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Effect of Physiologically Relevant Dehydration on the Dielectric Properties of Ground Beef

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ABSTRACT

Readily available animal tissue, such as ground beef, is a convenient material to represent the dielectric properties of biological tissue when validating microwave imaging and sensing hardware and techniques. The reliable use of these materials depends on the accurate characterization of their properties. In this work, the effect of physiologically relevant levels of dehydration on ex vivo tissue samples is quantified while controlling for variation within and between samples. Seven commercial ground beef samples (90% lean muscle, 10% fat) are dehydrated from 0.0% to 7.0% in 1.0% increments by weight. Dielectric measurements are collected using a conventional dielectric probe technique from 0.2 to 6 GHz. A linear mixed-effects model is used to control for within- and between-sample variation while modeling the effect of dehydration and dispersion across frequency. Significant ($p < 0.05$) changes are noted in both permittivity and conductivity due to sample dehydration. For a 1% change in weight due to dehydration, changes in permittivity (5.1%–5.6%) and conductivity (3.2%–5.7%) are reported. These changes are important for the use of large muscle-based phantoms in microwave sensing and imaging validation, as well as the feasibility of microwave hydration assessment. The statistical model used here can be applied to similar research questions and can augment existing frameworks for reporting dielectric measurements.

1 | Introduction

Excised animal tissues are used to validate microwave sensors, algorithms, and systems for biomedical applications. The dielectric properties of excised tissues closely mimic the in vivo properties of biological tissue over a wide frequency range and include complex behavior such as dispersion (Guido et al. 2021). The properties of tissues of a variety of species are similar. Many reference measurements used extensively to represent human tissues originate from measurements of animal tissue samples (Gabriel, Lau, and Gabriel 1996). Readily accessible tissues, such as commercially available ground beef or pork belly, provide convenient phantom material for numerous applications (Rice and Kiourti 2022; Deneris, Pe'a, and Furse 2019). However, the use of these materials for phantoms requires the accurate characterization of their properties due to confounding factors related to composition, temperature, and hydration (Porter et al. 2018).

Although dielectric measurements of tissue have been conducted for decades, the results are often difficult to interpret and reproduce due to differences in sample handling and measurement procedures. A recently introduced framework, dubbed MINDER (Porter et al. 2018), provides guidance on sample handling and reporting for measurements of biological tissues. This framework has motivated further work on

Summary

- The effect of dehydration on muscle tissues is quantified using commerically purchased ground beef samples.
- A linear mixed-effect model is used to control for within- and between-sample variation and quantify the effect of dehydration.
- For a 1.0% change in dehydration, 5.1%–5.6% and 3.2%–5.7% decreases in permittivity and conductivity are observed, respectively.

confounding factors such as probe pressure (Maenhout et al. 2020), temperature (Bonello et al. 2019), and dehydration (Maenhout et al. 2020). Missing from this framework and subsequent work is a discussion of the statistical modeling required to determine the significance of confounding factors and generalize results.

The effect of tissue water content on the dielectric properties of tissues has generally been investigated in the context of microwave heating of food. In Bengtsson and Risman (1971), various raw meats were measured using the resonant cavity method with decreases of 3.3% and 0.8% per percent decrease in water content noted in the permittivity and conductivity, respectively. Using previously reported measurements of assorted meat products (To et al. 1974), in Sun et al. (1995) it was found that while tissue water content is predictive of dielectric properties, the dielectric properties of food can be more accurately predicted by also considering their ash content.

