Electromagnetic Exposure Safety of the Carstens Articulograph AG100

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Abstract

Extremely strong magnetic fields at the frequencies used in an electromagnetic articulometer (EMA) system may pose a risk to the health of a subject. To avoid such risks, the field strengths produced by any EMA system should be measured, and compared to published permissible exposure standards. This letter reports measurements of the 2-50kHz magnetic field strength of the Carstens Articulograph AG100. The measured field strength (35μT at a distance of 7.5cm) is permissible under standards in Austria, Germany, the USA, and the UK, but is not permissible in Canada or Massachusetts, or under the 1995 European Community Prestandard.

I. Motivation

Electromagnetic Midsagittal Articulography (EMA) is a technique for obtaining real-time data about the motion of points on the surface of the tongue and other articulators using relatively low-cost, lightweight, and non-invasive equipment (Schönle, 1987, Perkell, 1992). EMA relies on alternating magnetic fields to measure the distance between fixed transmitter coils and movable receiver coils fixed to the surfaces of the articulators. The Carstens Articulograph AG100 is, at the time of this writing, the only commercially available EMA system capable of correcting for small misalignments of the receiver coils using a redundant third transmitter (Hoole and Nguyen, 1996). Because of its light weight and relative low cost, the Articulograph offers small laboratories a unique opportunity to collect large amounts of articulatory data.

Alternating magnetic fields generate electric current in any conducting medium, including human bones and blood. Fields of moderate strength at the frequencies used in the Articulograph (10-20 kHz) have not been conclusively linked to any health risk, but caution dictates that unnecessary exposure should be minimized. In particular, the American National Standards Institute has endorsed a standard which limits exposure to magnetic fields at frequencies above 3kHz (IEEE, 1992). The purpose of this article is to very briefly review the relevant safety considerations, and to describe measurements which show that the Articulograph AG100 meets the maximum permissible exposure standards endorsed by the American National Standards Institute.

II. Health Risks Associated with Alternating Magnetic Fields

A. General Principles: Magnetically Induced Current

At frequencies below approximately one megahertz, most biological tissue can be modeled as a purely conducting medium, and secondary magnetic fields produced by currents in the tissue can be neglected. This means that the current induced by an alternating magnetic field can be calculated using only Faraday's law and Laplace's equation, without simultaneously solving all of Maxwell's equations (Stuchly, 1995). Estimating the induced current in an object of finite dimension is usually only possible using numerical simulations, but in certain extremely simple cases, the current distribution can be expressed analytically. For example, if the medium is assumed to be infinite and homogeneous, the current density in a circular path of radius r perpendicular to a sinusoidally varying magnetic field of frequency f is

$$J = S\pi r B f \tag{1}$$

where J is the current density (in A/m^2), S is the conductivity of the medium (in $(\Omega m)^{-1}$), and B is the magnetic flux density (in Tesla).

At 10-100kHz, blood has been reported to have a conductivity of 0.55-0.68 $(\Omega m)^{-1}$, while bone and brain tissue have conductivities of approximately 0.0133-0.0144 and 0.12-0.17 $(\Omega m)^{-1}$, respectively (Foster, 1995). Thus, in an infinite conductor with the properties of brain tissue, a field of $100\mu T$ (microtesla) at 20kHz will induce a current density, in a circle of radius 10cm, of approximately 10 $\mu A/cm^2$. For comparison, stimulation of excitable cells requires peak currents at this frequency of more than 700 $\mu A/cm^2$ (IEEE, 1992), while ambient currents in the human body are typically less than 1 $\mu A/cm^2$ (IRPA, 1990) (and most of this energy is concentrated at extremely low frequencies).

The simple model given in equation 1 is useful for demonstrating the approximate relationship between current density, conductivity, flux density, and frequency, but it should be not be used to calculate current densities in a heterogeneous object. In a heterogeneous, finite object such as the human head, interfaces between different media create a series of resonances and anti-resonances, with the result that approximations based on equation 1 can easily be incorrect by more than an order of magnitude. Standards for maximum permissible electromagnetic exposure are typically based on computational and physical studies using realistic heterogeneous models of the human body.

