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Review article

Extremely low frequency electromagnetic fields and cancer: How source of funding affects results

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ABSTRACT

While there has been evidence indicating that excessive exposure to magnetic fields from 50 to 60 Hz electricity increases risk of cancer, many argue that the evidence is inconsistent and inconclusive. This is particularly the case regarding magnetic field exposure and childhood leukemia. A major goal of this study is to examine how source of funding influences the reported results and conclusions. Several meta-analyses dating from about 2000 all report significant associations between exposure and risk of leukemia. By examining subsequent reports on childhood leukemia it is clear that almost all government or independent studies find either a statistically significant association between magnetic field exposure and childhood leukemia, or an elevated risk of at least OR = 1.5, while almost all industry supported studies fail to find any significant or even suggestive association. A secondary goal of this report is to examine the level of evidence for exposure and elevated risk of various adult cancers. Based on pooled or meta-analyses as well as subsequent peer-reviewed studies there is strong evidence that excessive exposure to magnetic fields increases risk of adult leukemia, male and female breast cancer and brain cancer. There is less convincing but suggestive evidence for elevations in several other cancer types. There is less clear evidence for bias based on source of funding in the adult cancer studies. There is also some evidence that both paternal and maternal prenatal exposure to magnetic fields results in an increased risk of leukemia and brain cancer in offspring.

When one allows for bias reflected in source of funding, the evidence that magnetic fields increase risk of cancer is neither inconsistent nor inconclusive. Furthermore adults are also at risk, not just children, and there is strong evidence for cancers in addition to leukemia, particularly brain and breast cancer.

1. Introduction

The first indication that extremely low frequency (ELF) electromagnetic fields (EMFs) coming from power lines and electricity could result in human disease was the report by Wertheimer and Leeper (1979) who found elevations in rates of childhood cancer in children living in homes in Denver, Colorado that were close to power lines which were presumed, based on a variety of considerations, to generate elevated magnetic fields within the home. While this conclusion was received skeptically, subsequent studies in several countries confirmed the observation. Four meta-analyses were published between 1998 and 2000 that concluded that there was a consistent and statistically significantly elevated risk of childhood leukemia in relation to residential proximity to elevated magnetic fields that could not be explained by random variation. Wartenberg (1998) considered 16 studies and reported an odds ratio (OR) of 1.44 (95%CL = 1.10–1.87) from studies that used indirect, wire-code analysis for exposure. Angelillo and Villari (1999) reported an OR = 1.46 (1.05–2.04) for six studies on wire code configuration and OR = 1.59 (1.14–2.22) for 4 studies with 24 h measured magnetic fields. Greenland et al. (2000) conducted their meta-analysis on 15 studies and found an OR = 1.52 (0.99–2.33) based on measured magnetic field for children living in homes with magnetic fields > 0.3 μT as compared to 0.1–0.2 μT, and 1.65 (1.15–2.35) based on wire code comparing children in homes with very high current code as compared to ordinary low current code. Ahlbom et al. (2000) performed a pooled analysis of results of nine studies that included 3203 children with leukemia as compared to 10,338 controls. They found an OR = 2.00 (1.27–3.13) for increased risk of leukemia in children with a residential magnetic field > 0.4 μT. Based primarily on the data included in these reviews the International Agency for Research on Cancer rated extra-low frequency electromagnetic fields (ELF-EMFs) as a Group 2b, possible human carcinogen (IARC , 2002).

In spite of this body of information, many have remained skeptical of the conclusion that exposure to power line magnetic fields really

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increases risk of childhood leukemia. There are several reasons for this, including the general problem that most animal exposure studies have not found increases in cancer, and uncertainty as to the mechanism(s) responsible. Comments are often made that there are a number of studies that do not report positive associations, and thus the conclusions are inconsistent. Therefore the question of whether or not magnetic fields associated with electricity pose hazards to human health has remained controversial. In addition to childhood leukemia, several other human diseases have been reported to be elevated among individuals with excessive exposure to magnetic fields. The goal of this review is to summarize the results of more recent investigations into the magnetic fields and childhood leukemia but also review associations with other cancers. In addition the source of funding of studies will be identified.

