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There's a World Going on Underground—Infant Mortality and Fracking in Pennsylvania

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Abstract

Background: There has been a rapid global development of the horizontal drilling and hydraulic fracturing process termed fracking. This involves the dispersion of "produced water" which contains naturally occurring radioactive material (NORM) which may contaminate surface water and pose a health risk. **Objectives:** To investigate association between early (0-28 days) infant mortality by county in Pennsylvania and fracking. **Methods:** We compared early infant mortality for 2007-2010 after fracking developed with a control period 2003-2006, contrasting a group of the 10 most heavily fracked counties with the rest of Pennsylvania. **Results:** Whilst early infant deaths decreased by 2.4% in the State over the period, in the 82,558 births in the 10 fracked counties there was a significant increase in mortality (238 vs 193; RR = 1.29; 95% CI 1.05, 1.55; p = 0.011). For the five north east fracked counties Bradford, Susquehanna, Lycoming, Wyoming and Tioga the combined early infant mortality increased from 34 deaths to 60 (RR 1.66; 1.05, 2.51; p = 0.014), whereas in the south western 5 counties Washington, Westmoreland, Fayette, Butler and Greene the increase was modest, 157 to 178 (RR 1.18; 0.95, 1.46; p = 0.13). Increased risk was associated with exposure to groundwater, expressed as the county ratio of water wells divided by the number of births. **Conclusions:** Fracking appears to be associated with early infant mortality in populations living in counties where the process is carried out. There is some evidence that the effect is associated with private water well density and/or environmental law violations.

Keywords

Fracking, Hydraulic Fracturing, Unconventional Gas, Infant Mortality, Radioactivity, Pennsylvania, Radium, Uranium

1. Introduction

New unconventional gas extraction technology, involving horizontal drilling and explosive hydraulic fracturing of underground rock strata has been termed "fracking" a term which we employ here. The economic advantages of fracking have led to a rapid and on-going growth in the extraction of natural gas globally [1]. The method involves the explosive destruction of large volumes of underground gas and oil retaining rocks and the pumping down of large amounts of what is termed "produced water" which initially contains various chemical and sand additives [2] [3]. This produced water and backflow returns to the surface with a high load of dissolved and suspended solids including naturally occurring radioactive elements Uranium, Thorium, Radium and their decay products, collectively termed NORM (Naturally Occurring Radioactive Material) [2] [3] [4] [5] [6]. The contaminated water has to be safely disposed of but this is often associated with violations of legal disposal constraints.

It has long been known that Radium dissolved in fracked pore water or adsorbed on clay particles and grain coatings can dissolve and return to the surface in produced water [7] [8] a fact that has led to tightening of controls over radioactivity in the conventional oil industry. Radium and Total Dissolved Solids (TDS) in produced water are positively correlated [9] [10]. Radium is released though variation in ionic strength (salinity) differentials (Sturchio *et al.* 2001). As an example, over the course of 20 days, Radium concentration in flowback from a Marcellus Shale gas well in Greene County Pennsylvania increased by almost a factor of four from 74 Bq/L to 240 Bq/L [9] [11]. These high Radium activities are pointers to a more general radiological contamination of produced water from the ingrowth of Radium progeny and other dissolved radionuclides [12] [13]. These are radiologically significant activity levels; for example, the US Environmental Protection Agency (EPA) limit for Radium in drinking water is 0.185 Bq/L and for all NORM alpha is 0.555 Bq/L. These and other considerations have led to concerns about possible contamination of surface waters and local drinking water [14] [15] [16].

The health effects of exposure to low levels of NORM in drinking water even at the current legal limit have been the subject of a number of studies, which collectively raise the issue of the adequacy of this limit and current risk models underpinning it in protecting members of the public from the harmful effects of internal exposures to Uranium, Radium and their progeny [17]-[22]. One of the earliest gas fracking developments where these concerns are relevant was the exploitation of the Marcellus Shale beds in Pennsylvania where shales and sandstones contain significant quantities of NORM [10].

There is general concern about the lack of research into the health effects of fracking [14] [15] [16]. Two recent studies of Pennsylvania examined birth outcomes [23] [24]. In both studies of birth outcomes mothers' exposures were stratified by radial distance from the well head. One study, from 2007 to 2010 demonstrated an effect on birth weight and prematurity; the other which looked at a different database from 2009 to 2013 found a significant trend with preterm birth and doctor concerns about pregnancy risk. This latter was in central and north east Pennsylvania whereas the Stacey *et al.* study [23] examined Butler, Washington and Westmoreland Counties in South West Pennsylvania, counties which are not among the most highly fracked.

