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Dielectric Properties of Animal Tissues In Vivo at Frequencies 10 MHz — 1 GHz

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An open-ended coaxial line sensor in conjunction with an automatic network analyzer was used to measure in vivo the permittivity of several feline tissues (skeletal and smooth muscle, liver, kidney, spleen, and brain — gray and white matter) at frequencies between 10 MHz and 1 GHz. The estimated uncertainties of measurement were between 1.5% and 5%. The data are in general agreement with previously obtained data in vitro and in vivo. Significant differences in the properties of different types of the same tissue (eg, skeletal and smooth muscle) were observed. Many tissues were found to be non-homogeneous in its permittivity.

Key words: permittivity, in vivo, radio frequencies

INTRODUCTION

Dielectric properties of tissues are important in several areas of studies of the biological effects and interactions of nonionizing electromagnetic waves with living matter. Knowledge of the permittivity of tissues and its dependence on frequency and temperature is needed to explain on a molecular level the interaction of electromagnetic field with living matter [Schwan and Foster, 1980; Stuchly, 1979]. This knowledge is also essential for theoretical and experimental dosimetry as well as studies of biological effects and evaluation of potential health hazards due to exposures to radio frequency and microwave radiation [Stuchly, 1979; Durney, 1980]. More recently, two new areas of medical applications have emerged. Radio frequency and microwave induced hyperthermia [Samaras and Cheung, 1980] has become an accepted modality in cancer therapy. Knowledge of the permittivity of living tissue is vital for the development of effective treatment pro-

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cedures and for the design of efficient applicators. Finally, there are indications that diagnostic methods based on differences in the dielectric properties of normal and cancerous tissues are feasible [Schepps and Foster, 1980].

The first extensive in vitro measurements of the dielectric properties of tissue were performed by Cook [1951] followed by Schwan and his colleagues [Schwan, 1957], and the available data were summarized by Stuchly and Stuchly [1980a]. Recent progress in measurement techniques and instrumentation as well as revival of interest in the health aspects of radio frequency and microwave radiation, have resulted in refined measurements of several biological tissues in vitro [Foster et al, 1979; 1980].

Relatively few data are available on the permittivity of tissues in vivo. Variations of blood content cause the most pronounced difference between in vivo and in vitro measurements but other factors become significant a few hours after excision [Schwan, 1957]. The permittivity of canine muscle tissue was measured in vivo by Toler and Seals [1977] at frequencies between 10 and 100 MHz. The following tissues – canine muscle, kidney cortex, fat; and rat muscle, brain, and blood – were measured in vivo by Burdette et al [1980] at frequencies between 100 MHz and 10 GHz. In both studies a short monopole antenna was used as a probe. A comprehensive analysis of an open-ended coaxial line as a sensor for in vivo measurements of the tissue permittivity was presented by Athey et al [1981], and the accuracy of measurements of the in vivo permittivity of a few animal tissues was evaluated by Stuchly et al [1981].

In this paper, a brief description of the measurement method is provided and complete data on the in vivo permittivity is given for the following feline tissues: muscle (skeletal and smooth), liver, kidney, spleen, and brain (gray and white matter), at frequencies between 10 MHz and 1 GHz. The difference between the permittivity of various tissues and tissue homogeneity are discussed.

MATERIALS AND METHODS

Measurement Method and Instrumentation

The method used to measure permittivity is based on measuring the input reflection coefficient of an open-ended coaxial line placed against the test tissue. A sketch, an equivalent circuit and an external view of the line used as a sensor are shown in Figure 1. The dimensions of the line are selected for the range of frequencies and permittivities of interest [Stuchly and Stuchly, 1980b; Athey et al, 1981]. This selection is aimed at assuring minimal uncertainty in the determination of the permittivity.

An open-ended coaxial line provides several advantages over the short monopole used previously [Toler and Seals, 1977; Burdette et al, 1980], namely, better compatibility with the measured material, ability to use readily available components, and a simple relationship between the permittivity and the measured reflection coefficient. In this study a 50-Ω semirigid teflon-filled line with 8.3-mm external diameter (a = 3.6 mm, b = 1.1 mm Fig. 1a) was used. The sensor capacitance, affected by the test sample, was C_o = 0.0458 pF, and the capacitance resulting from the fringe fields in the teflon filled part of the sensor C_f = 0.0092 pF [Stuchly et al, 1981].