The question of whether or not magnetic field exposure causes cancer is extremely important, because in our modern world each of us is continuously exposed. Since there is no one that is unexposed studies must compare individuals with more vs. less exposure. While the risk estimates reported above are not particularly high, when the whole society is exposed to a carcinogen the implication for public health may be large.

2. Materials and methods

This review has been limited to those experimental studies of human cancer in relation to exposure to magnetic fields from power lines or other sources of electricity. Searches were done on pubmed and Google Scholar using the terms magnetic fields, ELF-EMF, power lines or electricity and cancer, leukemia, breast cancer, or brain cancer. For each cancer under consideration the results of recently published pooled or meta-analyses have been accepted and only more recently published additional peer-reviewed publications considered. For childhood leukemia search was for childhood leukemia studies after the meta-analyses published by Wartenberg (1998), Angelillo and Villari (1999), Ahlbom et al. (2000) and Greenland et al. (2000). For adult leukemia and brain cancer, studies were identified subsequent to the meta-analyses of Kheifets et al. (2008), for childhood brain cancer after the meta-analysis of Kheifets et al. (2010b). For male breast cancer studies were considered after the meta-analyses of Erren (2001) and Sun et el. (2013). For female breast cancer studies subsequent to Chen et al. (2013) and Zhao et al. (2014). Su et al. (2018) have published a meta-analysis specifically on parental occupational exposure to magnetic fields and risk of childhood central nervous system cancer. Zhang et al. (2016) published a meta-analysis of ELF-EMFs and all forms of cancer.

References were checked in several very recent reviews on magnetic fields to be sure that English-language, peer-reviewed publications were not missed. These include Kheifets et al. (2006, 2010a, b), Calvente et al. (2010), Zhao et al. (2014), Zhang et al. (2016) and Amoon et al. (2018).

3. Results

Table 1 shows results of peer-reviewed publications published since 2000 that report statistically significant associations between exposure to magnetic fields, either indirectly measured by wire code configuration, distance from the center of the power line (as magnetic fields decline to background over a distance of about 300 m) or directly measured, and childhood leukemia. The table includes numbers of cases and controls and the source of funding. Of these positive studies only one for which the funding source was identified was funded by an industry source.

Table 2 lists studies of childhood leukemia and magnetic field exposure that reported an elevated risk with an OR > 1.5, but for which the results are not statistically significant. All of these studies were funded by government agencies or private sources.

Table 3 lists studies of childhood leukemia and magnetic field exposure which do not show either a statistically significant association, nor have an OR greater than 1.5. All were primarily funded by industrial sources, although in some cases there was partial funding by governmental agencies.

There are three recent studies (Amoon et al., 2018; Crespi et al., 2019; Swanson et al., 2019), all supported by EPRI and National Grid, that have taken a new look at magnetic fields and childhood leukemia, and argue that neither distance from a power line nor measured magnetic fields alone predict risk. The authors acknowledge that there is "a small but consistent increased risk of childhood leukemia associated with exposures above 0.3 or 0.4 μT". Amoon et al. (2018) pooled results from 11 studies, and find a small but imprecise risk of childhood leukemia for residences < 50 m from 200 + KEV power lines, but argue that this result is not explained by high magnetic fields. The others argue that the risk values have been declining over time (Swanson et al., 2019) and, based on a model, that there is some other factor that is responsible for this elevated risk, not only magnetic field strength (Crespi et al., 2019). However they do not identify what other possible factor this might be.

In spite of these apparently discordant data, a recent meta-analysis of associations between measured magnetic fields and childhood leukemia show statistically significant associations (Zhou et al., 2014, government funded). In 11,699 case and 13,194 controls, they report an OR = 1.57 (1.03–2.40) when comparing exposures > 0.4 μT to < 0.1 μT, and OR = 2.43 (1.30–4.55) specifically for acute lymphocytic leukemia. When comparing exposures > 04 μT to < 0.2 μT they find OR = 1.31 (1.06–1.61).