A number of recent works have focused on the effect of dehydration on small excised tissue samples. In Maenhout et al. (2020), porcine liver samples 2 cm × 2 cm× 2 cm in size were measured over a 35 min period. The tissue dielectric properties reduced by up to 9% over this time. In a similar study (Shahzad et al. (2017), the dielectric properties of mouse liver samples (approximately 27 g and up to 9 mm thick) were measured for 3.5 h after excision with changes of more than 25% reported. Although both studies attribute these changes to sample dehydration, the amount of water loss was not characterized. In Pollacco et al. (2018), muscle tissue samples with an average size of 15 cm^{-3} were excised from mice and dehydrated up to 70% by weight. The dielectric properties of ex vivo tissues were measured at regular time intervals; for weight changes between 0% and 10%, an average 0.7% and 5.4% decrease in the real and imaginary permittivity, respectively, was observed across the measured 0.5–50 GHz frequency range. However, the exact change in weight was not reported. Thus, the direct relationship between tissue dehydration and dielectric properties, particularly, for levels of dehydration relevant for practical applications ($< 10\%$), remains unquantified. Quantifying the direct relationship between tissue properties and dehydration is more informative than the aforementioned time-based experiments, in which the change in water content over time is influenced by many confounding factors such as sample size, temperature, relative humidity, and airflow around the sample.

Previous work has investigated the relationship between tissue bulk permittivity and water content using theoretical and simulation models. In Garrett et al. (2019), a linear relationship between the Debye parameters used to describe frequency-dependent dielectric properties in the microwave frequency range and the fraction of water content is used to estimate the change in properties due to a small increase in dehydration. This model was then used in simulation to estimate the sensitivity of ultrawideband microwave techniques to changes in dehydration. In Pollacco et al. (2019), the relationship between tissue water content and properties was accurately modeled using a mixture model, however, a similar study (Balduino et al. 2019) found the predictive capabilities of these models were limited.

The relationship between changes in tissue water content and tissue bulk properties has also gained importance with recent work on microwave techniques for hydration assessment. Physiologically relevant changes in hydration can occur with as little as 2% increase in dehydration in humans (Cheuvront et al. 2010; Szinnai et al. 2005; Garrett et al. 2018). In veterinary settings, larger changes in hydration can be important for monitoring the health of animals. For example, outward signs of dehydration in newborn cattle do not present themselves until loss of over 5% of body water (Smith 2009). Using the close relationship between tissue water content and microwave dielectric properties (Foster and Schwann 1989), groups are exploring methods to detect physiologically relevant changes in hydration by estimating changes in tissue microwave properties. Microwave hydration assessment has been explored with absorption through the body (Moran et al. 2004), full-body resonant techniques (Oldroyd et al. 2015), and an ultrawideband time-of-flight method (Garrett and Fear 2019). Microwave hydration assessment has been tested in children (Oldroyd et al. 2015), athletes undergoing a rigorous practice session (Garrett and Fear 2019), fasting volunteers (Besler and Fear 2021), and volunteers undergoing heat-stress exercise trials (Agarwal et al. 2022). Although the in vivo results have been promising, the sensitivity of microwave assessment techniques has not been established. To assess the feasibility of this technology, the change in tissue properties for dehydration between 0% and 5% must be examined.

1.1 | Overview

The direct impact of tissue dehydration on the bulk properties of large tissue samples is explored here using ground beef. Ground beef was chosen as a practical and easily procured material that is increasingly being used in microwave sensing validation (Rice and Kiourti 2022). The complications related to working with ground beef are inherent in all dielectric measurements of excised tissue, demonstrating the need for rigorous statistical modeling. Although ground beef will lack the structure of in vivo muscle tissue with components such as fascia, blood vessels, and muscle strands not retaining their shape, the composition of ground beef and muscle tissue will be similar. Due to the subwavelength size of these structures at the frequencies of interest, the effect of structural differences will be minimal. The composition of lean ground beef (90% muscle, 10% fat) and human striated muscle are similar (Haytowitz et al. 2019; Forbes, Cooper, and Mitchell 1953).