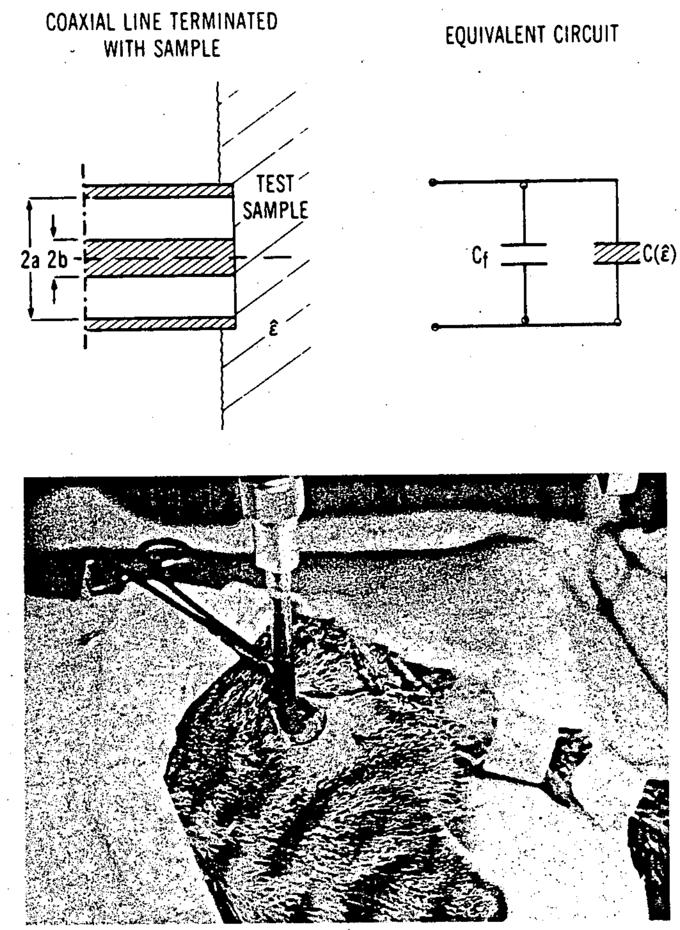

Fig. 1. Open-ended coaxial line as a sensor for measurement of the tissue permittivity in vivo. a) geometrical configuration; b) external view.

The input reflection coefficient was measured by a computer-controlled system employing two network analyzers (Hewlett Packard models 8407 and 8410) described by Athey et al [1981]. To assure maximum accuracy of measurements, a standard error correction procedure was used [Stuchly et al, 1981]. In this procedure three known terminations – a short circuit, an open circuit, and a matched load – are each in turn placed at the reference plane (where later the test sample is placed), and the reflection coefficients are measured. The coefficients are then utilized to correct for errors resulting from the imperfections of the system, such as limited directivity, frequency tracking, and mismatch. The uncertainties in the measured permittivities of animal tissue resulting from the estimated uncertainties in the measurements of the reflection coefficient are summarized in Table 1. In addition to these well-defined systematic errors, nonsystematic errors occasionally occurred [Stuchly et al, 1981]. These errors are frequently difficult to control, as a simple repetition of measurements cannot be used to eliminate them. The measured values of conductivity may be in error from 1% to 3% at frequen-

TABLE 1. Estimated Uncertainties in the Dielectric Properties of High Water Content Tissues, Resulting From the Uncertainties in the Measurements of the Input Reflection Coefficient (△ Modulus = 0.03, △ Phase = 0.3°)

Uncertainty	Frequency (MHz) 10	50	100	500	1,000
$\frac{\Delta\epsilon'}{\epsilon'}$	0.05	0.03	0.025	0.015	0.015
$\frac{\Delta\sigma}{\sigma}$	0.02	0.02	0.015	0.015	0.015

cies above 700 MHz. This may be due to a conductance term in the equivalent circuit that is neglected in the calculations [Stuchly and Stuchly, 1980b].

The sample volume that contributes to the measured permittivity is equal to the volume of a cylinder having a diameter of 8.3 mm and a height of 5 mm [Stuchly et al, 1981].