B. Health Risks of Magnetic Fields at Various Frequencies

Alternating magnetic fields generate electric current in any conducting medium. At very high frequencies or very high amplitudes, induced currents can heat biological tissue, causing thermal damage. At extremely low frequencies (ELF: 0-300 Hz), voice frequencies (VF: 300-3000 Hz), and very low frequencies (VLF: 3-30 kHz), tissue heating is not a problem, but if induced currents are too strong, there is a risk that they may stimulate electrically excitable cells. Health effects not linked to cell stimulation or tissue heating have been reported, but only a few of these effects have been demonstrated scientifically, and only at extremely low frequencies.

At frequencies above 100kHz, currents induced by electromagnetic fields can heat biological tissue. Heating of biological tissue can damage it; for example, the role of tissue heating in cataract development is well documented (IRPA, 1988). Tissue heating is also readily detectable by the animal, and even very low levels of electromagnetically induced tissue heating will sometimes cause a non-human primate to stop whatever it's doing, in order to "cool off."

At frequencies below approximately 100kHz, the current necessary to significantly heat biological tissue is greater than the current necessary to stimulate neurons and other electrically excitable cells. At power line frequencies (50-60 Hertz), excitable cells can be stimulated by current densities of 10-100 $\mu A/cm^2$ (IRPA, 1990). At higher frequencies, the threshold for stimulation of excitable cells increases; between 3kHz and 100kHz, the lowest reported thresholds for cell stimulation are greater than $(35f)\mu A/cm^2$, where f is expressed in kilohertz (IEEE, 1992).

At amplitudes which are too low to stimulate excitable cells, ELF electric and magnetic fields (specifically, 60Hz fields) have been conclusively linked to a small number of health effects, and other health effects have been suggested but not proven. According to the review by Stuchly (1995), exposure of healthy male volunteers to 20μT electrical and magnetic fields at 60Hz has been linked to a statistically significant slowing of the heart rate, and to changes in a small fraction of the tested behavioral indicators. There is evidence that nocturnal exposure to 60Hz magnetic fields affects melatonin production. Case studies have suggested that exposure to ELF electromagnetic fields may promote the growth of cancer, but laboratory tests involving rodents have been almost entirely negative.

C. Video Display Terminals and Reproductive Health

The only source of VLF magnetic fields which most people encounter in their daily lives is the horizontal deflection circuitry of a video display terminal or television set. The image on a television set or VDT is generated by an electron beam, which scans the screen in a series of horizontal lines from top to bottom.

The horizontal position of the electron beam is controlled by a VLF magnetic field, with a fundamental frequency of approximately 15-80 kHz. The vertical position of the beam is controlled by an ELF magnetic field, at approximately 30-100 Hz.

Haes and Fitzgerald (1995) have measured the strength of the VLF magnetic field in front of VDTs by a wide variety of manufacturers. The measured fields had flux densities (at a distance of 50cm from the screen) between approximately 0.002 μT and 0.1 μT. As discussed above, this is the strongest VLF field to which most people are routinely exposed; for comparison, the ELF fields produced by standard household appliances are typically in the range of 0.1 μT and 10μT at a distance of 50cm (Gauger, 1985).

Kavet and Tell (1991) describe fourteen epidemiological studies seeking to establish a link between VDT use and either spontaneous abortion or birth defects. Of these fourteen studies, one found a significant link between VDT use and spontaneous abortion, and one found a link between VDT use and first trimester spontaneous abortion; the first of these two was later faulted for interviewer bias in a study summarized by Haes and Fitzgerald (1995).