Previous works have investigated the relationship between tissue water content and dielectric properties in general (To et al. 1974), or with large changes in water content (Pollacco et al. 2018) that are not applicable in vivo or with large samples undergoing superficial dehydration. Understanding this relationship is important when using ground beef in phantoms and when developing microwave hydration assessment techniques. The aim of this work is to quantify the impact of physiologically relevant levels of water loss on the dielectric properties of heterogeneous muscle tissue. Toward this goal, a statistical model that controls for within- and between-sample variation is presented. This statistical model can be applied to answer other experimental questions related to tissue dielectric properties and to supplement existing frameworks for reporting dielectric measurements.

2 | Methods

A protocol is presented for accurately measuring heterogeneous tissue samples using a dielectric probe. It consists of empirically characterizing the measurement probe and sample volume, careful description of the sample preparation, and measuring multiple samples a number of times each to enable statistical modeling. A statistical model controlling for the within-sample variation, between-sample variation, frequency-dependent behavior, and dehydration level is developed to quantify the impact of changing water content.

2.1 | Dielectric Measurements

Measurements were taken with a Keysight N9923A Field Fox vector network analyzer (VNA), a Keysight N1501A-101 High-Temperature Probe kit, and the associated Material Measurement Suite software. The dielectric probe is the most common dielectric measurement technique for tissues at the frequencies of interest and is chosen over noncontact methods to avoid the precise sample geometries required by these techniques. The dielectric probe was calibrated with air, deionized water, and the provided shorting block with conductive elastomer disk. The calibration quality was inspected by ensuring that the S11 measurements were in the left half-plane of the polar plot when the shorting block was connected. Measurements were taken from 0.2 to 6 GHz in 0.02 GHz increments to cover the frequency range used in microwave hydration assessment. 5 dBm output power and 300 Hz IF bandwidth were used. Measurements were taken without signal averaging.

The minimum required dimensions of the sample were investigated before measuring the ground beef samples. Although the required minimum sample dimensions are reported in the probe datasheet, the sample volume was empirically determined by measuring deionized water with and without aluminum foil wrapped around the outside of the beaker. Figure 1 shows measured results for 300 and 500 mL samples of water with shortest distance between the foil and probe of 4 and 5 cm, respectively. Measurements were taken from 0.1 to 3 GHz. Higher frequencies are not expected to have boundary artifacts due to increased loss and electrical size. Based on this experiment, a sample volume of at least 500 mL was required for the foil to have a negligible effect (< 0.1% change in relative permittivity) on the estimated properties.

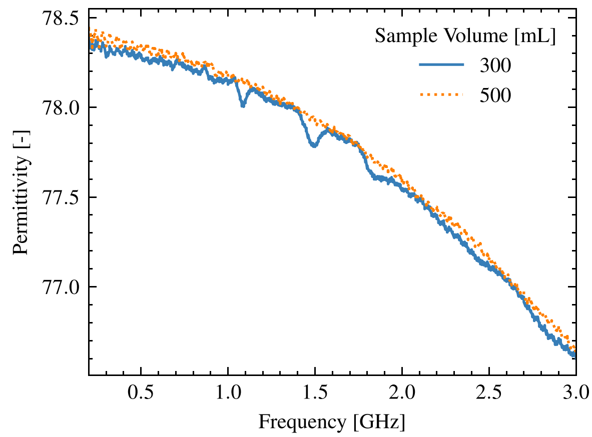

FIGURE 1 | Effect of aluminum foil on measurements of deionized water of various sizes.

FIGURE 2 | Dielectric probe in contact with ground beef sample during measurement.

Figure 2 shows the dielectric probe in contact with a ground beef sample. A lab lift was used to place the sample in contact with the probe without disturbing it while maintaining consistent positioning and pressure. Twenty measurements of the sample were taken at each dehydration level. Due to the heterogeneous nature of the samples, measurements were taken at five nonoverlapping locations on the sample. The sample was mixed and measurements were repeated. The probe was calibrated between measurements at each dehydration level and periodically if the measured results showed rippling due to probe movement. All measurements were conducted by the same operator. The VNA was left to warm up at least 1.5 h before measurements.

