5. **Comparing Laboratory and Human Exposures**

Studies of the bioeffects of power-frequency fields described in the preceding sections, involve many different subjects, exposure systems, and exposure regimens. Animal studies have examined field effects on rats, mice, miniature swine, cows, guinea pigs, and chicken eggs. in vitro studies have employed perfused nervous system tissue, cell cultures, and entire organs (e.g. heart, brain). This section describes electric and magnetic induction in these experimental systems and presents a comparison of the exposures in several specific experiments to the exposures in the set of common human exposure situations described in Section 2.6.

5.1. Laboratory Animals - Electric Induction

The factors that most affect electric induction are body shape, the orientation of the body relative to the field, and body grounding. The charge induced on the surface of the body is independent of both body size and the conductivity of body tissue. The conductivities of various body tissues do, however, affect the specific paths that induced currents take through the body.

Rough estimates of body-averaged quantities can be obtained from simple theoretical models such as those by Barnes and colleagues [Barnes 67] which approximate the body as an elongated sphere. Table 5-1 gives the body-average internal electric fields and current densities that such models predict for a number of different species under several exposure conditions.

The data in Table 2-9 show clearly that electrically-induced fields and currents are most intense when the applied field is parallel to the long axis of the body. For such a condition, the data also show that induced fields are greatest for the most elongated species (i.e. humans). Finally, these calculations indicate that body-average exposure intensity is more intense when the body is grounded than when it is ungrounded.

5.2. Laboratory Animals - Magnetic Induction

By Faraday's law, the intensity of the current induced at any point in the body by a spatially uniform magnetic field is proportional to the rate of change of flux through all closed current paths that include that point. This means that both magnetically-induced current density and magnetically-induced electric fields will tend to zero near the body center and reach maximum values at those areas of body surface that lie most parallel to the applied magnetic field. Both peak and volume-averaged magnetically-induced electric field and current density tend to scale with body radius.

Estimates of magnetically-induced electric fields and currents come primarily from theoretical models that treat the body as a homogeneous sphere, spheroid, or ellipsoid [Kaune 86, Spiegel 76, Spiegel 77]. A limited number of measurements have been made of magnetic induction in homogeneous human models [Guy 76]. These measurements demonstrate the presence of local induced fields that are several times stronger than volume-average values.

Using the same approach adopted above for comparing body-average electric induction in animals and humans, we have computed the magnetically-induced volume-averaged current density and the volume-averaged electric field induced in a set a spheroids with dimensions chosen to approximate the shape of several species including man. Our calculations are based on an analysis by Kaune that can be used to estimate the electric field at any point within a homogeneous spheroid exposed to a uniform

Table 5-1: Electric induction in various species by a 60 Hz uniform electric field of 1 kV/m. E_i is the average magnitude of internal electric field, and J_i is the volume-averaged current density. Estimates are presented for the field both parallel and perpendicular to the long axis of the body and for both the grounded and ungrounded condition. a/b is the ratio of the lengths of the long and short axes of the elongated sphere used to approximate body shape. Induced electric field is given in millivolts per meter. Current density is given in nanoamps per square centimeter. Adapted from [Barnes 67].

Specie	a/b	Grounding	Field orientation relative to long axis	E_i (mV/m)	J_i (nA/cm^2)
Human	5.5	Grounded	Parallel	1.0	**20.**
Human	5.5	Ungrounded	Parallel	.35	**7.**
Human	5.5	Ungrounded	Perpendicular	.035	**.7**
cow	4.5	Grounded	Perpendicular	**.04**	**.8**
cow	4.5	Ungrounded	Parallel	.25	**5.**
cow	4.5	Ungrounded	Perpendicular	.035	**.7**
Swine	**3.0**	Grounded	Perpendicular	.045	**.9**
Swine	**3.0**	Ungrounded	Parallel	.15	**3.0**
Swine	**3.0**	Ungrounded	Perpendicular	.035	**.7**
Mouse/rat	**2.7**	Grounded	Perpendicular	.045	**.9**
Mouse/rat	**2.7**	Ungrounded	Parallel	.13	**2.5**
Mouse/rat	**2.7**	Ungrounded	Perpendicular	**.04**	**.8**
Chick egg yolk*	1.0	Ungrounded	Either	**.02**	**.4**

.Field in yolk estimated using concentric sphere model with conductivities
of **2.5** S/m[15] and **7.2** S/m for yolk and albumin, respectively [Tinga **73].**

magnetic field [Kaune 86]. Magnetic induction was estimated for applied fields both parallel and perpendicular to the long axis of the body. The results of these calculations are presented in Table 5-2.

This analysis shows that magnetically-induced body currents are much larger for large species than for small ones. In comparing the magnetic fields used in lab animal experiments to the fields that humans commonly encounter, one may want to adjust laboratory exposure intensities to account for these differences in magnetic induction. Another conclusion one can draw from Table 5-2 is that induced currents are slightly larger when the field is applied perpendicular to the long axis of the body. This is a consequence of Faraday's Law, which says that induced currents are proportional to the area enclosed by the current loop.