4. Childhood brain cancer

Kheifets et al. (2010b) performed a utility-funded pooled analysis of ELF-EMFs and childhood brain cancer in relation to measured magnetic fields. In relation to 0.1–0.2 μT, those exposed to > 0.4 μT showed an OR = 1.14 (0.61–2.13). Other more recent reports were not found.

5. Adult cancers

The first publication reporting elevated rates of adult cancer in relation to magnetic field exposure was also by Wertheimer and Leeper (1982). They used a wire code to determine magnetic field exposure from neighborhood distribution lines but did not directly measure the magnetic fields: The wire code evaluated how close the line was to the home, how many wires were present, how thick the wires were (thicker wires indicating higher current flow) and how far the home was along the distribution system. The distance from the substation is important because the current flowing through the line decreases as it feeds other residences along the line. They determined wire code assignments into five categories of increasing magnetic fields in the homes of individuals who died from cancer as well as age , sex- and year of death-matched controls. They excluded most cases of lung cancer. They studied five different communities near to Denver, Colorado, and determined the ratio of cancer cases to controls. When comparing the highest to lowest surrogate of magnetic field exposure, the values varied between 121 and 164. (Using this method the value would be 100 if the rates were the same, would be greater than 100 if higher magnetic field posed a risk and less than 100 if magnetic fields were protective). There were statistically significant elevations for brain cancer, lymphoma, cancer of the uterus and breast, as well as non-significantly elevated cancers of the pancreas, bladder, kidney and prostate.

These results showing elevations in rates of several different types of cancer have been confirmed in more recent studies. Hakansson et al. (2002; government funded) investigated cancer in workers exposed to high levels of magnetic fields in industries using resistance welding in Sweden between 1985 and 1994. They studied 537,692 men and 180,529 women, and separated them into groups of low, medium, high and very high exposure based on their job title. Men in the high exposure category had increased incidence of kidney, pituitary gland and liver and biliary cancers, and the rates of these cancers increased with increased exposure. Women in the high exposure group had increased incidence of astrocytoma groups I-IV, and there was a clear exposure-response pattern. There were suggestions of an increase in uterine cancer and multiple myeloma, but these results were not statistically

Table 1
Studies reporting statistically significant positive associations between exposure to 50 or 60 Hz magnetic fields and childhood leukemia, and source of funding.

Authors	Type of measure	Level of Association	Funding
Schuz et al. (2001)	Measured (> 0.2 µT;		
	24 h	OR = 1.55 (0.65–3.67)	Government
	Night only	OR = 3.21 (1.33–7.80)	
	514 cases, 1301 controls		
Draper et al. (2005)	Distance (< 200 m)	RR = 1.69 (1 13-2.53)	Government
	Distance (< 600 m)	RR = 1.23 (1.02–1.49)	
	29081 cases of cancer, 9700 with leukemia, matched controls		
Kabuto et al. (2006)	Measured (> 4 µT)	OR = 4.67 (1.15–19.0)	Government
	312 ALL cases, 603 controls		
Mejia-Arangure et al., 2007 [a]	Measured (> 6 mG)	OR = 3.7 (1.05–13.1)	Government
	42 cases, 124 controls		
Lowenthal et al. (2007)	Distance (< 300 m for ages 0–15 years)		
		OR = 3.23 (1.26–8.29)	Private Foundations
	854 cases lympho- or myeloproliferative diseases, matched controls		
Svendsen et al., 2007 (Survival)	Measured		
	> 0.1 re < 0.2 µT	OR = 2.8 (1.2–6.2)	Government
	> 0.1 re > 0.2 µT	OR = 3.0 (0.9 = 9.8)	
	595 ALL cases		
Schuz et al. (2007)	Measured nighttime		EPRI
	0.1- < 0.2 µT	OR = 1.11 (0.91–1.36)	
	0.2 - < 0.4 µT	OR – 1.37 (0.99–1.90)	
	> 0.4 µT	OR = 1.93 (1.11–3.35)	
	1842 cases, 3099 controls		
Feizi and Arabi (2007)	Calculated (> 0.45 µT)	OR = 3.60, 1.11–12.39)	Not identified
	(70 cases, 69 controls)		
Rahman et al., 2008			Not identified
	Distance (< 200 m to > 200m)	OR = 2.30 (1.1–4.49)	
	(128 cases, 128 controls)		
Yang et al. (2008) [b]	Distance (< 50 m)	OR = 4.39 (1.43–13.54)	Government
	Distance (< 100 m)	OR = 4.31 (1.54–12.08)	
Sohrabi et al. (2010)	Distance (< 600 m) (300 cases, 300 controls)	OR = 2.61 (1.73–3.94)	Not identifiedGov
Tabrizi and Bidgoli, 2015	22 ALL cases 100 controls, prenatal and postnatal to power lines	OR = 3.6 (1.6-7.8)	