2.2 | Sample Preparation

Extra lean ground beef (approximately 90% muscle, 10% fat) was purchased from a local grocery store the day before measurements. Extra lean ground beef was chosen because it is the highest muscle composition ground beef commonly available and was expected to show the most dramatic impact of changes in water content. As shown in Table 1, the proximate (water,

TABLE 1 | Proximate composition of extra lean ground beef and human striated muscle.

	Water (%)	Protein (%)	Fat (%)	Ash (%)
Extra lean ground beef (Haytowitz et al. 2019)	69	20	10	1
Human striated muscle (Forbes, Cooper, and Mitchell 1953)	70	22	7	1

fat, protein, and ash) composition of extra lean ground beef is similar to that of striated muscle in humans (Haytowitz et al. 2019; Forbes, Cooper, and Mitchell 1953). For these commercially available samples, the exact composition, time of death, or time of processing is unknown. The ground beef was stored in an airtight container in the fridge until measurements were conducted. The sample was allowed to come up to room temperature and was thoroughly mixed by hand before any measurements to distribute fluids, fat, and muscle. A dielectric measurement and the sample initial weight were taken before dehydrating.

Seven samples weighing roughly 450 g, corresponding to the minimum required sample size determined earlier, were dehydrated in 1.0% increments from 0.0% to 7.0% by total sample weight. The samples were spread in a 1 cm layer and placed inside a food dehydrator (VVinRC, LT-28) set at 35°C with forced airflow. The dehydrator temperature was confirmed with an independent measurement. Dehydration was measured by weight ($\pm$ 0.1 g) using a laboratory scale (Sartorius, CP6201). The samples were removed from the dehydrator once the 1.0% change in dehydration was obtained. Samples were promptly combined into a ball approximately 10 cm in diameter and placed in an airtight plastic bag. Dehydrating a 450 g sample took approximately 7 min for each 1.0% increment. From visual inspection, dehydration mostly occurs on the surface of the sample, which makes thorough mixing of the sample important. Measuring multiple samples allows for the control of between-sample variation and increases the power of the statistical model leading to more robust analysis. Figure 3 illustrates the sample measurement procedure.

Although each sample would undergo some dehydration during the measurement period, this would be minimal due to the relatively small surface area to volume ratio of the sample. In addition to weight changes due to ambient dehydration, the sample weight also changed based on material transfer while handling and measuring the sample. For example, ground beef could stick to the plastic bag and fat could transfer to gloves while handling. The change in weight was accounted for when calculating the next 1.0% increase in dehydration.

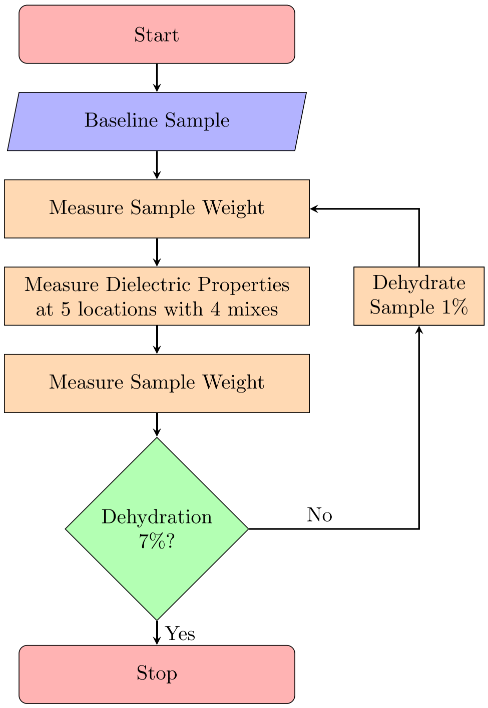

FIGURE 3 | Experimental procedure for dielectric measurements of ground beef at different dehydration levels.

