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The dielectric properties of the cranial skin of five young captive Steller sea lions (*Eumetopias jubatus*), and a similar number of young domestic pigs (*Sus scrofa*) and sheep (*Ovis aries*) between 0.1 and 10 GHz

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Abstract
To aid in the development of a long-range subcutaneous radio frequency identification tag to monitor the fate of sea lion pups, the dielectric properties of the cranial skin of young female otariids, and possible test subjects of similar size and age, or pigs (*Sus scrofa*) and sheep (*Ovis aries*) were obtained over a frequency range of 0.1–10 GHz at the base of their heads where the tag will be implanted. The resulting curves were similar in shape to adult human skin data, but the values were generally lower. Between subjects, variations were noted in all the species. Circuitry for the RF-ID tag is being designed to account for antenna detuning as a result of the lossy media or skin and the variation in dielectric properties.

Keywords: dielectric constant, dielectric loss, skin thickness, conductivity, multi-layer skin properties, permittivity, wild animals, *in vivo*

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Steller sea lions (*Eumetopias jubatus*) have been declining in the Aleutian Islands and Gulf of Alaska since the late 1970s and are listed as an endangered species in the United States.

Radio tags could help to determine why they are declining by monitoring the movements and survivorship of the young otariids—the age class thought to be at greatest risk. Unfortunately, radio tags glued to the fur of pinnipeds fall off when the animals molt or hairs break, and many implantable types are of limited range and longevity, too large or too surgically invasive for use in a young animal. A small radio frequency (RF) tag placed in the subcutaneous layer would be a possible means of electronically monitoring an immature individual pinniped.

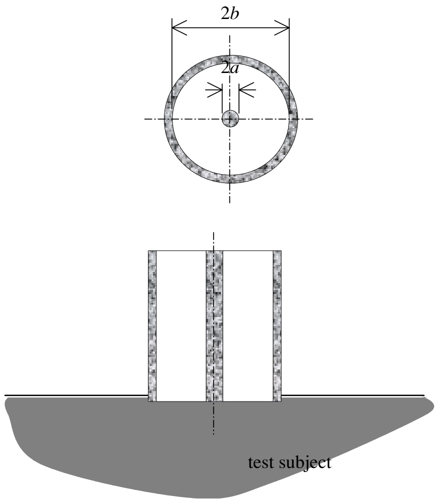
At the University of British Columbia, we are examining the possibility of a RF tag (with a 3-year working life) for placement under cranial skin. Knowing the dielectric properties of young Steller sea lions is important, as they are key parameters in electromagnetic radiation models used in antenna design. The dielectric properties are, however, not available for wild animals. Furthermore, they are not available for the skin of most domesticated species, and this is a concern, because due to the endangered status and the limited captive number of Steller sea lions, convention demands the tag be thoroughly tested in a suitable domesticated species (based on size and physically age) before employment in the sea lions (Pullman 1995). We also found little information about the dielectric properties of young skin. With rare exceptions, researchers conducting measurements of dielectric properties on biological subjects usually choose adults (see Peyman *et al* (2001)). Young skin changes quickly with age and is quite distinct from adult skin (Seidenari *et al* 2000). To help fill voids due to age and species, the following reports the dielectric properties of the cranial skin of non-sexually mature Steller sea lions, and domesticated pigs (*Sus scrofa*) and sheep (*Ovis aries*).