EPRI = Electric Power Research Institute.
ALL = Acute lymphocytic leukemia.
[a] Study of children with Down's Syndrome.
[b] Study of children with polymorphorisms of DNA repair genes.

significant. Zhang et al. (2016) performed a government-funded meta-analysis of all forms of cancer in association with ELF exposure. They reported on 42 studies with 13,259 cases, 100,882 controls, and found an overall OR = 1.08 (1.01–1.15). The strongest associations were for breast cancer and leukemia, and studies done in North America were more consistently positive than those from Europe.

6. Adult leukemia

There is a considerable body of evidence specifically on adult leukemia in relation to magnetic field exposure, a focus triggered by the studies of childhood leukemia. Feychting et al. (1997; government funded) studied adult leukemia in relation to both residential and occupational exposures. While neither alone showed significant results, when both sources of exposure were considered there was a significantly elevated risk of adult leukemia (OR = 3.7; 1.5–9.4). In a meta-analysis of data published up through 1997, Kheifets et al. (1997) concluded that most studies showed a small overall increase in risk [risk ratio (RR) = 1.18; 1.12–1.24]. Lowenthal et al. (2007) reported that children living within 300 m of a power line had an elevated (but not statistically significant) risk of developing leukemia (OR = 4.74; 0.98–22.9), while adults living within the same distance showed a smaller but significantly elevated risk (OR = 3.23; 1.26–8.29) (funded by private foundation).

Table 2
Studies showing non-significant elevations in risk with OR > 1.5.

Mizoue et al. (2004)	Distance (< 300 m)	OR = 2.2 (0.5–9.0)	Government
	Lived there long	OR = 3.4 (0.9–13.2)	
Malagoli et al. (2010)	Calculated > 0.1 µT from HVPL	OR = 3.2 (0.4–23.4)	Government
	64 cases, 64 controls		
Wuunsch-Filho et al., 2011	Measured (> 0.3 µT)	OR = 1.09 (0.33–3.61)	Government
	Distance (< 50 m)	OR = 3.57 (0.41–31.44)	
	Distance (< 200 m)	OR = 1.67 (0.49–5.75)	
Sermage-Faure et al. (2013)	ALL, HVPLs in France 2779 cases, 30,000 controls.	OR = 1.7 (0.9–3.6)	Gov/Private
	Distance (< 50 M of 225–400 KEV)		
	Distance (< 50 m of 63–150 KEV)	OR = 1.0 (0.6–1.7)	
Salvan et al. (2015)	409 cases, 569 controls Measured relative to < 0.1 µT		
	0.1–0.2 µT	OR = 1.87 (0,53-1.25)	Government
	> 0.2 µT	OR = 2.24 (1.03–4.88)	
	> 3 µT	OR = 0.75 (0.38–1.50)	

HVPL = high voltage power line.
KEV = killivolts

Table 3
Negative studies of magnetic or electric field exposures and childhood leukemia and source of funding.