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[15] S/m or, Siemens per meter is the unit for specific conductivity. The Siemen (S) is the same magnitude as the formerly used (ohm)-l '

Table 5-2: Magnetic induction in a homogeneous elongated sphere by a 60 Hz uniform magnetic field of 1 gauss. The long axis of the spheroid, a, and the ratio, a/b, of the lengths of the long and short axes are chosen to approximate the dimensions of various species. E_i is the average magnitude of the magnetically-induced electric field inside the body (in millivolts per meter) and J_i is the average magnitude of the magnetically-induced current density (in nanoamps per square centimeter). Based on analysis by Kaune [Kaune 86].

Specie	a (m)	a/b	Field orientation relative to long axis	E_i (mV/m)	J_i^* (nA/cm^2),
Human	1.7	5.5	Parallel	3.4	68.
Human	1.7	5.5	Perpendicular	4.4	88.
cow	2.5	4.5	Parallel	6.2	120.
cow	2.5	4.5	Perpendicular	8.0	160.
Swine	0.9	3.0	Parallel	3.3	66.
Swine	0.9	3.0	Perpendicular	**4.3**	86.
Mouse	0.08	2.7	Parallel	**0.33**	6.6
Mouse	0.08	2.7	Perpendicular	**0.42**	8.4
Rat	0.17	2.7	Parallel	**0.70**	14.
Rat	0.17	2.7	Perpendicular	0.89	18.
Chick Egg (Yolk)	0.025	1.0	Either	0.28	**200.**

•- Assumed conductivity is .2 S/m except 7.2 S/m for egg yolk [Schwan 57, Tinga 73].

5.3. **In Vitro Experiments**

This section describes the tissue currents associated with some of the in vitro experiments described in Section 3. The preparations used in these experiments include chick brains, cultured blood, cancer, and bone cells, and adrenal tissue. Exposure means include placing the preparation within magnetic field coils, exposing cells to special radio frequency fields in large wave guides, and by placing electrodes directly into their growth medium of the cells.

5.3.1. Pulsed Magnetic Field Exposures

The bioeffects literature contains many references to both in vivo and in vitro experiments that involve exposures to pulsed magnetic fields generated by Helmholtz coils. Many of these experiments involve pulses with rise times of about 100 microseconds and peak magnetic fields of about 10 Gauss. Such systems are capable of inducing peak electric fields of about 1 mV/cm in tissues of 1 cm diameter and proportionately larger electric fields in tissues of larger dimension. For typical tissue conductivities of .2 Siemens per meter, this corresponds to **a** current density of 200 nWcm^2. Induced fields and currents in tissues with dimensions greater than 1 cm are proportionately larger.

5.3.2. ELF-Modulated Radiofrequency Exposures

There are a number of experimental studies (those by Adey [Adey 82], Bawin [Bawin 75], Blackman [Blackman 85a], and Lyle [Lyle 83] being notable examples) that have demonstrated bioeffects of exposures to radiofrequency fields (100-1000 Mhz) that are amplitude-modulated at ELF frequencies (0-100 Hz). Amplitude modulation, as applied here, means that the intensity of the radiofrequency field is varied sinusoidally at ELF frequencies. Because electric fields induced in tissue are proportional to frequency, radiofrequency fields couple much more strongly to tissues than do ELF fields. The radiofrequency fields in the experiments listed above induce radiofrequency fields in the exposed tissue of 1-10 V/m.

Given evidence suggesting that the mechanisms by which fields interact with cells are nonlinear, some scientists have proposed that cells may be capable of "demodulating" amplitude-modulated fields. That is, cells may be able to extract the ELF component of the high frequency field. If this is true, the resulting ELF fields in tissue would be orders of magnitude larger than the ELF fields induced in humans by the power-frequency fields of power lines and appliances.

5.3.3. Calcium Efflux from Chick Brains

Blackman and colleagues have exposed chick brain halves to ELF electric fields to study effects on calcium efflux [Blackman 85a]. Brain halves were placed in test tubes along with enough saline solution to just cover the brain tissue. The test tubes were placed in an exposure chamber capable of creating ELF fields in air of 10-20 V/m. Blackman et. al. estimate that the electric field induced in the exposed brain tissue is about 10^{-7} V/m at 45 Hz and proportionately larger or smaller at other frequencies. This corresponds to an induced current density of .01 nA/cm^2. These intensities are comparable to the electric fields and currents induced in the body of a person standing in a vertical 60 Hz electric field of about 1 V/m.