2. Materials and methods

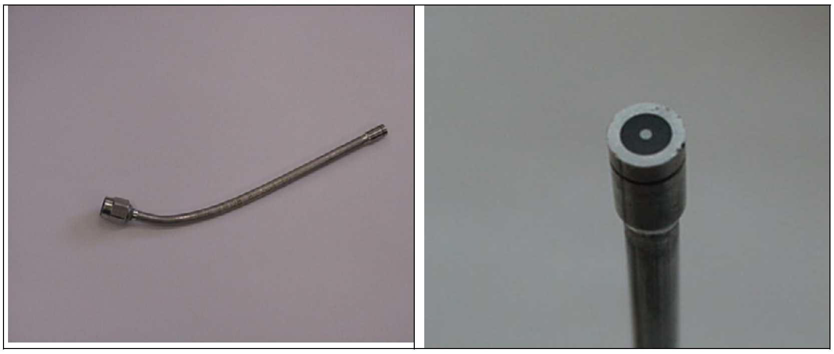
2.1. Measurement system

The dielectric properties of skin were measured over the frequency range of 0.1–10 GHz. A vector network analyzer (VNA) (Agilent 8720ES) and a specially constructed dielectric probe with an internal radius of 0.298 mm and an outer radius of 2.5 mm were used (figure 1). In this frequency range electrode polarization is not a problem (Schwan 1992). The open-ended coaxial probe was constructed out of stainless steel without flanges to alleviate measurement errors related to environmental factors associated with *in vivo* testing. The probe was built out of several sections of coaxial lines, and the final section at the probe aperture is a 2.3 mm borosilicate glass line, hermetically sealed to the stainless steel metal conductors (for additional details see Popovic and Okoniewski (2003)). The borosilicate glass probe does not have a ground plane, and this was done so that a consistent contact with the tissue across the whole aperture of the probe could be achieved (i.e. the contact areas of probes with and without ground planes are 2 cm and 4.5 mm diameter respectively). The absence of the ground plane is taken into account in the inverse algorithm in the coefficients of the rational function model (Popovic *et al* 2005).

While conducting the dielectric measurements, the probe (held manually and perpendicular to the skin) was slightly pressed into the skin at each site (resulting in a slight skin indentation). While testing the generally soft-skinned porcine subjects, the small probe had to be handled carefully so that it would not puncture the skin. Salt water (25 parts per thousand) was applied to the Steller sea lion skin to reflect the fact that otariids are normally wet with salt water in their natural environment. Care was taken to ensure that the cable connecting probe and network analyzer was not bent. The VNA calculated the reflection coefficient at several (pre-selected) frequency points. These data were stored in a computer and subsequently used to calculate the dielectric constant and loss over the frequency range.



(a)



(b)

Figure 1. Dimensions and pictures of the probe used for the dielectric measurements. (a) Probe cross-section, $a = 0.298$ mm and $b = 2.5$ mm. (b) Photographs of the probe.

The system was checked before use on the test animals. As part of this check, the dielectric properties of distilled water and two salt solutions at various temperatures were measured. Results in the frequency range of interest compared well with standard values (within 2%). An additional test found that values for the forearm of human skin on three volunteers fell midway between those reported in the literature (e.g. Hey-Shipton *et al* (1982) and Gabriel (1997)). The dielectric constant measurement error at the 95% confidence level based on triplicate readings on the same position was ±4.76, and the between subject variance ranged between 15 and 18%. This was well below the 23% between subject variations reported by Petaja *et al* (2003). As the testing methods gave reasonable results, animal testing proceeded.

2.2. Animal testing

Five available young captive Steller sea lions (three 4-months old and two 3-year old) housed at the Vancouver Aquarium Marine Science Centre, six porcine subjects (three 6-weeks old and three 4-5-months old) of comparable physiological ages as the Steller sea lions and three 8-month old ovine subjects of comparable physiological age as the 3-year old

Table 1. Skin thickness, surface temperature and weight of subjects (S: Steller sealion, P: porcine, O: ovine).

	Skin thickness (mm)		Temperature (°C)		
Subject	Range	Mean	Range	Mean	Weight (kg)
SA	1.5–2.3	2.7	26.0–27.0	26.8	36.2
SB	1.6–1.9	1.8	28.0–29.0	28.5	43.2
SC	2.0–2.3	2.5	29.0–31.0	30.0	33.8
SD	4.4–6.6	5.5	17.0–24.0	20.5	131.6
SE	4.7–6.3	6.0	17.0–24.0	20.5	112.4
PA	1.0–1.4	1.2	34.5–35.0	34.7	24.5
PB	1.4–1.4	1.4	29.5–30.7	30.1	22.5
PC	1.7–1.8	1.8	31.4–32.7	31.9	26.0
PD	1.6–2.2	1.9	33.2–34.5	34.0	85.0
PE	2.2–2.5	2.3	31.8–32.4	32.0	65.0
PF	1.4–1.9	1.7	34.3–34.6	34.5	89.0
OA	1.1–1.4	1.2	27.4–31.8	29.3	21.0
OB	0.4–1.4	1.0	25.6–32.3	29.7	21.0
OC	1.2–1.7	1.4	23.6–30.3	27.4	39.0