There may be another problem with these approaches. Ecological methods employing radial distance from a putative source as surrogate for exposure have been criticized in connection with nuclear site studies [25] [26] [27] since they presuppose a radial dispersion of the exposure, something which is not even true for airborne releases. For example, liquid contaminations generally flow downhill, and airborne contamination downwind; in either case, they are directional. If exposure to contaminated drinking water were a vector for the effect, we feel that the inclusion of a drinking water covariate might have been valuable. Nevertheless, both the studies in Pennslvania suggested an association with adverse effects on infant development, one which we follow up here.

Infant mortality (IM), particularly early (0-28 days) infant mortality (EIM), is an indicator of developmental harm. This may be roughly divided into (1) play of chance, (2) mothers' health and (3) congenital anomalies, which latter nowadays represent about half of the total number of early infant deaths [28]. Foetuses with congenital anomalies inconsistent with survival to term are often aborted in the first trimester [29] [30]. However, other anomalies do not become life threatening until after birth. An *in utero* existence protects the foetus from severe congenital heart defects and abnormalities of the gastrointestinal tract or lungs which only become life threatening after the baby is released from the umbilical connection at birth. In the Canadian Perinatal Surveillance system [29] that there were 45.8% of deaths due to severe congenital anomalies occurring shortly after birth.

Since Chernobyl, it has been increasingly argued that the effects on congenital anomaly rates of internal exposures to low levels of radioactivity are not safely described by current radiation risk models [31] [32] [33]. For example, the post-Chernobyl research reviewed by Schmitz-Feuerhake *et al.* 2016 [32] has directed attention back to an earlier proposed association between infant and perinatal mortality (EIM plus stillbirths) and atmospheric nuclear testing fallout [34] [35].

We therefore decided to examine directly the most obvious easily available indicator of harm, the 0-28 days infant mortality (EIM) trend in each of the 67 Pennsylvania Counties over two balanced 4-year periods, comparing immediately before (2003-2006) with immediately after (2007-2010) the fracking expansion began. These are justified as study periods because there were 44 fracking wells drilled before 2007 but 2864 in the 2007-2010 period [36] referred to in [24]. We further focus on the 10 most heavily fracked counties to see if there is an association between the increased risk of dying at age 0-28 days after fracking expansion began and if so, whether any result may be associated either with density of fracking wells, with exposures to water from private wells, or with violations of legal restrictions on disposal of produced water.

2. Method

Data on the number of live births and number of infant deaths 0-1 year and 0-28 days (EIM) for each of the 67 counties of Pennsylvania for the years 1999 to 2014 were obtained from the Commonwealth of Pennsylvania [37].

Data on the number of fracking wells and violations by county and year were obtained from the website of the Pennsylvania Department of Environmental Protection [38].

Data on the number of water wells drilled in the Pennsylvania counties was obtained from website of the Pennsylvania Department of Conservation and Natural Resources [39].

We first calculated the risk ratio (RR) of EIM rates (per 1000 live births) between the non-fracked and fracked periods as: RR = EIM (2007-2010)/EIM (2003-2006) for each county, for the entire State of Pennsylvania and for the aggregate of all Pennsylvania counties less the 10 most fracked counties. We then mapped the result RR to compare this with a similar map of fracking well density by county to use the simple John Snow method for any apparent associations.

3. Results

Figure 1 shows the counties of Pennsylvania with an indication of the density of fracking by county whilst **Figure 2** shows the Risk Ratio also by county.