UK Childhood Cancer, 2002	Measured (> 20 V/m cf to < 10 V/m) 273 cases, 276 controls	OR = 1.32 (0.73–2.39) All leukemia	Power Comp and private.
Foliart et al. (2007)	Measured 386 cases	No trend observed	EPRI/EDF
Kroll et al. (2010)	Modelled (each > 0.2 µT) 28,968 cases, 28,968 controls	OR = 1.14 (0.57–2.32)	Gov/National Grid
Schuz et al. (2012) (Survival)	Various (> 0.3 µT) 3074 cases	OR = 0.96 (0.49–1.89)	EPRI
Bunch et al. (2014)	Distance (< 200 m) Distance (< 599 m) 53,515 cases of childhood cancer matched to at least one control	RR = 1.12 (0.90–1.38) RR = 0.99 (0.89–1.10)	National Grid
Pedersen et al. (2014)	Distance (< 200 m) Distance (< 599 m) 1698 cases, 3396 controls	OR = 0.76 (0.40–1.45) OR = 0.92 (0.67–1.25)	Danish Energy and Private
Crespi et al. (2016)	Distance ((< 50 m) 5788 cases, 3308 controls	OR 1.4 (0.7–2.7)	EPRI and NCI

Kheifets et al. (2008) have done an extensive meta-analysis of 59 studies of ELF exposure and adult leukemia, including those reported earlier as well as those published since the 1997 report. When considering both the older and newer studies, the RR = 1.16 (1.11–1.22) for all leukemia. The strongest association was for chronic lymphocytic leukemia (CLL) (RR = 1.35; 1.10–1.65). This study was supported by EPRI.

There have been only a few studies since 2008 investigating adult leukemia and ELF exposure. Marcilio et al. (2011) reported on 1857 cases of leukemia and 4706 controls in a study funded by a utility. They report an RR = 1.47 (0.99–2.18) for residence within 50 m, and RR = 1.61 (0.91–2.86) for measured magnetic field > 3 mG. Huss et al. (2018) reported results from the Swiss national registry of 3.1 million death records using a job exposure matrix to different levels of ELF-EMFs as high, medium or low. They report a hazards ratio (HR) = 1.31 (1.02–1.67) for myeloid leukemias and HR = 1.26 (0.93–1.70) for acute myeloid leukemia. There was a non-significant elevation in HR for acute lymphocytic leukemia [HR = 1.21 (0.78–1.89)], chronic myeloid leukemia (CML) [HR = 1.20 (0.71–2.02)] and Hodgkin's lymphoma [HR = 1.27 (0.71–2.29)]. There was little evidence of associations with chronic lymphocytic leukemia, non-Hodgkin's lymphoma or multiple myeloma. Interestingly they also report a dose-dependent increase in lung cancer, although they suspect this is secondary to smoking, not ELF.

6.1. Adult brain cancer

There is also a significant body of evidence showing that exposure to excessive magnetic fields increases the risk of development of adult brain cancer. Kheifets et al. (1995) performed a meta-analysis of 29 reports of brain cancer. She found statistically significant elevations in the incidence of brain cancer among electrical engineers, welders, and power station workers, all of whom are routinely exposed to elevated magnetic fields.

Kheifets et al. (2008) performed a second meta-analysis of occupational ELF exposure and brain cancer in adults, funded by EPRI. On consideration of 47 studies they report an overall RR = 1.14 (1.07–1.22) for all brain cancers, and RR = 1.18 (1.1–1.26) for only glioma. In studies since that date, Coble et al. (2009) (government funded) reported finding no significant associations between job title classified based on expected magnetic field exposure, total years of exposure, cumulative lifetime exposure and average lifetime exposure for glioma (489 cases) or meningioma (197 cases) as compared to 799 controls. Baldi et al. (2011) in a government-funded study investigated adult brain cancer in France with measurement of both occupational exposure and residential distance from the power line. This is one of the few studies that found a higher odds ratio for meningioma [3.02 (1.10–8.26)] (84 cases and 174 controls) than glioma {1.20 (0.66–2.17)] (51 cases and 120 controls). There was no association between living within 100 m of power lines as compared to more than 100 m for glioma [OR = 0.66 (0.21–2.07)] but a non-significant elevated risk for meningioma [OR = 2.99 (0.86–19.40)]. Elliott et al. (2013) reported on adult brain cancer based on 6781 cases and 79,507 controls living or not living within 1000 m of a high-voltage power line, and found an OR = 1.22 (0.86–1.69)] (partial funding from utilities). Turner et al. (2014) (also partial funding from utilities) reported on adult primary glioma (1,939) and meningioma (1,822) from seven countries and based occupational exposure on a job matrix. They found no association with either cancer for life time exposure, but did report elevated associations for glioma [OR = 1.67 (1.36–2.07)] and meningioma [OR = 1.23 (0.97–1.57)] for exposures during the previous four years. They suggest that ELF may function as a promotor or stimulate progression of brain tumors. However Carlberg et al. (2018) (foundation funded) did not find any significant association between occupational exposure to magnetic fields and meningioma based on cumulative exposure, average exposure or maximum exposure.