Steller sea lions were measured (younger sheep are considered too small for the RF tag). All animals were shaved. Only non-sexually mature females were tested (generally females are chosen over males by research units as they are smaller and more docile), but as gender did not greatly affect skin electrical impedance values in adult humans when gender differences would be most apparent, not testing males was not considered a major issue (Nicander *et al* 1997). A University of British Columbia appointed Committee on Animal Care approved the procedures and methods.

Prior to testing, each animal was placed under anesthetics to restrict movement. The anesthetics, administered by a veterinarian on each of the subjects, consisted of Ketamine (for sedation) through intramuscular injection and Isoflurane vapors via facemask. Respiratory rate was monitored every 5 min during these periods. The effect of anesthetics on the dielectric measurement was expected to be marginal, as the testing area was generally free of vascular and muscle tissues or tissues that are known to be affected by such drugs. The porcine subjects were tested within heated laboratories, while the other subjects were tested in unheated research areas adjacent to their cages.

On each subject, four sites on the back of the head and behind the coronal suture (proposed implant site) were measured. The sites formed a rectangle of size 5 cm $\times$ 3 cm. These four sites were numbered and kept consistent across different test subjects by placing a cardboard template on the same head position. Time restrictions (due to the anesthetics, 30–60 min) permitted two repetitions per position in the otariids and three to four in the other subjects.

At the time of dielectric measurement, skin temperature and thickness were measured. Skin thickness (comprising epidermis and dermis) as measured by a veterinarian using the available portable ultrasound device (Seidenari *et al* 2000) varied somewhat between species (table 1) (using this equipment, it was not possible to distinguish between epidermis and dermis). The two oldest otariid subjects had the thickest skin (4.4–6.3 mm). In the rest of the subjects the skin thickness varied by 0.4–2.5 mm. Within the small test area it varied by 1–2 mm in the otariid subjects, and only by 0.3 mm in most porcine and ovine subjects.

A laser temperature sensor indicated that among animals of the same species, surface skin temperature varied by as much as 6° (table 1). Surface skin temperature fluctuations were most likely due to fluctuations in ambient temperature and not in sub-dermal body

