Effects of Electromagnetic Fields on the Reproductive Success of American Kestrels

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ABSTRACT

Reduced reproductive success of birds nesting near power lines has been documented but never directly attributed to electromagnetic fields (EMFs). Laboratory studies have identified EMF effects on embryonic development, but reproductive success of wild birds is dependent on additional factors, including fertility, egg size, hatching, and fledging success. We tested whether EMFs affect reproductive success of birds. Captive American kestrels (*Falco sparverius*) were bred for one season per year for 2 yr under either controlled or EMF conditions. EMF exposure was equivalent to that experienced by wild reproducing kestrels and was weakly associated with reduced egg laying in 1 yr only. In both years fertility was higher, but hatching success was lower in EMF pairs than control pairs. Fledging success was higher in EMF pairs than control pairs in 1995 only. Egg composition and embryonic development were examined in 1 yr only, but hatchlings were measured in both years. EMF eggs were larger, with more yolk, albumen, and water, but had thinner egg shells than control eggs. Late-term EMF embryos were larger and longer than control embryos, although hatchlings were similar in body mass and size. EMF exposure affected reproductive success of kestrels, increasing fertility, egg size, embryonic development, and fledging success but reducing hatching success.

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Introduction

Electrical power lines and towers are beneficial to birds, providing additional sites for perching, hunting, and nesting (Olendorff et al. 1981; Steenhof et al. 1993). Consequently, birds are exposed to electromagnetic fields (EMFs) generated by power lines. EMFs have affected the body mass of reproducing adult male American kestrels (*Falco sparverius*; Fernie and Bird 1999), the melatonin levels of adult and fledgling kestrels (Fernie et al. 1999), the growth of nestlings (Fernie and Bird, in press), and the behavior of adults throughout the breeding season (Fernie et al. 2000).

The potential effects of EMFs on the reproductive success of birds are poorly understood, and results have been equivocal. Overall nest success of raptors and ravens (*Corvus corax*) nesting on a 500-kV transmission line was similar to or higher than pairs nesting on surrounding substrates (Steenhof et al. 1993). However, reproductive success of tree swallows (*Tachycineta bicolor*) was lower under power lines, although this could not be directly attributed to EMF exposure (Doherty and Grubb 1996). Laboratory studies indicate EMF exposure affects early embryonic development, delaying development of chickens (*Gallus domesticus*; Ubeda et al. 1983, 1994; Juutilainen et al. 1987; but see Maffeo et al. 1988; Veicsteinas et al. 1996) and sea urchins (*Strongylocentrotus purpuratus*; Cameron et al. 1993) but, conversely, increasing body mass of chickens (Rooze and Hisenkamp 1985) and mice (Kowalczuk et al. 1994).

Avian reproductive success is a function of fertility, hatching, and fledging success. Furthermore, egg size and composition are positively related to embryonic development, hatching, and fledging success in some birds (Williams 1994; Finkler et al. 1998). However, research to date has not determined whether EMF exposure affects fertility, egg size, hatching, or fledging success. Previous EMF studies used domestic species (e.g., chickens) and artificial incubators to study embryonic development. EMFs can alter temperature and humidity in artificial incubators (I. Ritchie, unpublished data), affecting embryonic development and hatching (Martin 1992). Consequently, we used a wild species breeding in captivity, the American kestrel, with adult birds producing and incubating eggs and raising young, to test the hypothesis that EMFs influence reproductive success of birds.

Material and Methods

Fifty-six pairs of captive American kestrels from the Avian Science and Conservation Centre of McGill University were studied. In 1995, 28 pairs were randomly assigned to the control room, and 28 pairs were randomly assigned to the EMF room. In 1996, new birds were randomly assigned as 13 control pairs and 15 EMF pairs. Pairs were genetically unrelated within the past seven generations. Each bird had previous breeding experience. Within each sex, control and EMF adults were similar in age (2–5 yr old), body size (wing chord length), body mass, and condition at pairing, egg laying, and incubation (Fernie and Bird 1999).