5.4. Comparison of Exposures in Bioeffects Studies to Common Human Exposure Situations

Comparisons between the exposure conditions of several of the bioeffects studies described in Sections 4-3 and the exposures that people commonly encounter can, of course, be made along many different exposure dimensions. Figure 5-1 compares common human exposure situations with experimental exposures along just one of these dimensions, the volume-averaged, time-peak current density. The experimental exposures listed in Figure 5-1 span the range of common human exposure situations. This same observation is likely to hold for many other measures of exposure that one might choose to examine. In other words, biological effects of power-frequency fields have been demonstrated across the range of exposure conditions that people commonly encounter. Effects are not limited to situations involving only very intense or otherwise unusual fields.
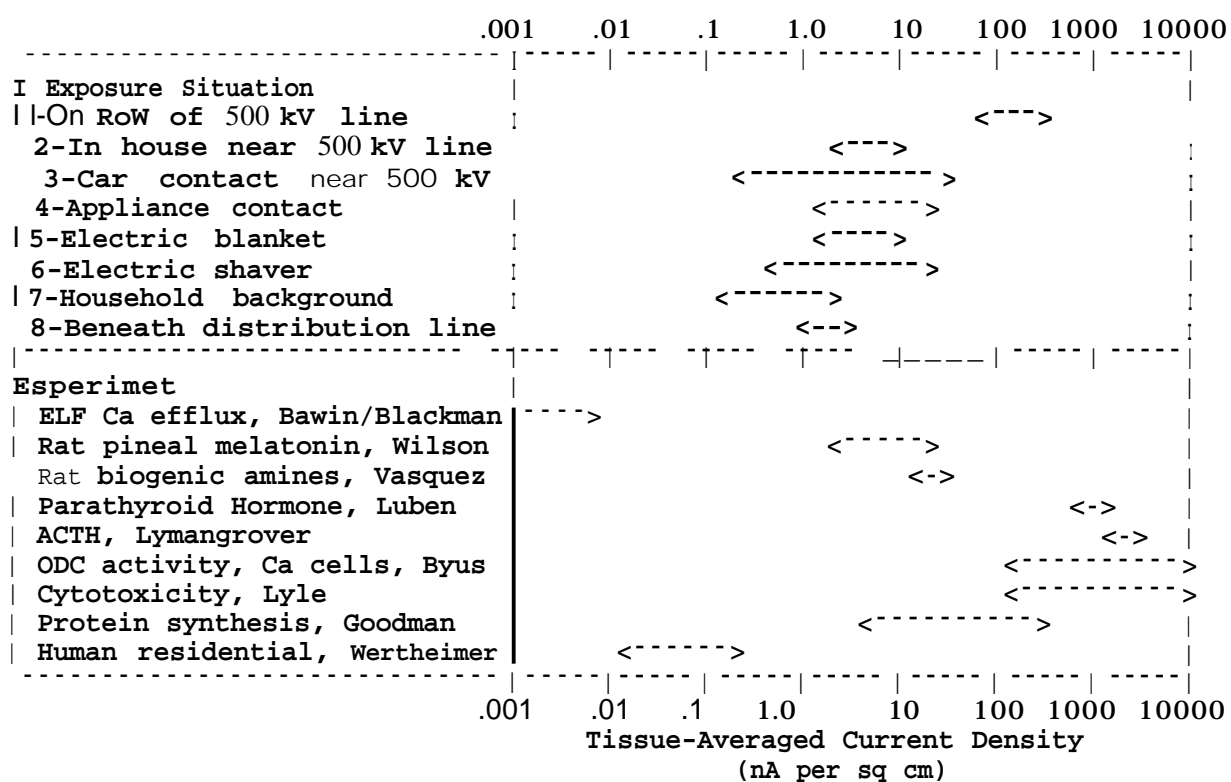
```
                              .001    .01     .1    1.0     10    100 1000 10000
-----------------------------------|-----|-----|-----|-----|-----|-----|-----|
I Exposure Situation               |                                          |
I l-On RoW of 500 kV line          |                           <--->          |
  2-In house near 500 kV line      |                  <--->                    |
   3-Car  contact  near 500 kV     |            <------------->               |
    4-Appliance contact            |            <------->                      |
I 5-Electric  blanket              |            <---->                         |
   6-Electric shaver               |          <--------->                      |
I 7-Household  background           |        <------>                          |
    8-Beneath distribution line    |        <-->                              |
|----------------------------------|----- -|---- -|---- -|--- -+----|-----|-----|
Esperimet                          |                                          |
| ELF Ca efflux, Bawin/Blackman |----->                                       |
| Rat pineal melatonin, Wilson      |              <------>                    |
  Rat biogenic amines, Vasquez      |                   <->                    |
| Parathyroid Hormone, Luben        |                            <->          |
| ACTH, Lymangrover                 |                              <->         |
| ODC activity, Ca cells, Byus      |                        <---------->     |
| Cytotoxicity, Lyle                |                       <---------->       |
| Protein synthesis, Goodman        |              <---------->                |
| Human residential, Wertheimer |      <------>                               |
----------------------------------|-----|-----|-----|-----|-----|-----|-----|
                              .001    .01    .1   1.0      10    100 1000 10000
                        Tissue-Averaged Current Density
                               (nA per sq cm)
```

Figure 5-1: Average current density associated with eight common human exposure situations compared to average current densities in a number of laboratory experiments. Adapted from [Florig 87b].