Tissues

A 3-kg female cat was maintained at least 30 days before use in a large cage with food and water provided ad libitum. Anesthesia was induced by pentobarbital (35 mg/kg IV) and maintained with ketamine HCl (30 mg/kg IV). Atropine sulfate (0.1 mg) was administered IM, and Procaine HCl was injected SC prior to all incisions. Tracheal intubation was performed to permit mechanical respiration. Arterial and venous lines were inserted in the right femoral artery and vein. Arterial blood pressure, (LI) EKG, and rectal temperature were measured. Using both a heating pad and a heat lamp, rectal temperature was maintained at 35 °C during first 2 hours postsurgery, and was later increased to 36.5 °C.

Various tissues were surgically exposed to permit dielectric measurements. Skeletal muscle (biceps femoris) was exposed following a skin incision in the thigh. Smooth muscles (gut) and various abdominal organs were exposed following an abdominal incision. The brain was exposed following a left craniotomy on the frontoparietal junction. In all cases, the tissue exposed to air was maintained moist with gauze soaked in normal saline. Just before measurements were taken, the tissue was blotted and brought into contact with the sensor probe. Tissue temperature was measured immediately prior to or following the dielectric measurements. At least three different tissue locations were measured for each tissue.

RESULTS

Complete permittivity data for various feline tissues are provided in Tables 2 and 3. Figures 2 and 3 show the dielectric constant and conductivity of smooth muscle and spleen, respectively. They are presented to illustrate the accuracy and repeatability of the measurements. The points represent data taken at various locations in the tissue. The vertical bars illustrate the measurement uncertainties (SD). A comparison between the electrical properties of two types of muscle is given in Figure 4; the permittivities of kidney, liver and spleen are shown in Figure

TABLE 2. Dielectric Constant of Cat Tissues (range of measurements of three to five samples, uncertainty as in Table 1)

Tissue	Skeletal muscle	Smooth muscle	Spleen	Kidney	Liver	Brain gray	Brain white
				T(°C)			
f(GHz)	31 ± 0.5	35 ± 0.5	35 ± 1	35	35 ± 0.5	33 ± 0.5	33 ± 0.5
0.01	170–190	459–462	352–410	190–204	251–265	237–289	190–191
0.02	114–115	230–244	193–231	118–119	148–162	162–176	132–134
0.03	90	150–157	140–159	88–91	111	123–139	100–101
0.04	89–90	124–130	119–127	76–81	98	110–121	90–92
0.05	83	108–112	102–114	70–73	85–88	97–113	78–80
0.06	80	99–103	91–104	67–71	81–83	89–100	75–77
0.07	78–80	94–97	86–95	66–70	76–79	83–95	70–71
0.08	74–75	87–88	78–88	61–64	72–74	76–90	64–66
0.09	72–74	82–84	75–82	58–60	69–70	73–85	59–61
0.1	67–72	77–78	71–76	56–62	65–68	65–80	58–64
0.2	62–67	65	59–60	51–52	56–58	58–63	49–50
0.3	60–64	60	54.5–56	47–48	52–54	53–57	43–44
0.4	59–62	58.5–59	53–54	45–47	50–52	50–54	41–42
0.5	58–61	56–57	51–52	44–45	49–50	48–52	39–40
0.6	57–60	55–56	50–51	43–45	48–49	47–51	38.5–39
0.7	57–59	55–56	50–51	43–44	47–49	47–51	38–39
0.8	57–59	55–56	50–51	43–44	47–49	47–51	38–39
0.9	57–59	55–56	50–51	43–44	47–49	47–51	38–38.5
1.0	57–59	55–56	50–51	43	47–49	47–51	37.5–38.5

TABLE 3. Conductivity (mS/cm) of Cat Tissues (range of measurements of three to five samples, uncertainty as in Table 1)

