investigation of similar problems.

Conclusion

In this large population-based, case–control study, none of the exposed groups exhibits a statistically significant increase in LBW risk when compared to the reference group. These results were confirmed by the results of the sensitivity analyses. In summary, analysis results based on data in Texas during 1996–2008 suggest that there is no significant association between maternal residential proximity to nuclear facilities and LBW in offspring.

Acknowledgements Some of the data used in the analyses were provided by the Center for Health Statistics in the Texas Department of State Health Services (DSHS). The authors appreciate the support from the Texas Department of State Health Services.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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