2.3 | Experimental Design

A linear mixed-effects model (LMM) (Bates 2010; Kuznetsova, Brockhoff, and Christensen 2017) is used to model the effect of dehydration and frequency on the measured dielectric properties while controlling for the variation in the samples. The relative permittivity and conductivity are the response variables and are modeled separately. Dehydration and frequency are modeled as fixed effects, and the sample variation is modeled as a random effect. The relative permittivity and conductivity are log-transformed to reduce the skew as all their values are greater than zero. The statistical model can be written as

$$\ln(X_{mijk}) = \mu + s_m + \beta_0 H_i + \beta_1 F_j + \beta_2 (H_i F_j) + \epsilon_{mijk}, \tag{1}$$

where

- X_{mijk} is a single measurement of permittivity or conductivity
- μ is the overall intercept or mean
- s_m is the intercept of the *mth* sample, $m = 0, ..., M$
- H_i is the *ith* dehydration level, $i = 0, ..., I$
- F_j is the *jth* frequency point in GHz, $j = 0, ..., J$
- $H_i F_j$ is the interaction between the *ith* dehydration level and *jth* frequency point
- ϵ_{mijk} is the random error associated with the measurement
- $\beta_0, \beta_1, \beta_2$ are the regression coefficients (slopes) associated with each variable of interest.

There are $M = 7$ samples, $I = 8$ dehydration levels, $J = 291$ frequency points, and $K = 20$ replications as seen in Table 2.

3 | Results

3.1 | Example Data

Figure 4 shows the relative permittivity and conductivity for all 20 measurements of a representative ground beef sample before dehydration. There is high variance in the measured signals due to the heterogeneous nature of the sample and the small sensing volume of the probe. The range of measured relative permittivity and conductivity values is similar to previously reported measurements of muscle samples: permittivity between 48 and 60 and conductivity between 0.7 and 5.2 S/m (Gabriel, Lau, and Gabriel 1996).

Figure 5 shows histograms of the relative permittivity and conductivity of the 20 repeated measurements for sample 0 at 2 GHz at baseline after 1.0% increase in dehydration. Tables 3 and 4 provide the summary statistics.

TABLE 2 | Experimental design parameters.

Parameter	Number	Values
Samples	7	0–6
Dehydration level	8	0.0%–7.0%
Frequency points	291	0.2–6 GHz, $\Delta f = 0.02$ GHz
Replications	20	0–19

3.2 | Aggregate Data

Figure 6 shows the weight of each sample over time. The total measurement time for a sample ranged from 3.5 to 8 h. The difference in measurement time is due to increased efficiency in taking measurements and the variation in number of measurements for the earlier samples as the measurement procedure was refined. For pilot samples 0, 1, and 2, 50 repetitions were completed. However, this many replications were deemed infeasible and unnecessary; for the remaining samples only 20 repetitions were conducted. The first 20 replications were used in all analyses in this work. The weight of a control sample of ground beef left at room temperature and ambient conditions