In **Table 1** we focus on the 10 most highly fracked counties and the State of Pennsylvania and show the numbers of births and fracking wells drilled in the period 2007-10 and also the number of violations in 2011 by county. In **Table 2** are shown the values of the Risk Ratio and associated statistical results for the most fracked counties and Pennsylvania and also for further aggregation of the fracked counties into those in the North East and those in the South West, since these two areas enjoy different geologies, and we calculate Risk Ratios separately for these two groups. Note that we do not employ ratios of Standardised Mortality Ratios (*i.e.* SMRR = SMRR (2007-10)/SMRR (2003-6) where SMRR = RR (county)/RR (Pennsylvania). This would represent a more accurate indicator but

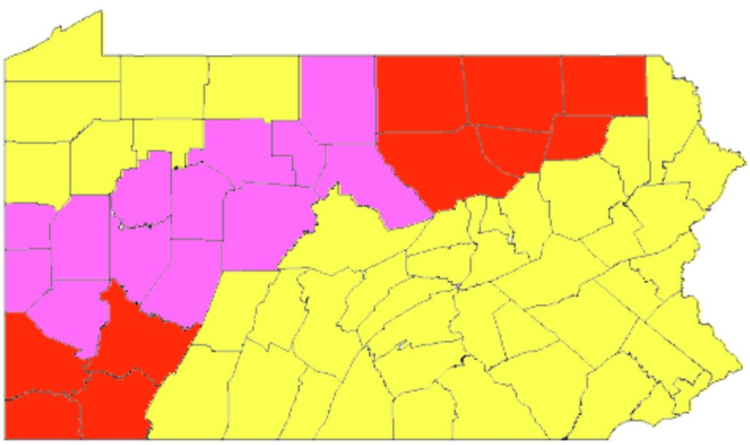

Figure 1. Map of Pennsylvania Counties coloured to show fracking well density range: Many (red), Some (pink), Very few or none (yellow).

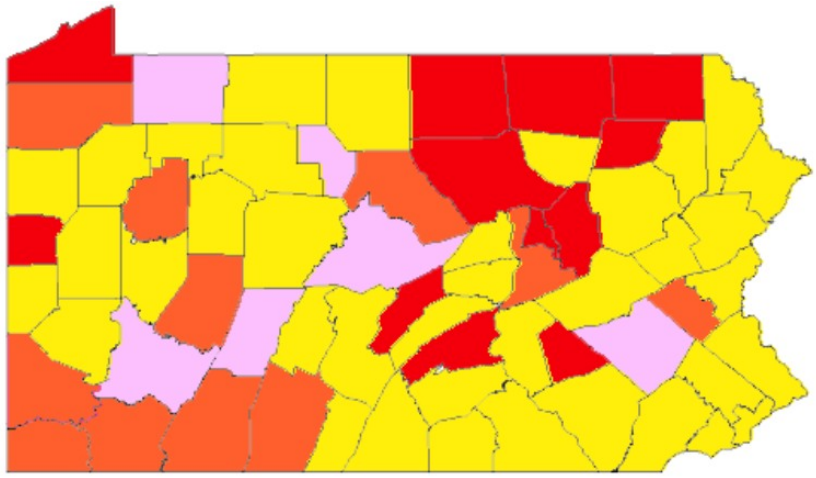

Figure 2. Map of Pennsylvania Counties coloured to show Risk Ratio (RR) of Early Infant Mortality in the 4 years 2003-2006 before, and the 4 years 2007-2010 after fracking expansion. (Legend: below 1.0 (yellow); 1.0 - 1.2 (pink); 1.2 - 1.5 (orange); >1.5 (dark red)).

would only slightly increase any effect tabulated by about 2% because of the slight fall in the EIM ratio for the State of Pennsylvania.

Since we are interested in the clear difference in RR between the north east and south west group we define a water-well index of exposure W which is simply the number of water wells in the county per unit birth. This index W is given in Table 3 for each of the 10 highly fracked counties and in Figure 3 we plot the RR for each county against the Index W.

4. Discussion

There are two questions: 1) Is there a significant increase in EIM in the fracked counties after fracking began? And 2) Can we say anything about the likely cause from the results? The answer to the first question is that there is such an increase, which appears in 9 of the 10 main fracked counties although the small numbers do not permit any statistical certainty for each county on its own. Overall, it is possible to say that for all the 10 counties combined there is a 29% increase in EIM between the 4-year period before fracking began and the 4-year period after it expanded. The two tailed 95% confidence interval for the 29% increase lay between 5% and 55%. If we base this increase on the 2.5% fall in the EIM rates in all Pennsylvania (which becomes about 4% reduction if considering the non-fracked counties) this represents a 33% increase relative to the non-fracked county rate ratio.