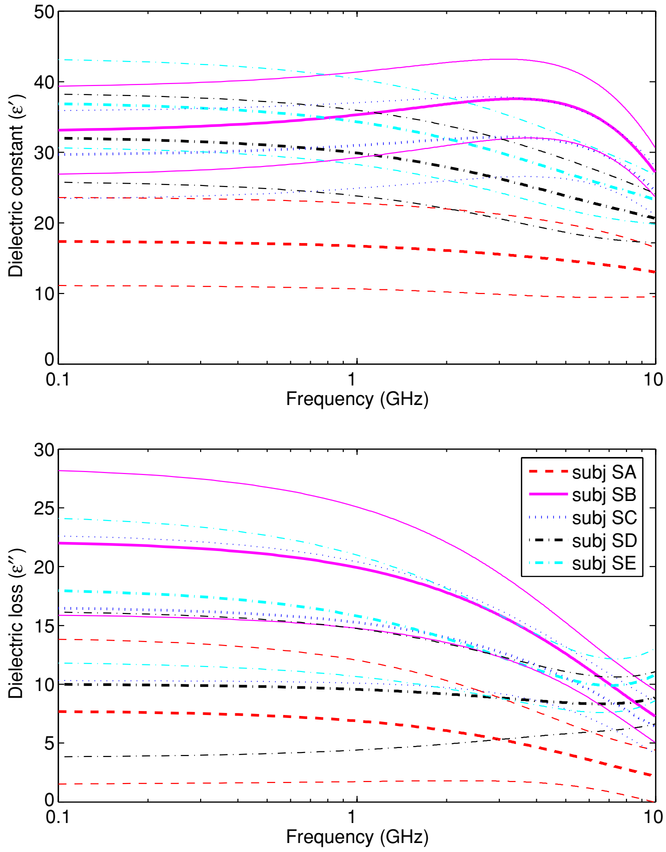


Figure 2. Permittivity and loss factor of wet young otariid skin from the base of the head measured *in vivo* ($n = 6$–8). Light-colored lines represent the 95% uncertainty interval.

temperature, as all the surface temperatures were considerably lower than core temperatures for the animals (sheep: 39.5, sea lion: 38 and pig: 39.2 °C). To confirm this, conductivity data were normalized for surface skin temperature using temperature coefficients of 2%/°C for frequencies 1 GHz and −2%/°C for above 2 GHz (Foster and Schwann 1996). As the adjustments gave unrealistic negative values on both wet and dry skin, we reached the conclusion that the temperature gradient is superficially located.

2.3. Statistical analysis

Dielectric measurement requires that the subject remain still. This was not always the case in our study as some of the subjects occasionally breathed deeply or shook slightly. Data resulting from movement resulted in a higher than normal variation between replicate readings, and values far lower or higher than expected. As a rule, such data were considered spurious and were discarded if they fell outside twice the average range as calculated using all the data for a particular subject.

Of interest was the effect of the subject on dielectric properties, as this would offer some idea of variation to be used in our electromagnetic models. As dielectric properties vary with frequency, graphs were generated that showed curves representing both the subject mean and

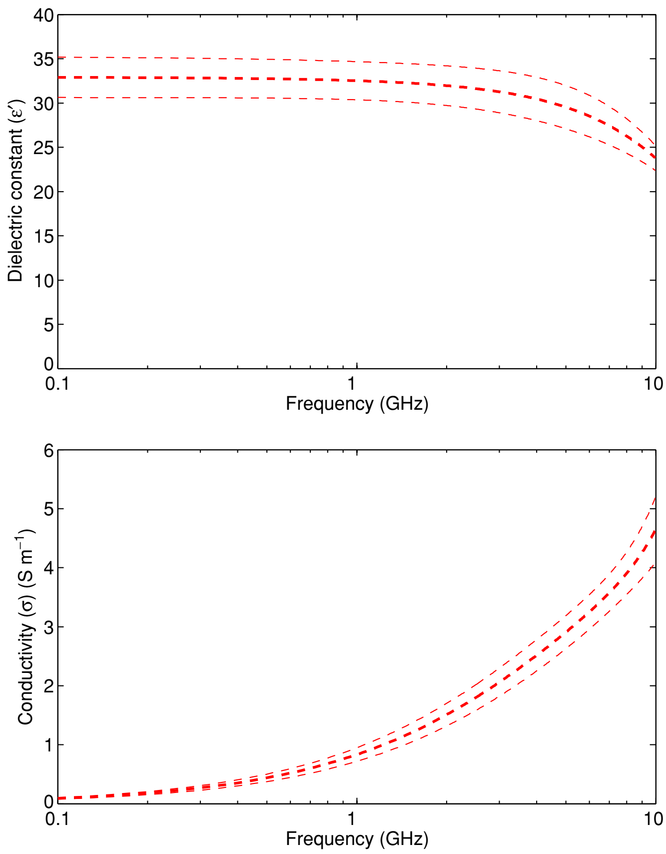


Figure 3. Average permittivity and conductivity of wet otariid skin from the base of the head measured *in vivo* ($n = 31$). The light-colored lines represent one standard deviation.

95% uncertainty intervals (based on the honestly significant difference (HSD)) (Andrews *et al* 1980, Steel and Torrie 1960). The decision rule was subject means are different if uncertainty intervals do not overlap. The 95% uncertainty intervals were plotted as lightweight lines while the mean values were plotted as heavyweight lines of the same style as the lightweight lines.