A report by Carlberg et al. (2017) (foundation funded) drew a similar conclusion to that of Turner et al. (2014) with regard to recent EMF exposure. They studied life time occupational job matrix magnetic field exposure of 1346 glioma cases and 3485 controls, and results were analyzed relative to the grade of glioma. They found no significant association with cumulative µT-years or maximum exposed job, but an OR = 1.3 (1.003–1.6) (p for trend = 0.04) for occupational exposure where the average level was 0.27 µT or greater. For astrocytomas grades I to III (n = 363), there were no significant associations with cumulative exposure, average exposure or maximum exposure, but for astrocytoma grade IV (n = 687), commonly known as glioblastoma, there were significant associations with cumulative exposure of 8.52 µT years or more (0R = 1.5; 1.05–2.1) and average exposure of 0.27 µT or more (OR = 1.4; 1.03–2.0). However the significant associations were only for 1–4 years, 5–9 years and 10–14 years before diagnosis, with no significant association of 20 or more years. Thus these results are quite consistent with the conclusion that exposure in the recent past is important, as suggested by Turner et al. (2014). There was a significant p for trend between level of exposure and grade IV astrocytomas for years 1–14, but not for 15 or more years, and no significant association with all glioma in either 1–14 or 15 or more years. Their conclusion was that occupation exposure to ELF EMF serves as a promotion or progression factor, rather than as an initiator.

Hardell and colleagues have reported a number of studies showing an increased risk of gliomas and especially glioblastomas in individuals that have used mobile phone extensively (Hardell and Carlberg, 2009), and therefore they examined interactions between mobile phone use and ELF exposure on gliomas and astrocytomas grade IV. They did not find any interaction between ELF and mobile phone use for gliomas, indicating that they are independent risk factors. They conclude that radiofrequency EMFs are the major risk factor for gliomas.

6.2. ELF exposure and breast cancer

Erren (2001) reported a meta-analysis of ELF and female breast cancer from 24 studies, and found RR = 1.12 (1.09–1.15). Chen et al. (2010) reported a meta-analysis of 24,338 cases and 60,628 controls in 15 publications in relation to female breast cancer risk. They found no statistically significant associations (OR = 0.988; 0.898–1.088). However a different Chen et al. (2013)] also reported a meta-analysis of case-control studies published between 1990 and 2010 and found an OR = 1.07 (1.02–1.13) for 23 studies. Associations were positive for estrogen-positive and premenopausal breast cancer, but not for other forms. Zhao et al. (2014) have also published a meta-analysis of results of 16 studies published between 2000 and 2007 that reported on pre- and post-menopausal breast cancer. They find an OR = 1.10 (1.01–1.20) overall, and OR = 1.25 (0.93–1.18) for pre-menopausal women. There was no significant association for post-menopausal women. Zhang et al. (2016) also performed a meta-analysis of 23 studies of female breast cancer and reported an OR = 1.07 (1.00–1.15).