Taking all the counties, we have mapped the RR value for each county as a colour code in a John Snow map in Figure 2. This can be compared with Figure 1 where counties are coloured according to the number of fracking wells reported in 2011. It seems clear that there is qualitatively an association between the counties showing the excess risk in the post-fracking period and increased risk of dying in the first month of life.

We have focused on EIM but have also examined infant (0 - 1 y); there are in

Table 1. Counties in Pennsylvania with highest numbers of fracking wells drilled showing births in the periods 2003-6 (before) and 2007-10 (after) fracking expansion, number of fracking wells, number of violations and number of private water wells in 2011 (Source: see text).

County	Births 2003-6	Births 2007-10	Frack wells 2011	Water wells	Violations 2011
			North East Group		
Susquehanna	1658	1653	1079	5463	795
Bradford	2962	2910	1097	7527	765
Wyoming	1243	1236	228	2998	142
Lycoming	5411	5029	832	6548	636
Tioga	1662	1765	661	4611	507
All N. East	12,936	12,593	3897	27,147	2845
			South West Group		
Washington	8250	8170	1146	5052	153
Westmoreland	13505	13261	251	7302	-
Greene	1664	1547	870	2397	111
Fayette	5761	5474	257	1604	-
Butler	8194	7556	321	11,685	-
All S. West	37,404	36,008	2845	28,040	264
			All 10 fracked counties		
All	50,340	48,601	6742	55187	3109
			State of Pennsylvania		
Pennsylvania	583,418	587,098	-	-	-

creases here also in the fracked counties; they are more modest, though still significant, but for the purposes of examining the effects of fracking they do not add to the picture.

One immediate result was the difference in RR between the south west counties and those in the north east. In the 5 north east counties are found a combined RR of 1.67 ($1.1 < RR < 2.51$; $p = 0.014$) but for the south west group we find RR = 1.18 ($0.95 < RR < 1.46$; $p = 0.13$). Comparison of the two groups north east and south west by standardisation [40] gives an Odds Ratio of 2.8 (1.76, 4.36; $p < 0.0001$). This may be relevant in searching for a cause. Two possible explanations are the density of private water wells in the two regions and the number of violations in the regions, both adjusted to the number of births. These may not be independent. In **Table 3** we see that there is almost 3 times the number of water wells in the north east per birth. This is a significant difference at the < 0.001 level. Why could this be important? Because if the increases were driven by contamination of drinking water in private wells, then the effect would not occur in those populations whose water supply were piped from a reservoir, as in the larger towns. It would be those with private wells which would become contaminated, either by surface water contamination from illegally disposed

Table 2. Early infant mortality before (2003-2006) and after (2007-2010) fracking expansion in Counties of Pennsylvania with associated Risk Ratio and Statistics (95% Confidence Interval, p-value). Rates are per 1000 live births.

County	Early infant deaths (EIM) 2003-6 (rate)	Early infant deaths (EIM) 2007-10 (rate)	Risk Ratio (deaths)	*Statistics
		North East Group		
Susquehanna	3 (1.81)	8 (4.82)	2.7	NS
Bradford	9 (3.03)	15 (5.15)	1.7	NS
Wyoming	2 (1.6)	3 (2.43)	1.5	NS
Lycoming	19 (3.5)	28 (5.56)	1.47	NS
Tioga	3 (1.8)	6 (3.39)	2.0	NS
All N East	36 (2.78)	60 (4.76)	1.67*	1.10 < RR < 2.51 p = 0.014
		South West Group		
Washington	30 (3.6)	38 (4.65)	1.27	NS
Westmoreland	62 (4.59)	69 (5.2)	1.11	NS
Greene	6 (3.6)	7 (4.52)	1.17	NS
Fayette	27 (4.67)	35 (6.39)	1.30	NS
Butler	32 (3.9)	29 (3.83)	0.90	NS
All S West	157 (4.19)	178 (4.94)	1.18	0.95 < RR < 1.46 p = 0.13
		All 10 fracked Counties		
All	193 (3.8)	238 (4.9)	1.29*	1.05 < RR < 1.55 p = 0.011
		State of Pennsylvania		
Pennsylvania	3015 (5.17)	2969 (5.05)	0.98	0.93 < RR < 1.03 p = 0.4

*Statistical tests employed conventional Contingency Tables and Chi-Square statistics.

process water, or by contamination of the relevant aquifer following the explosive decomposition of underground strata with the associated release of NORM, hitherto stably adsorbed on rock or shale. In addition, or alternatively, the geology of the north east is shale and sandstone and the aquifers are closer to the surface than in the south west where the geology is granitic, and thus there will also be acidity and mobilisation differences in the groundwater aquifers [39].