Tissue	Skeletal muscle	Smooth muscle	Spleen	Kidney	Liver	Brain gray	Brain white
				T(°C)			
f(GHz)	31 ± 0.5	35 ± 0.5	35 ± 1	35 ± 1	35 ± 0.5	33 ± 0.5	33 ± 0.5
0.01	8.55–8.65	7.0–7.2	5.0–5.3	5.0–5.7	4.2–4.6	4.5–6.3	2.9–3.1
0.02	8.75–8.85	8.0–8.3	5.8–6.2	5.3–6.2	4.7–5.0	5.0–6.8	3.3–3.5
0.03	8.9–9.0	8.4–8.7	6.2–6.6	5.5–6.5	4.9–5.3	5.4–7.3	3.6–3.8
0.04	9.0–9.1	8.7–8.9	6.5–6.8	5.6–6.6	5.1–5.5	5.6–7.5	3.8–4.0
0.05	9.0–9.2	8.9–9.1	6.7–7.0	5.6–6.6	5.3–5.6	5.9–7.7	4.0–4.1
0.06	9.1–9.3	9.0–9.2	6.8–7.1	5.7–6.6	5.4–5.7	6.0–7.9	4.2–4.4
0.07	9.2–9.3	9.2–94.	6.9–7.2	5.8–6.6	5.5–5.8	6.2–8.2	4.3–4.5
0.08	9.3–9.4	9.25–9.5	7.0–7.3	5.9–6.7	5.6–5.9	6.3–8.3	4.5–4.7
0.09	9.4–9.5	9.3–9.6	7.1–7.4	5.9–6.7	5.8–6.1	6.4–8.4	4.7–4.8
0.1	9.5–9.9	9.4–9.7	7.3–7.6	6.6–7.2	6.0–7.1	5.2–8.5	4.8–5.1
0.2	9.7–10.6	9.8	7.7–8.0	7.1–7.2	6.5–7.4	6.0–8.2	5.2–5.4
0.3	10–11	10.1–10.2	7.9–8.3	7.2–7.4	6.9–7.7	6.0–8.4	5.3–5.4
0.4	10.5–11.2	10.5	8.2–8.5	7.4–7.6	7.1–7.8	6.6–8.9	5.8–5.9
0.5	10.8–11.6	10.6–10.7	8.4–8.8	7.4–7.7	7.3–7.9	7.1–9.3	6.1–6.2
0.6	11.5–12.0	11.5	9.1–9.5	8.0–8.6	8.2–8.8	7.5–9.8	6.5–6.6
0.7	12.3–12.7	11.9–12	9.7–10.0	8.4–9.0	8.5–9.2	7.8–10.4	6.9–7.0
0.8	13.1–13.6	12.5–12.6	10.2–10.4	8.6–9.1	8.9–9.5	8.2–10.9	7.3–7.5
0.9	13.4–14	12.6–12.9	10.4–10.7	8.8–9.2	9.0–9.8	8.6–11.2	7.7–7.8
1.0	13.8–14.5	13.2–13.3	10.9–11.3	9.5–9.7	9.5–10.3	8.9–11.7	8.1–8.2