In the control and EMF rooms, humidity, temperature, and photoperiod were similar and mimicked natural field conditions (45°30′N, 73°26′W; Fernie et al. 1999). Noise levels and average light intensity at head level of the birds were similar between rooms (Fernie et al. 1999). Noise levels are indicative of mechanical vibrations from the EMF equipment (D. Nguyen, personal communication).

A 60-Hz electrical current in the EMF room created a magnetic field of 30 microtesla (μT) and an electric field of 10 kV/m. EMFs were equivalent to those experienced by wild kestrels when nesting under a 735-kV transmission line running at peak capacity. The EMFs were controlled by a computer to provide consistent and uniform fields (Nguyen et al. 1991). The magnetic field of the control room was 2 μT, and the electric field was 0.03 kV/m.

Kestrels were paired on May 11, 1995, and May 13, 1996. EMF exposure to pairs began immediately and lasted for 95 d in 1995 and 91 d in 1996, which was 1 wk after the last nestling fledged. Kestrels were exposed to EMFs for approximately 21 h/d in 1995 and 23.5 h/d in 1996. These exposure periods are comparable to those potentially experienced by wild kestrels incubating eggs or brooding nestlings and perch hunting from power lines (Fernie et al. 2000).

Each pair was housed in a visually isolated breeding pen (0.7 × 0.7 × 1.2 m), with a wooden nest box (0.3 × 0.3 × 0.4 m) and rope perch provided. Wood shavings served as bedding and nesting material. Metal materials were minimized to reduce disturbance of the electric field and to reduce the possibility of shocks to the birds (F. Renaud, personal communication). Magnetic fields penetrated all housing materials (D. Nguyen, personal communication).

Nest boxes were checked every morning at feeding (approximately 0800 hours). Newly laid eggs were labeled with a nontoxic marker to indicate when they were laid in the completed clutch. Twenty days after incubation began, as calculated from the lay date of the penultimate egg (Bird 1988), eggs were weighed, candled (Weller 1956) for fertility, and categorized as living or dead embryo, addled, or infertile. Egg length and width were measured to the nearest 0.01 mm using digital calipers, and egg volume was calculated using Hoyt's (1979) equation: volume $(mm^3) = width^2 \times length \times 0.51$. All measurements were performed by the same individual to reduce observer effects.

In 1995, for composition analysis, we collected the third eggs immediately following laying. Eggs were immediately boiled and stored frozen (−20°C) before composition analysis (Ricklefs 1982). Dry weights are reported in Table 2. Eggshell width, measured to the nearest 0.001 mm using a micrometer, was determined using five measurements around the egg's widest circumference.

In 1995, fertile eggs that failed to hatch 7 d after their estimated hatch date were opened. Age at death was calculated using aging criteria established for American kestrels (Bird et al. 1984). Wet mass was recorded to the nearest 0.1 g. Morphometric measurements were taken to the nearest 0.01 mm (digital caliper) on the right side of embryos aged 12 d or older. The total length of the uncurled embryo; length of the midtoe, tarsus, and antebrachium bones; and width of the eyeball were measured (Bird et al. 1984).

Hatchlings were measured in the morning before adults were fed. Body mass was measured to the nearest 0.1 g, and length of the right tarsus and right antebrachium were measured to the nearest 0.01 mm (digital caliper; Negro et al. 1994).

When no year effects were found, data were pooled where appropriate. Differences between treatment groups were tested with Mann-Whitney *U*-tests for clutch parameters and one-way ANOVAs for egg components and hatchling measurements. One hatchling per nest box was randomly selected. A possible association between egg laying and treatment was tested by logit analysis (Sokal and Rohlf 1995). Ratio estimators (Cochran 1977) and *t*-tests determined treatment effects on fertility, hatching, and fledging success. The body mass of each nestling and the volume of the egg from which it hatched were correlated using Pearson's product-moment correlations.