For Table 3 also we find that the number of Violations per birth is much greater in the north east than in the south west. We have no information about how this parameter may connect with the water-well density parameter. However, there does seem to be a trend in the central crude RR of each county and an exposure covariate which we have defined as W, the number of water wells in each county per birth. This relationship is shown in Figure 3. There is a significant trend with W in the north-east group but not in the south-west (Chi-square for trend 3.75; p = 0.052).

However, with considerable caution owing to the wide confidence intervals in each county, we can apply some analysis to this. If it were the water-well exposure, we should predict RRs in the north east to show the trend Susq > Tioga >

Table 3. Water wells per birth and violations per annual birth in highly fracked Pennsylvania Counties.

County	Water wells per birth	Violations per birth	RR
	North East Group		
Susquehanna	13.5	1.9	2.7
Bradford	9.7	1.03	1.7
Wyoming	9.45	0.44	1.5
Lycoming	4.9	0.51	2.0
Tioga	11.9	1.16	1.5
All North East	8.4	0.22	1.67
	South West Group		
Washington	2.5	0.08	1.27
Westmoreland	2.1	0	1.1
Greene	5.4	0.25	1.17
Butler	5.7	0	0.9
Fayette	1.13	0	1.3
All South West	3.01	0.007	1.28

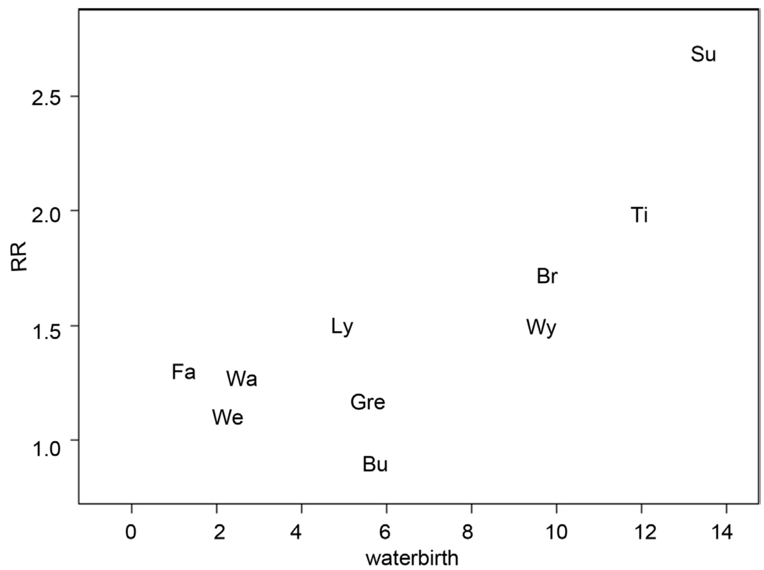

Figure 3. RR for Early infant mortality after fracking plotted against "Exposure" defined as Water Wells per Birth (waterbirth) in the 10 fracked counties of Pennsylvania 2003-2010. (Chi-square for trend is significant in the North East group but not in the South West group).

Bradford = Wyoming > Lycoming.

But we find:

Susq > Tioga > Bradford > Wyoming = Lycoming, which is a good match.

If it were Violations that were driving the effect in the north-east we would expect the trend to be Susq > Lycoming > Bradford > Wyoming = Tioga which is a poor match.

Similar examination of the south-west would suggest Greene would have the highest risk if it were Violations, but the highest RRs are in Washington and Fayette where there are higher W values but zero Violations listed.

The results therefore seem to support the suggestion that the vector for the effect is exposure to drinking water from private wells. This is a mechanistically plausible explanation. However the findings do not prove such a suggestion. We may examine other possible explanations for possible health effects which have been advanced [14]. First, exposure to some kind of airborne contaminant. But such an effect should show a similar RR for the north east and south west counties. Then there are the social disruption arguments, rapid growth in small communities, noise, diesel fumes, effects on herd immunity and so forth; again, these do not persuasively distinguish between the north east and the south west group.