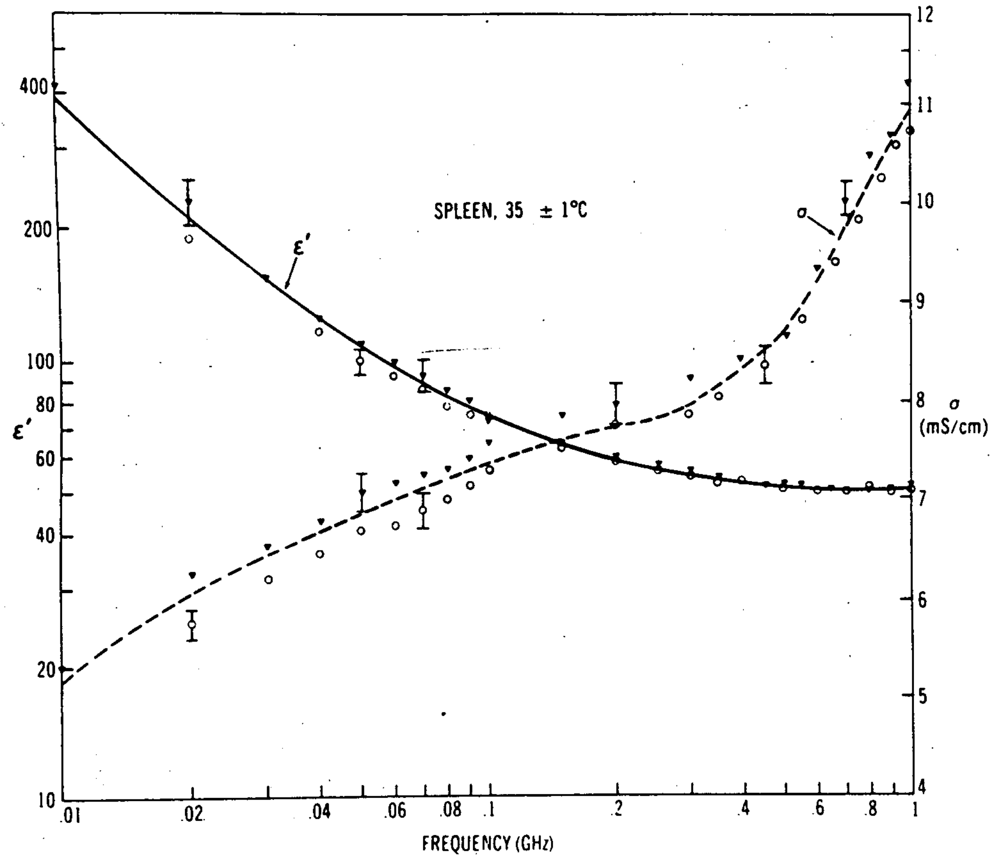

Fig. 2. Permittivity of cat smooth muscle in vivo, ▼ and ○ show results obtained for two different samples (locations in the tissue); the vertical bars show the uncertainty due to the estimated measurement errors (SD).

5. The permittivity of brain tissues is shown in Figure 6. Table 4 shows the permittivity of white matter (brain tissue) 1 minute after the animal died, and before death.

DISCUSSION

The dielectric constant (Table 2) and the conductivity (Table 3) of the same tissue measured at different locations fall within a range of values as indicated in the tables. For some tissues (eg, muscle) the experimental values are within the estimated uncertainties (Table 1). This is clearly illustrated in Figure 2, which shows the results obtained at two locations. Similar reproducibility of results was obtained at three additional locations. A few measurement points outside the estimated uncertainty range may be attributed to a nonsystematic error occurring at a particular frequency.

The internal organs – liver, kidney, spleen – and the gray matter of the brain are electromagnetically heterogeneous, and the dielectric properties vary significantly depending on location. This is illustrated in Figure 3. Repeated