Embryonic growth analyses were restricted to 23–27-d-old embryos because age effects on embryo growth were linear and most of the embryo mortality occurred at this age. Within this sample, a significant amount of variation could be explained by age for all measurements except mass (ANCOVA, $P > 0.45$, $N = 42$). We controlled for age effects by regressing each variable, except mass, against age and by using the residual values. EMF effects on embryonic development were tested in two ways. First, overall growth effects were tested using six linear measurements as input variables in a principal components analysis (PCA). The first principal component (PC1) of the PCA was used as an index of overall embryo size. Second, given the PC1 results, we tested which morphological character was most affected by EMF exposure, analyzing each character separately and using a sequential Bonferroni procedure to correct α values (Rice 1989).

Results

Clutch size, the number of days from pairing to clutch initiation, and the length of the laying sequence were similar between EMF and control pairs (Mann-Whitney *U*-tests, all $P > 0.05$). In both years, 67% or more of the pairs laid one clutch (Table 1). Second clutches were not laid. EMF exposure was weakly associated with a reduction in the number of pairs laying a clutch in 1995 ($\chi^2_1 = 3.19$, $P = 0.07$) but not in 1996 ($P = 0.55$).

Fertility was higher in EMF clutches than in control clutches in 1995 ($t_{47} = -2.10$, $P < 0.05$) and in 1996 ($t_{18} = -7.18$, $P < 0.001$; Table 1). Fertility was higher in 1995 than in 1996 ($t_{67} = 19.48$, $P < 0.001$).

Mean egg volume per clutch was larger for EMF clutches (13.8 ± 0.3 cm^3) than for control clutches (12.9 ± 0.4 cm^3; $F_{1,65} = 4.43$, $P < 0.05$). Individual EMF eggs used for composition analysis were also larger in volume than control eggs ($F_{1,42} = 6.48$, $P < 0.05$; Table 2). EMF eggs had heavier yolks ($F_{1,42} = 6.48$, $P < 0.01$) and albumen ($F_{1,42} = 4.29$, $P < 0.05$) and contained more water ($F_{1,42} = 4.17$, $P < 0.05$). Eggshells of EMF eggs tended to be thinner than control eggshells ($F_{1,42} = 3.12$, $P < 0.08$). EMF exposure had no effect on lipid content or water loss from fertile eggs after 20 d of incubation (all $P > 0.89$). After correcting for egg volume (dividing components by volume), EMF eggs had significantly thinner eggshells ($F_1 = 8.80$, $P < 0.01$; Table 2) and slightly more dried albumen ($F_1 = 3.42$, $P = 0.07$) than control eggs.

In 1995, EMF embryos were structurally larger overall (PC1, $F_{1,21} = 5.93$, $P < 0.05$) and longer ($F_1 = 11.67$, $P < 0.01$) than control embryos. EMF embryos were 45.5 ± 0.8 mm long, and control embryos were 41.3 ± 0.9 mm long.

EMF and control hatchlings were similar in body mass and size (tarsus, antebrachium lengths; all $P > 0.12$). Egg volume was not correlated with body mass of hatchlings (all $P > 0.46$).

Hatching success, measured as the percentage of fertile eggs that hatched, was lower in EMF clutches than control clutches in 1995 ($t_{47} = 2.00$, $P < 0.05$) and in 1996 ($t_{18} = -2.11$, $P < 0.05$; Table 1). Hatching success was lower in 1995 than in 1996 ($t_{35} = -3.36$, $P < 0.01$).

Fledging success, the percentage of hatched young within a clutch that fledged from the nest, was higher in the 1995 EMF group than in the control group ($t_{47} = -9.17$, $P < 0.001$; Table 1). All 1996 hatchlings fledged, but sample sizes were small ($N < 3$ per group).

Discussion

To the best of our knowledge, this is the first study that identified that EMF exposure directly affected reproductive success of birds, used a wild species under controlled EMF conditions, and used natural incubation to identify EMF effects on embryonic development. EMFs had no effect on clutch size, the period of clutch formation, or clutch initiation date. These parameters for the American kestrels used in this study were consistent with data for captive and wild American kestrels (Bird 1988).