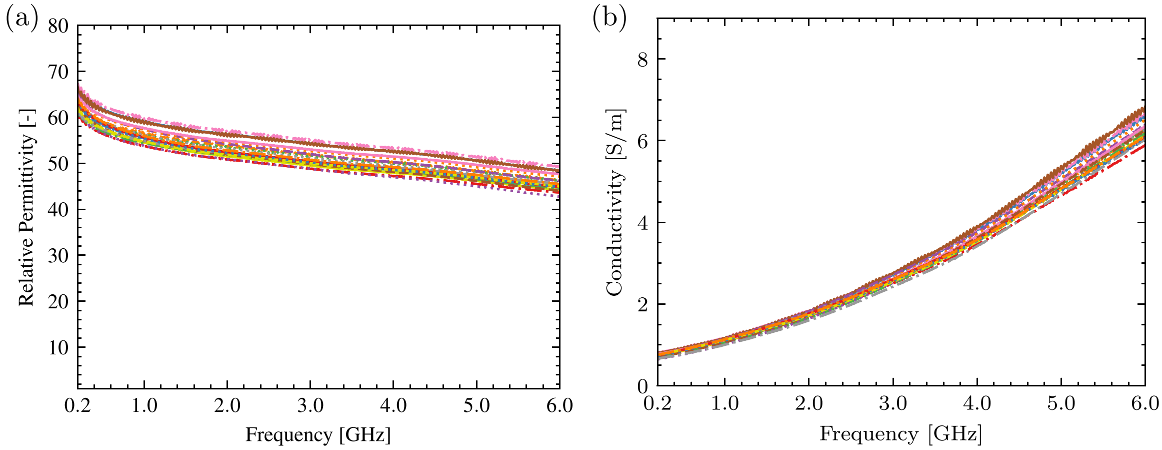

FIGURE 4 | (a) Permittivity and (b) conductivity of 20 replicate measurements of a representative ground beef sample (Sample 0) at baseline hydration.

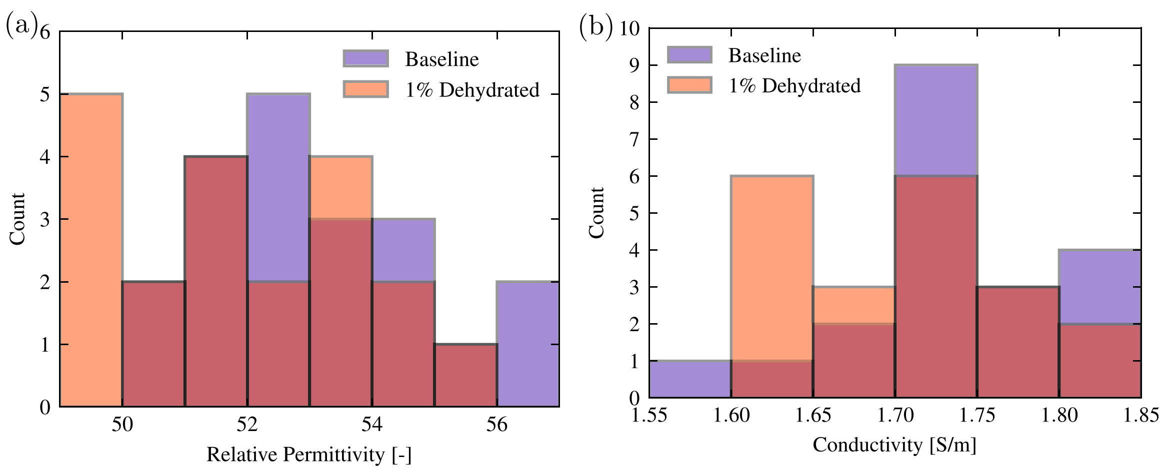

FIGURE 5 | Histograms of (a) relative permittivity and (b) conductivity of 20 replicate measurements of a representative ground beef sample (Sample 0) at 2 GHz for baseline hydration and after 1.0% increase in dehydration. Darker coloring represents overlap between distributions.

TABLE 3 | Summary statistics of relative permittivity for 20 measurements of sample 0 at 2 GHz. Baseline hydration vs 1.0% change dehydration.

	Minimum	1st quartile	Median	Mean	3rd Qquartile	Maximum
Baseline	50.7	51.9	52.6	53.1	54.3	56.8
1.0% dehydration	49.3	50.1	51.6	52.0	53.4	55.9

TABLE 4 | Summary statistics of conductivity for 20 measurements of sample 0 at 2 GHz. Baseline hydration vs 1.0% after dehydration.