3. Data interpretation and sensing depth

Accurate dielectric characterization of tissue requires the sample between the probe and sensing boundary to be homogeneous. As inhomogeneities in the skin have been considered small as compared with the wavelength of the radiation in skin (Hey-Shipton *et al* 1982), we initially set up the tests assuming the skin is the sample and the sensing boundary is the beginning of the subcutaneous fat layer. The probe sensing depth was set to be equal to skin thickness of a Steller sea lion pup or 3 mm as measured by Jonker and Trites (2000). Sensing depth as defined by Hagl *et al* (2003) is the smallest distance between the probe and boundary for which the magnitude and phase errors in the reflection coefficient remain below a defined error threshold. A theoretical sensing depth of 3 mm was achieved through choice of probe dimension and careful calibration (Hagl *et al* 2003). With this probe and calibration method,

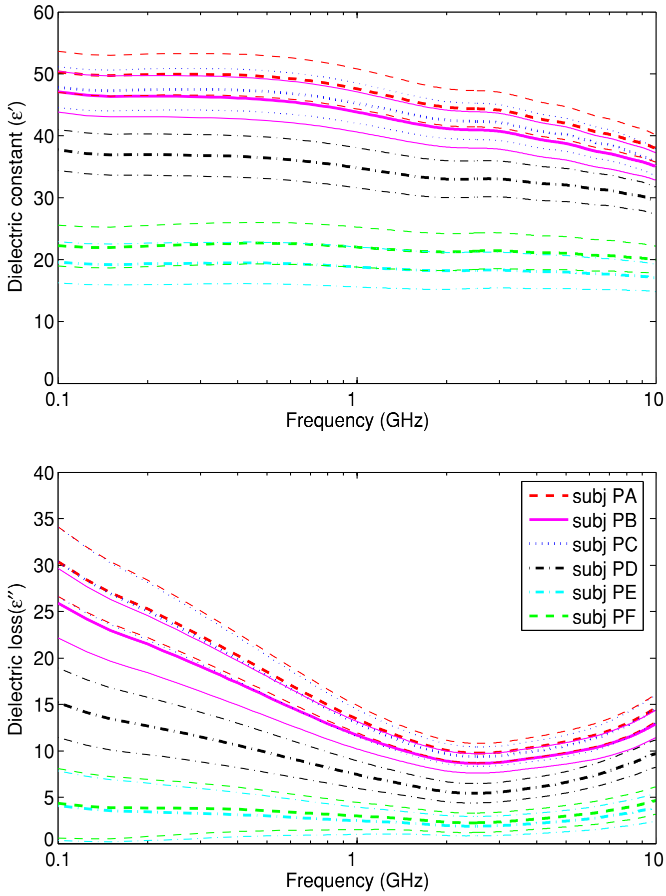


Figure 4. Permittivity and loss factor of dry young porcine skin from the base of the head measured *in vivo* ($n = 7$–16). Light-colored lines represent the 95% uncertainty interval.

skin dielectric measurement was expected to be accurate to within 10% as long as the skin thickness exceeded 3 mm. Ten per cent is considered normal for a co-axial probe (Gabriel *et al* 1996b).

In the end the skin of most of the animals including the pups did not reach the prerequisite 3 mm. We therefore reviewed the available 'state of the art' and methods to interpret the data and determine for each species the skin layer most likely affected by the measurement. A smaller probe might have resolved the issue of the 3 mm, but we elected not to pursue that approach due to the likelihood a smaller probe would have punctured skin at the pressures required to hold it in place.