Kavet and Tell (1991) also describe studies at four laboratories seeking a link between exposure to VLF magnetic fields and reproductive outcome in rodents. The waveforms used in these studies were all sawtooth waveforms similar to those generated by a VDT, at frequencies of 18-20kHz. After scaling to a human equivalent exposure based on "induced current considerations," the maximum field strengths in these studies were 1.25, 1.25, 5.51, and 16.7 μT respectively; in the two studies which tested multiple field strengths, no effect of field strength was reported. Kavet and Tell report that one of the laboratories found a significant link between VLF exposure (at 1.25 μT equivalent) and spontaneous abortion when measured per fetus, but they question the statistical validity of the result, because analysis results per litter were not reported.

A recent epidemiological study by Lindbohm et al. (1992) suggests that chronic exposure to the ELF fields of a VDT, rather than the VLF fields, may increase the risk of spontaneous abortion. For each of their subjects and controls who reported using a VDT during her pregnancy, Lindbohm et al. examined company records to determine the make and model of the VDT, and then measured the ELF and VLF emissions of a similar monitor. They found that VDT use did not increase the risk of spontaneous abortion, but that using

Institution	Occupational	General Public
ACGIH (1996 TLVs and BEIs)	200	
ANSI/IEEE (C95.1-1991)	205	205
Austria		440
Canada (H46-2/90-160E, 1989)	6.16	2.75
European Prestandard (ENV 50166-1, 1995)	52.8	21.1
FRG (VDT 0848 Teil 2, 1986)	314	314
Massachusetts (105 CMR 122.000, 1997)	1.99	
United Kingdom NRPB (1993)		80
USAF (AFOSH 48-9, 1997)	205	205

Table 1: Magnetic field exposure standards at 20kHz, expressed in microtesla.

a monitor with strong magnetic fields did. Using a monitor with "strong" ELF emissions (greater than 0.9 μT) significantly increased the risk of spontaneous abortion, and the risk increased when field strength was weighted by the amount of time the subject used a monitor. Use of a monitor with strong VLF emissions (rate of change greater than 30 mT/s, corresponding to a field of 0.24 μT at 20kHz) caused a non-significant increase in risk, which became significant when weighted by usage time. VLF and ELF emissions of all monitors were highly correlated ($r = 0.76$); when VLF and ELF emissions were considered together, strong ELF emissions were found to increase risk significantly, while strong VLF emissions actually decreased risk by a non-significant amount.

III. Exposure Standards

Table 1 lists a selection of magnetic field exposure standards which apply between 10kHz and 20kHz, and which do not apply exclusively to VDT emissions. Standards originally quoted in units of Amps/meter were converted to microtesla using a conversion factor of $\mu_0 = 4\pi \times 10^{-7} T/(A/m)$. United States standards, including the ANSI/IEEE, ACGIH, Massachusetts, and USAF standards, were reviewed in the preparation of this article. Other standards in table 1 are as cited in the handbook by Polk and Postow (1996), except the FRG standard, which is cited in Haes and Fitzgerald (1995).

Many exposure standards are based on the industrial standard practice set by either the 1982 or 1991 ANSI/IEEE standards. The ANSI/IEEE standard is designed to keep the induced current in biological tissue at least a factor of ten below the lowest reported stimulation thresholds for electronically excitable cells. The 1982 standard (ANSI C95.1-1982) set a threshold limit value (TLV) of approximately 2μT in the VLF frequency range, based on relatively simple models of induced current. Research since 1982 using more realistic heterogeneous human models indicates that there is no danger of cell stimulation at levels below approximately 2000μT, so, after taking into account a margin of safety, the IEEE published the new standard, C95.1-1991, cited above. C95.1-1991 recommends that the average exposure, averaged over any six minute period and over a cross section of the human body, should not exceed 205μT. Less stringent standards apply to partial-body exposures, but the less stringent standards specifically do not apply to the eyes.

In designing the standard, the committee considered peer-reviewed articles investigating the relationships between electromagnetic fields and fourteen different categories of health effect, without regard for the mechanism causing each effect. The mechanisms of tissue heating and cell stimulation were chosen as the basis for standard exposure thresholds because they are quantifiable, and because "no reliable scientific data exist indicating that nonthermal (other than [electric] shock) or modulation-specific sequelae of exposure may be meaningfully related to human health."