Fertility was higher for EMF pairs than for control pairs, although observed copulatory rates were similar between groups (Fernie et al. 2000). In contrast, Sikov et al. (1984) found that fertility was unaffected in rats exposed to a 10-fold-higher electric field (100 kV/m) than was used in our study. Light intensity (Davis et al. 1993) and elevated ambient temperatures (McDaniel et al. 1995) affect fertility in birds but were similar between the EMF and control rooms (Fernie et al. 1999). We can offer no explanation for the better fertility of EMF pairs.

EMF clutches were larger in volume than control clutches. In some birds, egg size increases with laying date and rising ambient temperatures (Perrins 1996). Cold temperatures during follicular and egg development reduced (Magrath 1992) or increased egg size (Williams and Cooch 1996). Yet laying dates were similar for control and EMF pairs, as were temperature and humidity between the two experimental rooms. Prey or food availability can influence egg size of raptors (Hakkarainen and Korpimäki 1994; Wiebe and Bortolotti 1995). However, kestrels in this study were fed ad lib. before and throughout the reproductive season, and there were no EMF effects on courtship feeding rates (Fernie et al. 2000) or food intake (Fernie and Bird 1999).

The larger volume of EMF eggs cannot be explained by differences between parent birds. EMF and control females were similar in body size, mass, and condition at pairing and during egg laying (Fernie and Bird 1999). Mean egg volume was positively correlated with body condition of female American kes-

Table 1: Reproductive traits of American kestrels exposed to electromagnetic fields (EMFs) or controlled conditions for one breeding season per year, 1995 and 1996

	1995		1996	
Variable	Control (%)	EMF (%)	Control (%)	EMF (%)
Pairs, one clutch laid ……	96	79	77	67
Fertility/total eggs ……….	46.8 ± 7.1	50.9 ± 6.5*	6.1 ± 3.1	35.6 ± 12.6***
Hatch/fertile eggs ………..	13.6 ± 4.2*	11.1 ± 4.3	33.3 ± 5.9*	12.5 ± 12.1
Fledging/hatched ……….	57.1 ± 4.7	71.4 ± 6.2***	100[a]	100[a]

[a] All 1996 hatchlings fledged, but sample sizes were small ($N < 3$ per group).

* $P < 0.05$.

*** $P < 0.001$.

Table 2: Components of eggs laid by American kestrels exposed to electromagnetic fields (EMFs) or controlled conditions for one breeding season, 1995 only

Variable	Control	EMF	*F* Value[a]	*P* Value
Sample size (number of eggs)	25	19		
Not corrected for volume:				
Volume (cm^3)	13.99 ± 2.00	14.65 ± 1.83	5.56	.02
Shell width (mm)	.145 ± .002	.138 ± .004	3.12	.08
Yolk (g)	1.54 ± .02	1.65 ± .04	6.48	.01
Albumen (g)	.40 ± .02	.47 ± .02	4.29	.05
Water (g)	8.14 ± .16	8.61 ± .15	4.17	.05
Corrected for volume:				
Shell width (mm)	1.0 ± .02 × 10^{-5}	.9 ± .03 × 10^{-5}	8.8	.01
Albumen (g mm^3)	2.9 ± .1 × 10^{-5}	.32 ± .01 × 10^{-5}	3.42	.07

[a] df = 1, 42.

trels before egg laying (Wiebe and Bortolotti 1995). Furthermore, younger females and females with minimal breeding experience produce smaller eggs in some species (Williams et al. 1993; Hipfner et al. 1997). Age and breeding experience were controlled for and were similar between EMF and control groups (Fernie and Bird 1999).

The larger volume of EMF eggs is not a function of clutch size and laying sequence, as in some species (Slagsvold et al. 1984; Williams 1994). Clutch sizes were similar between treatments, and the effect of laying sequence was eliminated by using the mean volume per clutch. Consequently, increased egg volume per clutch was a function of EMF exposure.

The thinness of EMF eggshells may be a function of the EMFs acting on the adult female, disrupting the deposition of shell in the oviduct. Furthermore, while egg size increased, the calcium supply within the female did not increase proportionally to maintain eggshell thickness in relation to the larger egg size. The thinness of EMF eggshells is not related to embryonic skeletal development because eggshell thickness was measured in freshly laid eggs when shell resorption was minimal.