For the wet otariid subjects, the skin layer most highly affected was the lower layer or the dermis when the skin was greater than 3 mm and both the dermis and the underlying subcutaneous fat when the skin was less than 3 mm. This follows from dielectric measurements conducted on wet and dry skin (Gabriel 1997, Raicu *et al* 2000). We corrected our data to obtain the dielectric properties of the <3 mm skin without the effect of the underlying subcutaneous fat following methods suggested by Alanen *et al* (1998, 1999) for a probe closest to our probe size. The corrections required the dielectric properties of fat, and these were obtained from Foster and Schwan (1996). The corrections were applied to the entire frequency range,

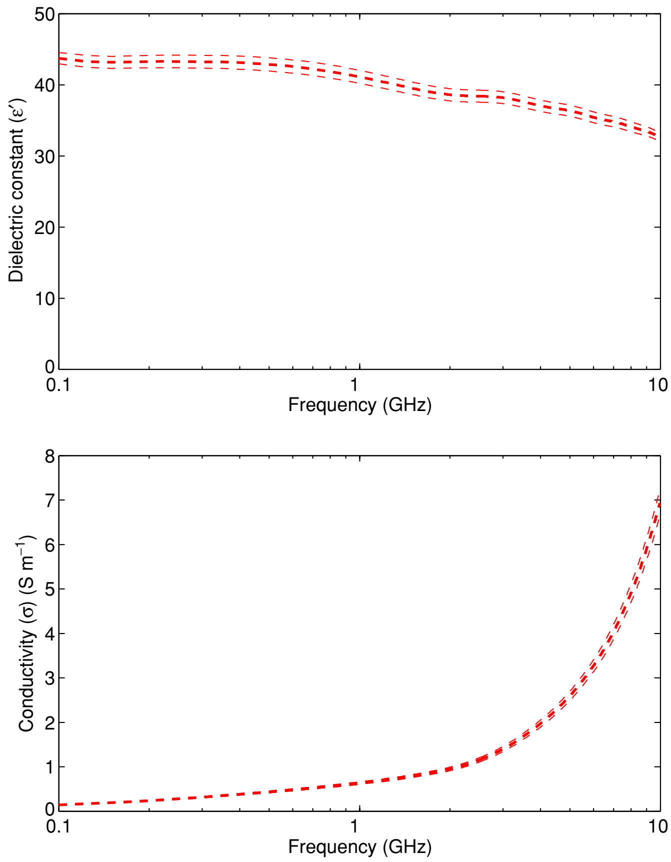


Figure 5. Average permittivity and conductivity of dry porcine skin (youngest three subjects) from the base of the head measured *in vivo* ($n = 21$). The light-colored lines represent one standard deviation.

although they would be most valid on measurements less than 2 GHz where the capacitive model of the probe works.

For the thin dry skin of the porcine and ovine subjects, the skin layer most highly affected by the measurement was the upper skin layer or the dry thin low-dielectric substratum corneum. This follows from experiments conducted on wet and dry skin (Gabriel 1997).

4. Data presentation

In general, the effect of sampling position within the small test area on the dielectric properties can be considered negligible, as the range of values obtained for each subject fell within the predicted accuracy of the method or 10%. Examples of the measurements on the three species, across the frequency range, are given in figures 2–6.

4.1. Otariid subjects

On the dielectric plot, four of the five uncertainty intervals overlapped, and the shapes of these four curves were generally similar, meaning dielectric properties from subjects SA < SB = SC = SD = SE (figure 2). The curve of the dielectric loss was nearly flat