Many other standards applicable in the United States have recently been modified based on the research cited in C95.1-1991. The ACGIH standard TLV was raised from 2μT to 200μT in 1995, and the US Air Force standard was raised in 1997. The FCC recently adopted C95.1-1991 as the basis for its own internal standards (Curtis and Straus, 1997a). Commonwealth of Massachusetts law has not yet changed to reflect the new industry consensus, but the current law explicitly cites C95.1-1982 and the ACGIH as justification for the prescribed TLVs, so a modification to reflect the new standards will probably occur after a reasonable period of review.

IV. Articulograph Field Strengths

Alternating magnetic fields generated by the Articulograph AG100 in the VLF frequency range were measured at several distances from each of the transmitter coils. The generated fields were 140-160μT on the surface of each transmitter coil. This level is below the exposure standard approved by the American

Distance (cm)	Blue Coil (uT)	Green Coil (μT)	Red Coil (μT)
3.5	150.0	132.8	131.1
4.5	100.0	93.4	100.0
5.5	66.5	65.3	70.0
6.5	48.0	48.0	45.0
7.5	38.2	33.6	35.3
8.5	26.5	25.3	22.0
9.5	20.0	18.4	18.4
10.5	15.7	16.3	13.7

Table 2: Table 2: Magnetic field strengths perpendicular to the midsagittal plane. Distances shown are the distances between transmitter axis and probe axis; a distance of 3.5cm is obtained by resting the probe on the surface of the transmitter.

National Standards Institute.

Magnetic field strength was measured using a Narda Model 8532 Precision ELF/VLF Gaussmeter.[1] This meter uses an induction coil to measure the true RMS field strength of a magnetic field along a single axis, with an accuracy better than +/- 5% (typically 1%) over the specified frequency range. The frequency range switch was set to the VLF range (2kHz to 50kHz), in order to filter out contributions from ELF fields. All measurements reported in this article have been converted from milligauss to microtesla using the conversion $10mG$=1μT.

The transmitter coils in the Articulograph were turned on more than two hours before testing, in order to let them reach a steady operating temperature, as recommended in the manual (Carstens, 1993). All three transmitters were set to operate at maximum power (E-value=255).

The strength of the field perpendicular to the midsagittal plane was measured at 1cm increments in the vicinity of each of the three transmitter coils, beginning with the probe coil touching the coil of the transmitter. The results are shown in table 2. The minimum distance in table 2, 3.5cm, is the sum of the 2.5cm radius of the transmitter coil and the 1cm radius of the probe coil.

Fields generated by the blue transmitter coil were also measured in two directions parallel to the midsagittal plane. These fields were much weaker than the fields perpendicular to the midsagittal plane, and also

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[1] An initial measurement with a broadband meter calibrated for 60Hz fields (the Magnetic Sciences International MSI-25) resulted in measurements which were an order of magnitude too large. Examination of the meter specifications revealed that the sensitivity of the MSI-25 increases with frequency in an unspecified way, and is therefore unsuitable for VLF field measurements. Of the three commercially available VLF meters investigated, one (the Holaday Industries HI-3603) is only capable of measuring flux densities of up to 2.5uT, and one (the HI-3637) does not appear to be available for rent. Only the Narda model 8532 was found to be both suitable to the desired measurements and available for rent.

Distance (cm)	Vertical fields (μT)	Horizontal fields (μT)
3.5	10	15
4.5	3.4	4.5
6.5	1.9	1.8
10.5	0.4	0.4

Table 3: Table 3: Magnetic field strengths generated by the blue transmitter coil along axes within the midsagittal plane.

much more variable: over the course of several seconds, the strength of a parallel magnetic field sometimes varied by as much as a factor of two. Representative values at several distances are given in table 3. In this table, "vertical fields" were measured parallel to, and "horizontal fields" perpendicular to, a straight line in the midsagittal plane passing through the blue and green transmitters.