Erren (2001) reported a meta-analysis of 15 studies of male breast cancer in relation to ELFs, and found a RR = 1.37 (1.11–1.71). Sun et al. (2013) performed a meta-analysis of 18 studies of male breast cancer in relation to EMF exposures. This included seven case-control and 11 cohort studies. They report a pooled OR = 1.32 (1.14–1.52, $p < 0.001$). All of these breast cancer studies were funded by government agencies. Grundy et al. (2016) investigated occupational exposure to magnetic fields and male breast cancer in 115 cases and 570 controls. They classified magnetic field exposures into three categories based on job histories and duration. They found an elevated risk of breast cancer in men who were exposed to > 0.6 μT [OR = 1.80 (0.82–3.95)] as compared to men exposed to < 0.3 μT. In addition they found that men with any occupational exposure to magnetic fields for at least 30 years had an elevated risk of breast cancer [OR = 2.77 (0.98–7.82)] as compared to men with only background exposure.

6.3. Other cancers

There are also a few studies focused on other specific cancers. Baumgardt-Elms et al. (2002) found no elevated risk of testicular cancer in men who had ever worked near high voltage power lines [OR = 0.7 (0.38–1.18. Charles et al. (2003) reported an elevated risk of prostate cancer mortality in workers at US electric utility companies when comparing those with greater than 4.4 μT-years exposure as compared to those with < 0.6 μt years exposure (funded by EPRI and government). The author suggest that further study is needed on this association.

6.4. Parental ELF exposure and childhood cancer risk

There have been a number of studies of parental exposure to ELF-EMF and cancers in offspring. Feychting et al. (2000) followed 235,635 children from birth to14 years based on parent's job title. They did not find elevations in any childhood cancer based on mother's occupational exposure but did find a significant elevation in risk of leukemia (but not brain cancer) based on father's exposure [RR = 2.0 (1.1–3.5). By contrast Infante-Rivard and Deadman (2003) found an OR = 2.5 (1.2–5.0) for childhood leukemia based on mother's occupational exposure during pregnancy in a government-funded study. In a later study the same group performed a similar investigation of brain cancer in offspring of mothers' with ELF exposure estimated by a job title matrix and reported an OR = 1.5 (1.0–3.4) for astroglial tumors (Li et al., 2009). Among sewing machine operators, who are exposed to high magnetic fields, there was an OR = 2.3 (1.0–5.4) for all childhood brain tumors (government funded). Su et al. (2018) (government funded) performed a meta-analysis of 22 studies (21 case-control and one cohort study) of parental occupational exposure and childhood brain cancer. They report a strong association with maternal exposure [OR = 1.16 (1.06–1.26) and childhood brain cancer and a non-significantly elevated association with paternal exposure [OR = 1.15 (0.98–1.34)].

Pearce et al. (2007) reported on a population based registry of young people with cancer from Northern England, and examined risk of leukemia in offspring of men likely exposed to EMFs based on parental occupation on the child's birth records (funded by foundations). There was a significant elevation in childhood lymphoid leukemia in children whose fathers' occupation was as an electrician [OR = 1.59 (1.12–2.26). Hug et al. (2010) (government funded) studied German children's (ages 0 to 14) risk of developing cancer in relation to parents' pre-conceptual ELF exposure, based on occupation. They had 2382 controls and 2.049 cases, of which 846 were acute leukemia, 159 with non-Hodgkin's lymphoma, 444 with brain tumors and 600 with other solid tumors. They found no elevated risk in children whose fathers had occupational exposure to ELF-EMFs greater than 0.2 μT. Reid et al. (2011), in a government funded study, found no elevated risk of acute lymphocytic leukemia of either maternal [OR = 0.96 (0.74–1.25)] or paternal [OR = 0.78 (0.56–1.09)] occupational exposure. Auger et al. (2019) have reported on 784,944 Canadian newborns followed for one decade (government funded). There were 1114 children who developed cancer. They found a borderline elevated risk for development of any cancer [OR = 1.08 (0.98–1.20)], hematopoetic cancer [OT = 2.04 (0.88–1.23)] and solid tumors [OR = 1.11 (0.99–1.25)] for children living within 80 m of a transformer station as compared to > 200 m. However they did not find any association with living near to transmission lines.