With the drinking water explanation in mind we return to mechanism. We acknowledge the existence of chemical contaminants in the produced water and put such an explanation to one side as a possible but unknown factor. However, we earlier drew attention to recent work focusing on the genetic effects of internal radioactive contamination [32]. The EPA levels for Radium in drinking water (0.18 Bq/L) were calculated on the basis of the concept of absorbed dose, which in turn represents the physical deposition of energy per unit mass of tissue. This is not the same calculation for external exposures as for internal exposures especially to Uranium and Radium, both DNA seekers, for various technical reasons discussed elsewhere [21]. There is already evidence that exposures to low levels of NORM in drinking water causes increased levels of cancer, leukemia and birth defects [17] [18] [19] [20]. A recent example, the increases in heritable effects found in the post Chernobyl studies, particularly those of Wertelecki in the Ukraine, who carefully defined the contamination levels of the mothers by measurement, revealed significant effects at doses that were comparable with those considered by the EPA to be safe [41] [42]. Thus the legal limits of exposure currently believed to protect may now need to be revisited.

Early infant mortality is a flag for genetic damage, and thus represents a "miner's canary" for other ill health effects in children and adults, particularly cancer, though there is a temporal lag in cancer between exposure and clinical expression. Unfortunately, cancer incidence data is not made available for researchers, in certain areas does not exist. The results obtained here would suggest that studies of infant mortality, particularly early infant mortality, can provide an early assessment of risk to putative agents of environmental harm. It is suggested that further research in Pennsylvania might involve comparison of birth outcomes with measurements of NORM in private drinking water wells located near fracking wells.

5. Conclusion

Babies born in the 4 years after fracking expansion (2007-2010) in those counties of Pennsylvania with most wells were 28% more likely to die in the first month than babies born in those counties in the 4 years before fracking began (2003-2006). There were about 50 more babies died in these 10 counties than would have been predicted if the rate had been the same over the period as all of Pennsylvania, where the incidence rate fell over the same period. The association was also greater in the 5 north east counties of Susquehanna, Bradford, Wyoming, Lycoming and Tioga (67% increased risk) than in the 5 south west counties of Washington, Westmoreland, Greene, Butler and Fayette (18% increased risk). There is some analytical evidence based upon the distribution of risk by county that this may be because of differences in the source of drinking water in these counties, with a greater proportion of drinking water being from private wells in the north east than in the south west. Evidence is discussed which supports the contamination of the drinking water by naturally occurring radioactive material, including Radium as a cause of the increased risk.

References

[1] Cueto-Felgueroso, L. and Juanes, R. (2013) Forecasting Long Term Gas Production from Shale. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 19660-19661. https://doi.org/10.1073/pnas.1319578110

[2] EPA (2016) Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States. US Environmental Protection Agency, Report EPA-600-R-16-236ES, Office of Research and Development, Washington DC.

[3] Small, M.J., Stern, P.C., Bomberg, E., Christopherson, S.M., Goldstein, B.D., Israel, A.L., *et al.* (2014) Risks and Risk Governance in Unconventional Shale Gas Development. *Environmental Science & Technology*, **48**, 8289-8297. https://doi.org/10.1021/es502111u

[4] Brown, V.J. (2014) Radionuclides in Fracking Wastewater: Managing a Toxic Blend. *Environmental Health Perspectives*, **122**, A50-A55. https://doi.org/10.1289/ehp.122-A50

[5] Vengosh, A., Jackson, R.B., Warner, N., Darrah, T.H. and Kondash, A. (2014) A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. *Environmental Science & Technology*, **48**, 8334-8348. https://doi.org/10.1021/es405118y

[6] Vidic, R.D., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D. and Abad, J.D. (2013) Impact of Shale Gas Development on Regional Water Quality. *Science*, **340**, Article ID: 1235009. https://doi.org/10.1126/science.1235009

[7] Langmuir, D. and Riese, A.C. (1985) The Thermodynamic Properties of Radium. *Geochimica et Cosmochimica Acta*, **49**, 1953-1601.

[8] New York Times (1990) Radiation Danger Found in Oilfields across the Nation. http://www.nytimes.com/1990/12/03/us/radiation-danger-found-in-oilfields-across-the-nation.html?pagewanted

[9] Rowan, E.L., Engle, M.A., Kirby, C.S. and Kraemer, T.F. (2011) Radium Content of Oil- and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data. USGS Scientific Investigation Report 2011-5135, United States Geological Survey, Reston, Virginia. https://pubs.usgs.gov/sir/2011/5135/

[10] Sturchio, N.C., Banner, J.L., Binz, C.M., Heraty, L.B. and Musgrove, M. (2001) Radium Geochemistry of Ground Waters in Paleozoic Carbonate Aquifers, Midcontinent, USA. *Applied Geochemistry*, **16**, 109-122.