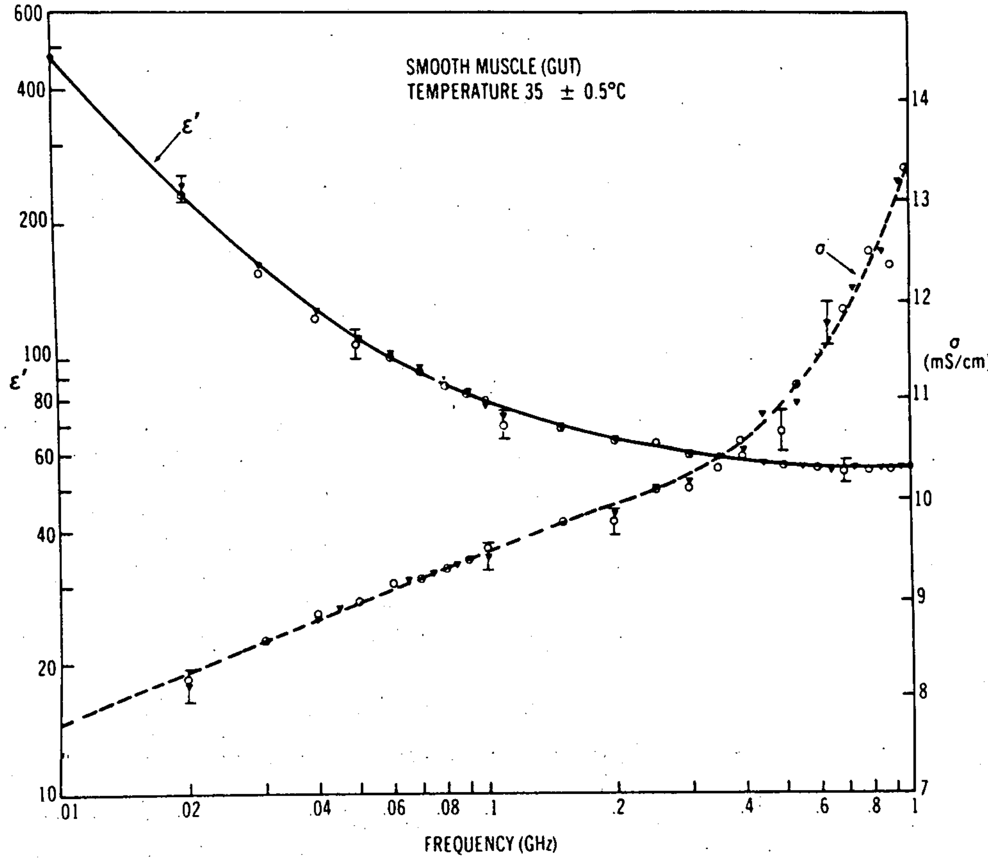

Fig. 3. Permittivity of cat spleen in vivo, ▼ and ○ show results obtained for two different samples (locations); the vertical bars show the uncertainty due to estimated measurement errors (SD).

measurements at the same location invariably produced results well within the estimated uncertainties. The shapes of the curves illustrating the frequency dependence of the dielectric constant and conductivity remains the same at various locations of a given tissue. The tissue nonhomogeneity may be attributed to variations in blood perfusion, and therefore water content [Schwan, 1957; Schwan and Foster, 1980].

The dielectric properties of skeletal muscle (biceps femoris) of cat are very close to those of dog measured in vivo [Burdette et al, 1980; Toler and Seals, 1977]. There are no previously published data on the permittitivity of smooth muscle. The difference between the permittivity of smooth and skeletal muscle at frequencies above 100 MHz may be caused by differences in water content or ionic concentration. However, the behavior at lower frequencies (below 100 MHz) likely indicates a differing structure of intracellular and cell membranes that results in different relaxation frequencies and distributions of the Maxwell-Wagner type dispersion [Schwan and Foster, 1980]. Differences in the type of protein and its concentration may also be contributing factors.

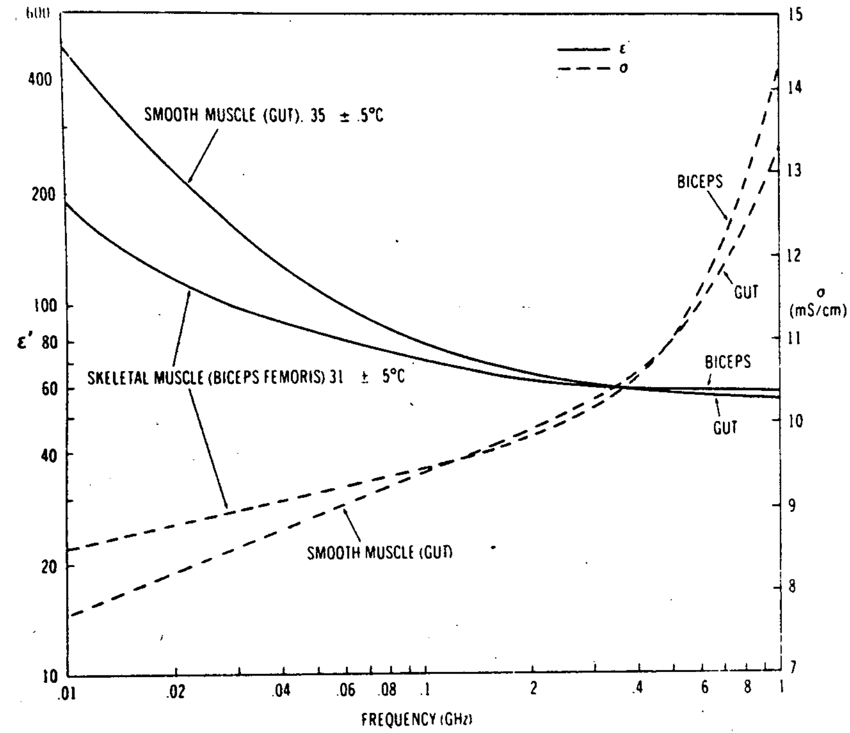

Fig. 4. Average permittivity of two types of cat muscle in vivo (five samples for each point).