Field strengths perpendicular to the midsagittal plane were modeled using the formula

$$B = \frac{\alpha}{r^2} \tag{2}$$

where B is the field strength, r is the distance from the transmitter axis, and A is a constant chosen to minimize the model mean squared error. The constant for the blue transmitter is $A = 1910\mu T cm^2$, and the best-fit constants for the red and green transmitters were both $A = 1750\mu T cm^2$. Figure 1 shows the measured field strengths and best-fit model field strengths as a function of distance r.

V. Discussion

Measurements of the magnetic field strength generated by an Carstens Articulograph AG100 show that the field strength is approximately $150\mu T$ measured at the surface of the coils ($r = 3.5cm$), and decreases as $1/r^2$ at greater distances from each coil. This field is below the $205\mu T$ maximum permissible exposure defined in ANSI/IEEE standard C95.1-1991. In normal use, the surface of a subject's head will typically be at least 5cm from the surface of any of the transmitter coils, or 7.5cm from the axis of any transmitter. At this distance, the field to which the subject is exposed will be less than or equal to approximately $35\mu T$ over the entire volume of the head, and the average exposure level will be considerably less.

A. Repeatability of these measurements

The measurements reported in this article were obtained using the three coils of one Articulograph, on one day. The variability of Articulograph fields from day to day, or from device to device, has not been addressed in this study, but some speculation is possible.

The positions of the receiver coils are calculated by comparing the transduced magnetic field to a standard level, which is defined when the device is calibrated during system installation. Any significant change over time in the magnetic fields would require the device to be recalibrated. Since recalibration is a time consuming and undesirable task, the device has presumably been designed to minimize any change in the magnetic field strengths over time.

Electrical failures are extremely unlikely to cause transient increases in magnetic field. Each transmitter coil is presumably the inductor in a simple resonant circuit; a short circuit anywhere in this circuit will cause the current in the coil, and the magnetic field it produces, to decrease monotonically toward zero. Although an electrical failure seems to present no danger of transient magnetic fields, it does seem to present significant danger of electrical shock, and safety precautions to prevent an electrical failure and protect subjects from shock are therefore discussed at some length in the user's manual (1993).

The transmitter coils in the Articulograph are apparently hand-wound, and although they must meet relatively strict specifications in order to be useful in the device, some variation from device to device is to be expected. In the measured device, for example, the blue coil was somewhat stronger than the red and green coils, with field strength constants of $A = 1910 \mu T cm^2$ and $A = 1750 \mu T cm^2$, respectively. If these three measurements are presumed to be taken from a Gaussian distribution, then standard statistical analysis can be used to calculate 95% confidence intervals for the distribution's mean and variance. The sample mean is $A = 1800 \mu T cm^2$, with 95% confidence limits of 1620 and $1980 \mu T cm^2$. The sample standard deviation is $92 \mu T cm^2$, with 95% confidence limits of 43 and $280 \mu T cm^2$. Since the three coils in the measured device were presumably created in sequence, it is possible that the variation among devices may be somewhat larger than the variation among these three coils.

B. Comparison of Articulograph and VDT use

Epidemiological and laboratory studies suggest that the VLF magnetic fields produced by a video display terminal do not increase the risk of spontaneous abortion. It should be noted, however, that there are important differences between exposure to the VLF fields of a VDT and exposure to the fields generated by the Articulograph, which make comparison difficult.

First, the fields to which a subject is exposed in an Articulograph are several orders of magnitude higher than the VLF fields of a VDT. This is in part because the Articulograph transmitters produce stronger fields than any VDT, and in part because subjects are closer to the Articulograph transmitters than they would be to a VDT. At a distance of 50cm, a single Articulograph transmitter coil produces a field of 0.7-0.8μT. This is the equivalent of 7-8 worst-case VDTs (VDTs taken from the top of the range measured by Haes and Fitzgerald), or the equivalent of 50-60 typical VDTs (VDTs taken from the logarithmic midpoint of the Haes and Fitzgerald range).