EMF exposure increased embryonic growth in 1995 through the larger volume, yolk, albumen, and water content of EMF eggs. The increase in albumen and yolk is consistent with changes in egg size of other bird species (Mills 1979; Ankney 1980). Albumen and water content are the main factors determining near-term embryo size (Finkler et al. 1998). The larger and longer EMF-exposed kestrel embryos are consistent with similar studies of EMF-exposed mouse fetuses (Kowalczuk et al. 1994) but contrast with other research in which EMF exposure either had no embryonic effects (Maffeo et al. 1988; Kowalczuk et al. 1994; Veicsteinas et al. 1996) or caused disruption to early embryonic development of chicks, sea urchins, rats, and mice (Ubeda et al. 1983, 1994; Juutilainen et al. 1987; Cameron et al. 1993).

Hatching success of kestrels was reduced by EMF exposure. In contrast, prenatal mortality was unaffected in rats (Burack et al. 1984; Sikov et al. 1984). The reduced hatching success of the larger EMF eggs was surprising, as larger eggs have better hatching success in several bird species (Wiebe and Bortolotti 1995; Amundsen et al. 1996; Perrins 1996). Smaller female kestrels had poorer hatching success (Bortolotti and Wiebe 1993), but EMF and control females were similar in body size and mass before and during incubation (Fernie and Bird 1999).

Kestrel eggs and associated embryos that failed to hatch showed no visible deformities. Most of these unhatched embryos had died within 5 d before hatching. Death of older ostrich (*Struthio camelus*) embryos was related to malpositioning and edema (Brown et al. 1996). Malpositioning of embryos was, unfortunately, not recorded in our study. Edema is correlated to water loss and egg size; heavier eggs lose proportionally less water (Martin and Arnold 1991). Eggshell thickness and porosity affect shell conductance, which governs water loss and oxygen regulation (Vleck and Vleck 1996). Although the EMF eggs were heavier (Fernie 1998) and had thinner eggshells, water loss from fertile EMF eggs at 20 d of incubation was similar to controls. Shell porosity and gaseous exchange were not measured but require further study given the thinner eggshells and poorer hatching success of EMF pairs.

The larger size of the EMF embryos may also explain the reduced hatching success of the EMF pairs, particularly because hatchlings were similar in body mass and size between groups. EMF exposure may have affected the thyroid hormones, growth hormone, and/or insulin-like growth factors of these embryos, as these parameters are involved in embryonic development (Schew et al. 1996; McMurtry et al. 1997). EMF exposure affected melatonin in fledgling and adult male kestrels (Fernie et al. 1999).

Although the EMF young hatched from larger eggs, there was no correlation between egg size and hatchling mass. A lack of correlation between egg size and body mass is also reported for other birds (Williams 1994).

Although EMF eggs were larger than control eggs, EMF hatchlings were similar in body mass and size but had better fledging success than controls. These results do not support the hypothesis that egg size has no residual effect on chick survival until fledging (Williams 1994). Furthermore, our results contrast with the reduced fledging success of tree swallows under power lines (Doherty and Grubb 1996). The better fledging success of the 1995 EMF group may be related to the EMF nestlings being heavier and larger than the control nestlings (Fernie and Bird, in press). Our results indicate that EMFs increase the mortality of young before hatching but have no adverse effect on fledging success.

The fertility, hatching, and fledging success of the control and EMF kestrels within our experiment are lower than the average success of 75% or more for captive and wild American kestrels (Bird 1988). The low reproductive success in our study and, particularly, the reduced hatching success of 1995 versus 1996, are very likely a function of the high degree of disturbance as previously observed with captive kestrels (Muir 1995).

In summary, EMF pairs had higher fertility but poorer hatching success. Fledging success was higher in 1995 EMF pairs than controls. Mean egg volume, egg components, and embryonic growth were greater in the EMF group, but EMF eggshells were thinner than control shells. EMF exposure had no effect on hatchling mass or size, and there was no correlation between egg size and hatchling mass. EMF exposure to adult American kestrels affected reproductive success, particularly increasing fertility, egg size, embryonic development, and fledging success but reducing hatching success.

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