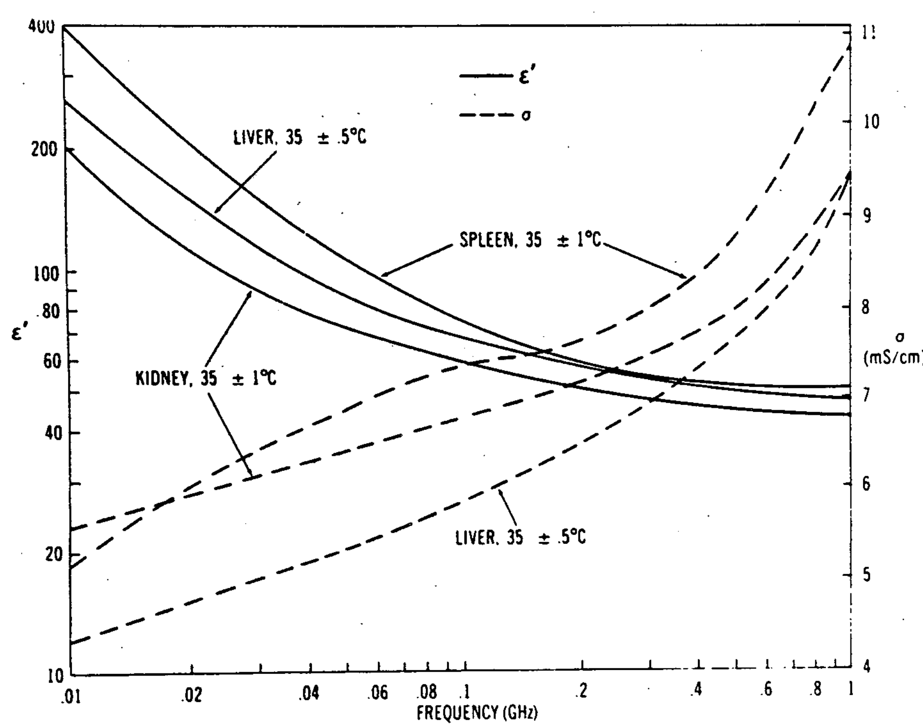

Fig. 5. Average permittivity of cat internal organs in vivo (three to five samples for each point).

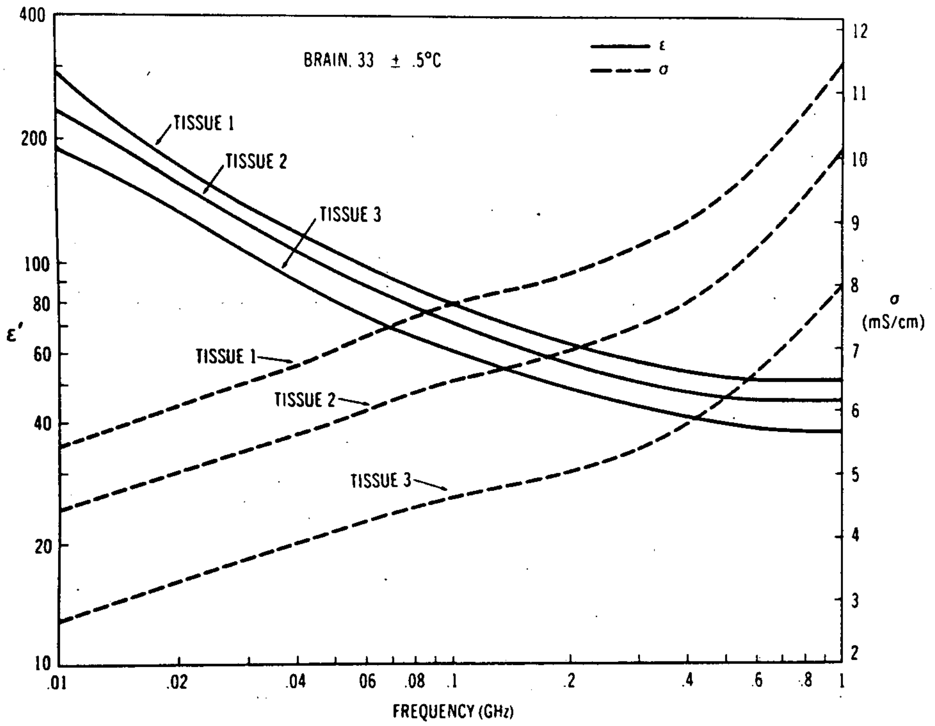

Fig. 6. Permittivity of cat brain. tissue 1 – gray matter; tissue 2 – gray matter, 3 mm thick over white matter; tissue 3 – white matter.