The comparison in the preceding paragraph is not entirely accurate, because subjects are typically much closer to the Articulograph coils than they would be to a VDT. If the head of a subject is approximately 7.5cm from the axis of the nearest transmitter coil, the subject will be exposed to fields of up to approximately 30-35 μT, which is the equivalent of sitting 50cm from a coil with the strength of 2200-2600 typical VDTs.

Second, exposure to the fields of an Articulograph is acute (usually lasting less than a few hours), while exposure to a VDT is chronic (often continuing eight hours a day for many years). Although neither acute nor chronic exposure to VLF fields has been linked to any health risk, the study of Lindbohm et al. (1992) suggests that exposure to ELF fields carries a risk which increases with the duration of exposure.

C. Comparison to typical ELF fields

Some household appliances may produce 60Hz fields with the same flux density as the fields of the Articulograph, but because of the difference in frequency of the transmitted fields, the effects are not comparable.

As noted in section 1, the current induced by a magnetic field increases with frequency, so the current produced by a 20kHz field at 35μT is much stronger than that produced by a 60Hz field at 35μT. As noted in section 2, the threshold for stimulation of excitable cells also increases with frequency, so that neither a 35μT 20kHz field nor a 35μT 60Hz field will stimulate biologically excitable cells, despite the greater induced current density of the VLF field.

Finally, ELF fields below the threshold of cell stimulation have been linked to other biological effects, while VLF fields have not been linked to any such effects.

D. Other exposure standards, and other EMA systems

Table 1 lists three exposure standards which do not permit use of the Articulograph AG-100. The Canadian Ministry of National Health and Welfare and the Commonwealth of Massachusetts do not permit use of the AG-100 under any circumstances, although Massachusetts law allows exceptions for facilities on United States Government property. Massachusetts law is explicitly based on the 1982 ANSI and ACGIH standards, and Canadian regulations may also be partly based on these standards, so it is possible that these laws may change to reflect the new ANSI and ACGIH standards, after a reasonable period of review.

The European electromagnetic exposure prestandard (ENV 50166-1) allows occupational exposure to the fields produced by the Articulograph, but does not allow the general public to be exposed to such fields. The Single European Act of 1986 allows member countries to ignore European Commission standards if their own national standards provide better "protection of the environment or the working environment," so in the interest of economic uniformity, many European Commission standards are more stringent than the standards of any individual member country (Curtis and Straus, 1997b). If ENV 50166-1 becomes an approved standard, researchers in the European Community may find it necessary to define whether subjects in Articulograph experiments are "workers" or members of the "general public."

Hoole and Nguyen (1996) review three EMA systems, including the Carstens Articulograph, the Botronic Movetrack system, and the MIT system. They report that the Movetrack and the MIT systems both expose subjects to fields of less than 1μT, which is below the maximum permissible exposure specified by all of the regulations listed in table 1. The MIT system is, however, not a commercial product. The Movetrack system is a commercial product, but because of its two-transmitter construction, the Movetrack is considerably more susceptible than the Articulograph to tracking errors caused by misalignment of the receivers.

VI. Conclusions

The transmitter coils of the Articulograph AG100 generate 10-20kHz VLF alternating magnetic fields which have a flux density of approximately 35μT at a distance of 7.5cm from the coil axis. This field strength is well below the maximum permissible exposure specified by the American National Standards Institute in ANSI standard C95.1-1991.

There seems to be little experimental data concerning the biological effects of magnetic fields of more than a few microtesla at frequencies in the VLF range, and epidemiological studies are even more limited, since few people routinely encounter VLF magnetic fields which are stronger than 0.1μT. Despite the scarcity of existing data, however, the most relevant existing studies seem to support the conclusion that alternating magnetic fields at this field strength and in this frequency range present minimal risk to the health of experimental subjects.