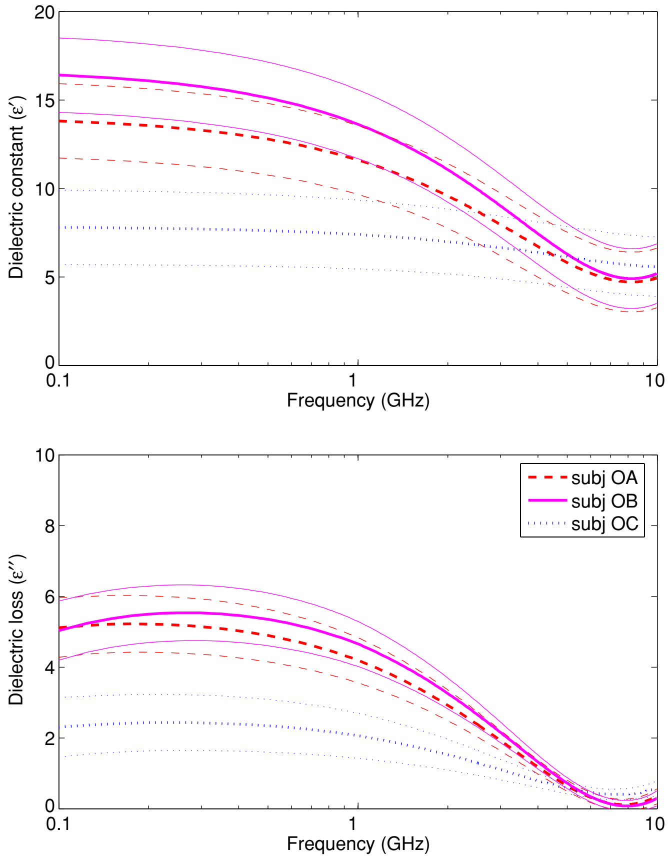


Figure 6. Permittivity and loss factor of dry young ovine skin from the base of the head measured *in vivo* ($n = 10$ for each subject). Light-colored lines represent the 95% uncertainty interval.

throughout the frequency range. From the dielectric loss plot, two groups of skins emerged after an inspection of the uncertainty intervals, namely one had a dielectric loss of approximately 30 and the other of approximately 10 (subjects SB = SE = SC; SA = SC = SD = SE, figure 2). Variation in individual fat content might have caused the variation in dielectric loss; fat plays such a major role in sea lions that skin fat and blubber levels are used as a way to distinguish nutritional status (Jonker and Trites 2000). Loss data were converted to conductivity data for ease of comparison to published data sets. Curves representing the dielectric constant and conductivity (figure 3) from the four subjects with indistinguishable dielectric constants are similar to the curves representing wet human skin (Gabriel *et al* 1996a, 1996b, Gabriel 1997). Our values, however, are lower.

4.2. Porcine subjects

From an inspection of the uncertainty intervals (figure 4), it becomes apparent that the dielectric constant and loss from the three youngest porcine subjects were distinct from those of the three oldest (subjects PA = PB = PC > PD > PE = PF). The shapes of the dielectric constant and conductivity curves from the three youngest animals are similar to the curves from dry human skin (Gabriel *et al* 1996a, 1996b, Gabriel 1997) (figure 5). Our values, however, are lower.

Surface lipid chemical composition changes in skin from birth to adolescence (Ramasastry *et al* 1970), and as fat is considered dry, it is possible the increase in skin lipid content is the cause of the difference in dielectric properties due to age. The animals of dissimilar age came from distinct environments so it is also possible that diet and not age caused the difference in dielectric properties.

4.3. Ovine subjects

From an inspection of the uncertainty intervals (figure 6), it becomes apparent that the dielectric constant and loss from one of the young ovine subjects was distinct from the other two (subjects OA = OB > OC). The shapes of the dielectric constant curves are similar to the curve generated from dry human skin (Gabriel *et al* 1996a, 1996b, Gabriel 1997). Our values, however, are considerably lower.

5. Comments and conclusions

We conducted *in vivo* dielectric measurements on the cranial skin of young Steller sea lions, pigs and sheep using a small probe. The curves were similar in shape to each other and to the curves generated from human skin. The values varied with subject and, in the case of the porcine subjects, with age. The porcine subjects of dissimilar age did not originate from the same location or live in similar environments, so it is not clear whether age or some other factor caused the segregation in the data. This question may be answered in the future, as we are planning to implant our RF tag into young porcine subjects and measure over time their skin dielectric properties. We will attempt if permitted the time (under anesthetics) to measure both wet and dry skin, and develop correction models applicable for a multi-layer skin applicable beyond 2 GHz. New circuitry is being developed for our RF-ID tag to account for the effect of this lossy media (i.e. the skin) on antenna detuning. The results have also been used to calculate the power budget.

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