[11] Chapman, E.C., Capo, R.C., Stewart, B.W., Kirby, C.S., Hammack, R.W., Schroeder, K.T. and Edenborn, H.M. (2012) Geochemical and Strontium Isotope Characterization of Produced Waters from Marcellus Shale Natural Gas Extraction. *Environmental Science & Technology*, **46**, 3545-3553. https://doi.org/10.1021/es204005g

[12] Nelson, A.W., Eitrheim, E.S., Knight, A.W., May, D., Mehrhoff, M.A., Shannon, R., Litman, R., Burnett, W.C., Forbes, T.Z. and Schultz, M.K. (2015) Understanding the Radioactive Ingrowth and Decay of Naturally Occurring Radioactive Materials in the Environment: An Analysis of Produced Fluids from the Marcellus Shale. *Environmental Health Perspectives*, **123**, 689-696.

[13] Nelson, A.W., May, D., Knight, A.W., Eitrheim, E.S., Mehrhoff, M., Shannon, R., Litman, R. and Schultz, M.K. (2014) Matrix Complications in the Determination of Radium Levels in Hydraulic Fracturing Flowback Water from Marcellus Shale. *Environmental Science & Technology Letters*, **1**, 204-208. https://doi.org/10.1021/ez5000379

[14] Werner, A.K., Vink, S., Watt, K. and Jagals, P. (2015) Environmental Health Impacts of Unconventional Natural Gas Developments. *Science of the Total Environment*, **505**, 1127-1141.

[15] Shonkoff, S.B., Hays, J. and Finkel, M.L. (2014) Environmental Public Health Dimensions of Shale and Tight Gas Development. *Environmental Health Perspectives*, **122**, 787-795. https://doi.org/10.1289/ehp.1307866

[16] Adgate, J.L., Goldstein, B.D. and McKenzie, L.M. (2014) Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. *Environmental Science & Technology*, **48**, 8307-8320. https://doi.org/10.1021/es404621d

[17] Guseva Canu, I., Laurent, O., Pires, N., Laurier, D. and Dublineau, I. (2011) Health Effects of Naturally Radioactive Water Ingestion: The Need for Enhanced Studies. *Environmental Health Perspectives*, **119**, 1676-1680. https://doi.org/10.1289/ehp.1003224

[18] Lyman, G.H., Lyman, C.G. and Johnson, W. (1985) Association of Leukemia with Radium Groundwater Contamination. *JAMA*, **254**, 621-626. https://doi.org/10.1001/jama.1985.03360050059026

[19] Bean, J.A., Isacson, P., Hausler Jr., W.J. and Kohler, J. (1982) Drinking Water and Cancer Incidence in Iowa. I. Trends and Incidence by Source of Drinking Water and Size of Municipality. *American Journal of Epidemiology*, **116**, 912-923. https://doi.org/10.1093/oxfordjournals.aje.a113493

[20] Cech, I., Patnaik, A., Burau, K.D. and Smolensky, M.H. (2008) Spatial Distribution of Orofacial Cleft Defect Births in Harris County and Radium in the Public Water Supplies: A Persistent Association? *Texas Medicine*, **104**, 56-63.

[21] Busby, C. (2013) Aspects of DNA Damage from Internal Radionuclides. In: Chen, C., Ed., *New Research Directions in DNA Repair*, InTech.

[22] Busby, C. (2015) Editorial: Uranium Epidemiology. *Jacobs Journal of Epidemiology and Preventive Medicine*, **1**, 009. http://jacobspublishers.com/index.php/journal-of-epidemiology-articles-in-press

[23] Casey, J.A., Savitz, D.A., David, A., Rasmussen, S.G., Sara, G., Ogburn, E.L., Pollack, J., Mercer, D.G. and Schwartz, B.S. (2016) Unconventional Natural Gas Development and Birth Outcomes in Pennsylvania USA. *Epidemiology*, **27**, 163-172.