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List of Figures

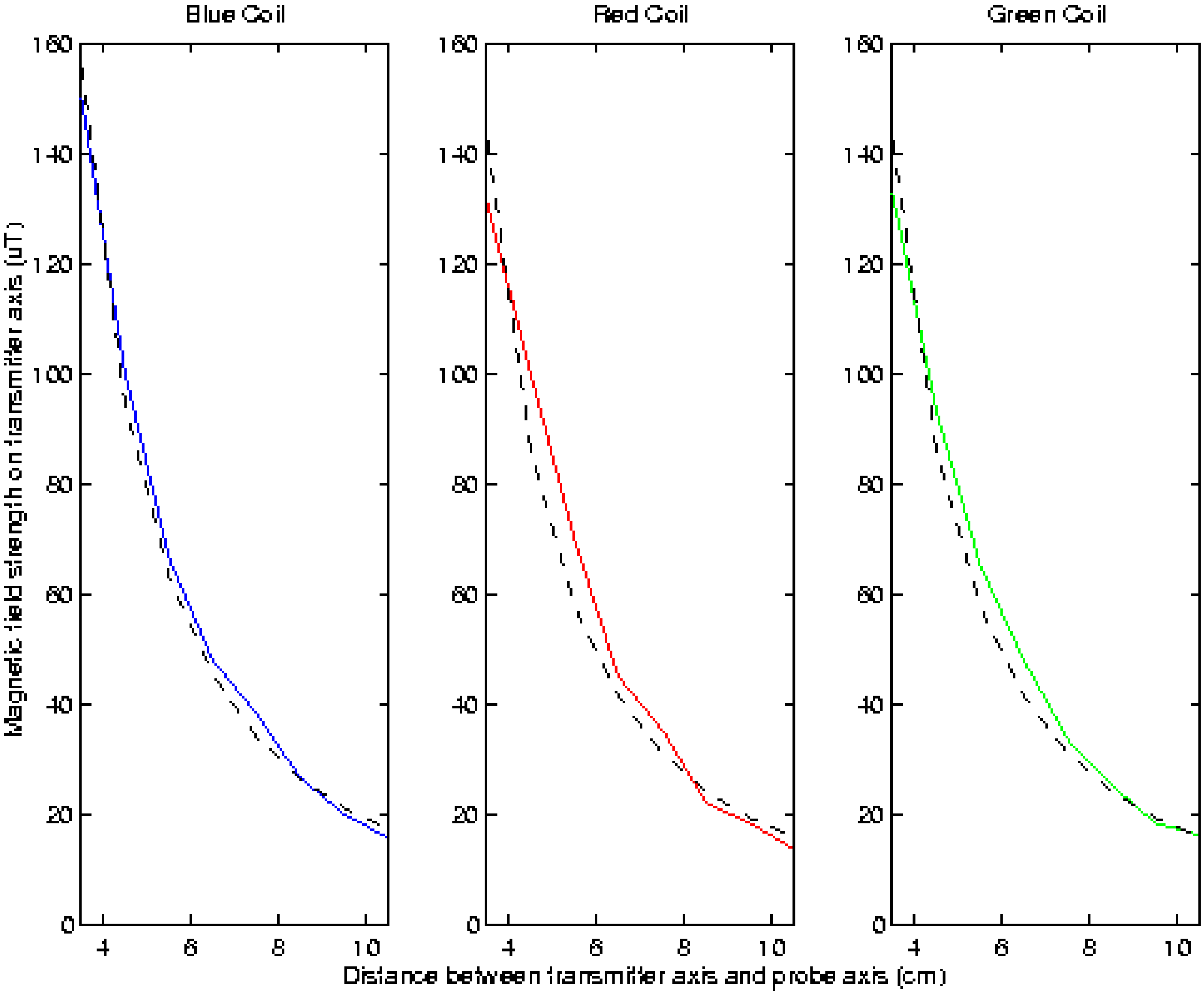

Figure 1: Figure 1: Measured field strengths (solid line) and modeled field strengths (dotted) as a function of distance from each of the transmitter coils.