7. Discussion

It is remarkable that in the 40 years after Wertheimer and Leeper (1979) first reported an association between exposure to magnetic fields from residential power lines and elevated risk of childhood cancer, and the large number of subsequent investigations, that there is still controversy over the question “Does exposure to magnetic fields cause cancer?” One contributing cause of the confusion is clear from the analysis of the source of funding. When childhood leukemia studies are funded by governments or private sources they consistently find that elevated exposure increases risk. When those studies are funded by utilities they consistently do not find positive associations. In some cases the same investigators find positive associations when funded by government and then go on to report negative finding when funded by utilities. The differences in findings cannot be explained by numbers of cases or other methodological factors, leading to the conclusion that conflicts of interest based on source of funding have influenced the results, whether this was due to conscious or unconscious design.

A similar finding of different results obtained based on funding source has been reported for use of mobile phones and brain cancer, where reports funded by the industry were least likely to find associations (Huss et al., 2007). Other have also commented on the degree to which ties to industry influences conclusions as to risks of cancer from EMF exposures, and how this goes beyond reports of original research to influences on national and international committees that issue summary reports (Hardell et al., 2006; Maisch, 2006; Starkey, 2016; Hardell, 2017). The overall result arising from these conflicts of interest is that the public is confused and many times the press declares that results are “inconsistent” when in fact they are very consistent if one does not consider the results of industry-funded studies.

While much of the debate as to whether magnetic fields increase the risk of cancer has focused on childhood leukemia, the evidence for an elevated risk for several adult cancers is strong and surprisingly consistent. While there remains a possibility of conflicts of interest here as well, it is not as apparent as in the case of childhood leukemia. But meta-analyses on magnetic field exposure and adult leukemia, brain cancer and breast cancer in both men and women are almost all positive. The data on parental exposure and childhood cancer is less strong and consistent, but there is sufficient indication that there may be an association so as to merit additional study.

The specific mechanisms whereby exposure to magnetic fields increases risk of cancer are still uncertain, but we know that generation of reactive oxygen species and gene induction are involved (Belpomme et al., 2018). The recent animal studies from the Ramazzini Institute also provide additional insight, when considered in light of some of the human studies. Bua et al. (2018) did not detect any increase in cancer in Sprague-Dawley rats exposed to 50 Hz ELF-EMFs over their lifetime. However the same groups demonstrated that there was synergistic cancer promotion when magnetic fields were added to exposure to formaldehyde (Soffritti et al., 2016a) or an acute low-dose of ionizing radiation (Soffritti et al., 2016b). These results are consistent with the suggestion in the reports of Turner et al. (2014) and Carlberg et al. (2017) that magnetic fields function of promotors, not inducers, of cancer.

There are other implications of this analysis. We have accepted results of meta-analyses done by a number of different authors. However in none of these meta-analyses have industry-funded studies been excluded. If studies were included that were biased, the overall conclusions may have been underestimations of the true associations.

While the significant elevations in risk for the various forms of cancer are not large (significant ORs usually not much greater than 2), the reality is that everyone is exposed at various degrees, and therefore there is no unexposed population for comparison. This means that in each study one is comparing disease in individuals with more as compared to less exposure. This also will result in an underestimation of the true risk. The overall evidence presented above shows a clear increase in risk of various cancers associated with elevated field magnetic exposure, but these consideration lead to the conclusion that the actual risk is likely even greater than indicated by the meta-analyses because of bias in some reports as well as in the individual studies and because of the lack of an unexposed comparison population.

In spite of the evidence for there being an elevated risk of various cancers upon excessive exposure to magnetic fields, there has not been a general acceptance that such exposure is a hazard to human health of sufficient magnitude to merit doing anything about it. This represents a failure on the part of international and national institutions, as well as the medical and public health communities, and is in great part a consequence of the distortions promoted by those with clear conflicts of interest. But to have regulators, scientists and the public remain ignorant of the evidence of harm from excessive exposure is unacceptable. The concept of “prudent avoidance”, developed by Granger Morgan (1988) from Carnegie Mellon University some 30 years ago, remains invaluable. We are not going to reduce our use of electricity, but there are many simple ways to reduce excessive exposure to magnetic fields that do not interfere with the quality of life but will reduce the risk of developing cancer.

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