[24] Stacey, S.L., Brink Lu, A.L., Larkin, J.C., Sadovsky, Y., Goldstein, B.D., Pitt, B.R. and

Talbott, E.O. (2015) Perinatal Outcomes and Unconventional Natural Gas Operations in Southwest Pennsylvania. *PLoS ONE*, **10**, e0126425. https://doi.org/10.1371/journal.pone.0126425

[25] Busby, C. (2015) Editorial: Epidemiology and the Effects of Radioactive Contamination: Time for a New Approach. *Jacobs Journal of Epidemiology and Preventive Medicine*, **1**, 003. http://www.jacobspublishers.com/images/Epidemiology/J_J_Epidemiol_Prevent_1_1_003.pdf

[26] CERRIE (2004) Report of the Committee Examining Radiation Risk from Internal Emitters (CERRIE). National Radiological Protection Board, Chilton, UK.

[27] Busby, C.C., Bramhall, R. and Dorfman, P. (2004) CERRIE Minority Report 2004: Minority Report of the UK Department of Health/Department of Environment (DEFRA) Committee Examining Radiation Risk from Internal Emitters (CERRIE). Sosiumi Press, Aberystwyth, UK.

[28] Kramer, M.S., Liu, S., Luo, Z., Yuan, H., Platt, R.W. and Joseph, K.S. (2002) Analysis of Perinatal Mortality and Its Components: Time for a Change? *American Journal of Epidemiology*, **156**, 493-497. https://doi.org/10.1093/aje/kwf077

[29] Adams, M.M. (1995) The Continuing Challenge of Preterm Delivery. *JAMA*, **273**, 739-740. https://doi.org/10.1001/jama.1995.03520330069041

[30] Sheperd, T.H., Fantel, A.G. and Fitzsimmonds, J. (1989) Congenital Defect Rates among Spontaneous Abortions: Twenty Years of Monitoring. *Teratology*, **39**, 325-331. https://doi.org/10.1002/tera.1420390404

[31] Busby, C., Lengfelder, E., Pflugbeil, S. and Schmitz-Feuerhake, I. (2009) The Evidence of Radiation Effects in Embryos and Fetuses Exposed by Chernobyl Fallout and the Question of Dose Response. *Medicine*, *Conflict and Survival*, **25**, 20-40.

[32] Schmitz-Feuerhake, I., Busby, C. and Pflugbeil, P. (2016) Genetic Radiation Risks: A Neglected Topic in the Low Dose Debate. *Environmental Health and Toxicology*, **31**, e2016001.

[33] Busby, C. (2016) Letter to the Editor on "The Hiroshima/Nagasaki Survivor Studies: Discrepancies between Results and General Perception" by Bertrand R. Jordan. *Genetics*, **204**, 1627-1629. https://doi.org/10.1534/genetics.116.195339

[34] Sternglass, E.J. (1971) Environmental Radiation and Human Health. *Proceedings of the 6th Berkeley Symposium on Mathematical Statistics and Probability*, **6**, 145-221.

[35] Whyte, R.K. (1992) First Day Neonatal Mortality Since 1935: A Re-Examination of the Cross Hypothesis. *British Medical Journal*, **304**, 343-346. https://doi.org/10.1136/bmj.304.6823.343

[36] Pennsylvania Department of Environmental Protection (2014) Oil and Gas Reports.

[37] Pennsylvania Department of Health. http://www.statistics.health.pa.gov/HealthStatistics/VitalStatistics/BirthStatistics/Pages/default.aspx

[38] Pennsylvania Department of Environmental Protection. http://www.nytimes.com/1990/12/03/us/radiation-danger-found-in-oilfields-across-the-nation.html?pagewanted=all

[39] Pennsylvania Department of Conservation and Natural Resources. http://dcnr.state.pa.us/topogeo/groundwater/pagwis/records/index.htm

[40] Fleiss, J.L. (1981) Statistical Methods for Rates and Proportions. John Wiley, New York.

[41] Wertelecki, W. (2010) Malformations in a Chornobyl-Impacted Region. *Pediatrics*,

125, e836. https://doi.org/10.1542/peds.2009-2219

[42] Wertelecki, W. (2014) Blastopathies and Microcephaly in a Chornobyl Impacted Region of Ukraine. *Congenital Anomalies*, **54**, 125-149. https://doi.org/10.1111/cga.12051