At frequencies between 0.1 and 1 GHz, the average dielectric constant of feline kidney was found to be lower than that of canine kidney, whereas the conductivity was very close [Burdette et al, 1980]. The data for liver and spleen may only be compared with the previously obtained in vitro data [Schwan, 1957; Schwan and Foster, 1980]. At frequencies below 400 Hz, the dielectric constant of feline liver measured in vivo was about 15% lower than the dielectric constant of human liver, measured in vitro, whereas above 400 MHz the differences are smaller. The conductivities of liver tissue for both species were very close. The dielectric constant and conductivity of feline spleen were found to be lower than those for human spleen measured in vitro at frequencies between 25 and 100 MHz. Comparison data are not available at other frequencies. A comparison of the average permittivity of the three internal organs (Fig. 5) indicates differences that cannot be explained fully by water content, and indicates structural and compositional differences.

The dielectric properties of brain tissue are of great importance as recently explained by Foster et al [1979].

Information on the dielectric properties of the human brain may be found by comparing information on the properties of the cat brain to the human brain. Comparisons using cat brains are made as cats are frequently used in experiments of this nature. While the white matter of cat brains was found to have rather uniform properties, the permittivity of gray matter as indicated in Tables 3 and 4 was found to vary from one location to another. Spacial variation is especially

TABLE 4. The Permittivity of Cat Brain Tissue (white matter) ***In Vivo*** **and After Death (T = 32.6 °C)**

GHZ	E′	Lostan	E″	Sigma (MMHO/CM)
Animal alive				
0.100	63.32	1.22	77.52	4.31
0.200	49.79	0.90	44.92	4.99
0.300	44.31	0.70	31.17	5.20
0.400	41.53	0.62	25.75	5.73
0.500	39.62	0.55	22.07	6.14
0.600	38.58	0.50	19.40	6.47
0.700	38.31	0.46	17.70	6.89
0.800	38.14	0.43	16.40	7.30
0.900	38.84	0.39	15.36	7.69
1.000	37.69	0.39	14.55	8.09
1 min after death				
0.100	63.76	1.19	75.95	4.22
0.200	49.12	0.89	44.10	4.90
0.300	43.89	0.69	30.62	5.11
0.400	41.15	0.61	25.41	5.65
0.500	39.60	0.54	21.73	6.04
0.600	38.59	0.49	19.26	6.42
0.700	39.07	0.46	17.61	6.85
0.800	38.15	0.42	16.28	7.24
0.900	38.74	0.39	15.23	7.62
1.000	37.71	0.39	14.45	8.04

large for the loss factor (conductivity). However, Foster et al [1979] found that the properties of the gray matter are nonhomogeneous only within ± 10%, and variations in our measurements reflect the changes in the thickness of the gray matter layer. The shape of the curves (Fig. 6) supports the former conclusion of Foster et al [1979] that the difference between the dielectric properties of gray and white matter is due to differing water content. The dielectric constant of feline brain tissue (both white and gray matter) was found to be about 20% lower, especially at frequencies below 200 MHz, than that of human brain tissue measured in vitro, whereas the conductivity was only slightly lower. The dielectric properties were found, as expected, to be unchanged following death by injection of an overdose of pentobarbital (Table 4).

CONCLUSIONS

We have shown permittivity measurements of feline tissues (in vivo), using an open coaxial line sensor with a computer-controlled network analyzer that is accurate over 2 decades of frequency. The data obtained indicated differences between various types of the same tissue (muscle), heterogeneity within tissues of various internal organs, and species differences in the dielectric properties of brain tissue.

Further studies of the dielectric properties should be extended to lower RF frequencies (below 10 MHz) and temperatures above 36 °C. Knowledge of the change in permittivity with temperature is particularly important in an application of effective hyperthermia.

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