	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
Baseline	1.60	1.71	1.74	1.74	1.77	1.83
1.0% dehydration	1.60	1.65	1.70	1.70	1.75	1.83

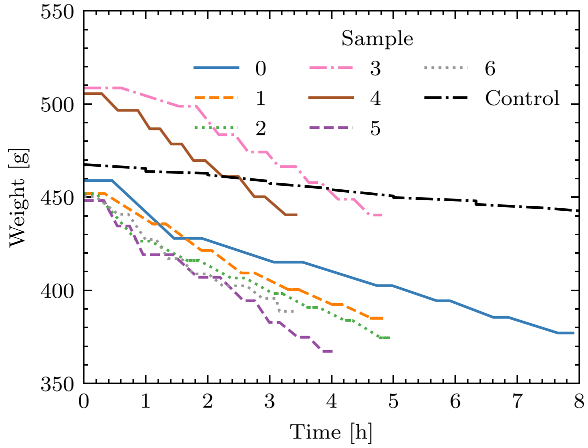

FIGURE 6 | Weight of ground beef samples after dehydration since time of first measurement.

was measured hourly for 8 h. At each hour the sample was mixed in a similar manner as during measurements to ensure that the sample was dehydrating homogeneously. On average 2.5 g was lost per hour due to dehydration and 1 g was lost after each mixing.

Figure 7 shows the average relative permittivity and conductivity of each sample before dehydration. Most of the samples had similar properties, however, Sample 1 is an outlier and falls well outside the expected values for a 90% muscle, 10% fat mixture so is removed from subsequent analysis.

Figure 8 shows the average permittivity and conductivity of all samples at each dehydration level. A clear trend is seen, with both permittivity and conductivity decreasing as dehydration increases. Permittivity decreasing with reduced water content is expected from previous work on tissue measurements and microwave hydration assessment (Bengtsson and Risman 1971); Garrett and Fear 2019). A decrease in conductivity also aligns with previous measurements (Bengtsson and Risman 1971). These changes will now be quantified via an LMM statistical model.

3.3 | Linear Mixed-Effects Model

The LMM is applied to the data for all samples except sample 1 ($M = 6$), hydration levels ($I = 8$), and repetitions ($K = 20$) without prior averaging. The null hypothesis is that permittivity and conductivity are not related to sample dehydration, measurement frequency, or their interaction, that is, $\beta_0 = 0, \beta_1 = 0, \beta_2 = 0$. As shown in Tables 5 and 6, dehydration, frequency, and their interaction significantly ($p < 0.05$) impact both relative permittivity and conductivity, and therefore the null hypothesis is rejected. These tables also report the overall mean, fixed effects, and standard error for permittivity and conductivity.

The overall mean for relative permittivity was $e^{\mu} = 59.1$ and the overall mean for conductivity was $e^{\mu} = 0.683\,\text{S/m}$. Figure 9 shows the random effects, or per sample mean, for each sample combined with the overall mean ($e^{\mu}e^{s_m}$) and the sample standard deviation due to individual measurement variation.

The log-transformed results can be readily interpreted by exponentiating both sides of the model

$$X_{mijk} = e^{\mu}e^{s_m}e^{\beta_0 H_i}e^{\beta_1 F_j}e^{\beta_2 (H_i F_j)}e^{\epsilon_{mijk}}. \quad (2)$$

Instead of each model component adding together linearly, the components scale each other and changes can be interpreted in relative terms. For example, keeping the other terms constant, and assuming random error is small, the relationship between the properties at two dehydration levels H_i and H_{i+1} can be expressed as a relative change

$$X_{i+1}/X_i = e^{(H_{i+1}-H_i)(\beta_0+\beta_2 F_j)}. \quad (3)$$

Thus, a unit change in dehydration ($H_{i+1} - H_i = 1.0\%$) causes an $e^{\beta_0+\beta_2 F_j}$ change in the response variable. This change can be expressed in percentage as $100(e^{\beta_0+\beta_2 F_j} - 1)$. The other terms in the model can be interpreted in a similar manner. Figure 10 shows the sensitivity of permittivity and conductivity to a percent change in weight due to water loss in this frequency range.

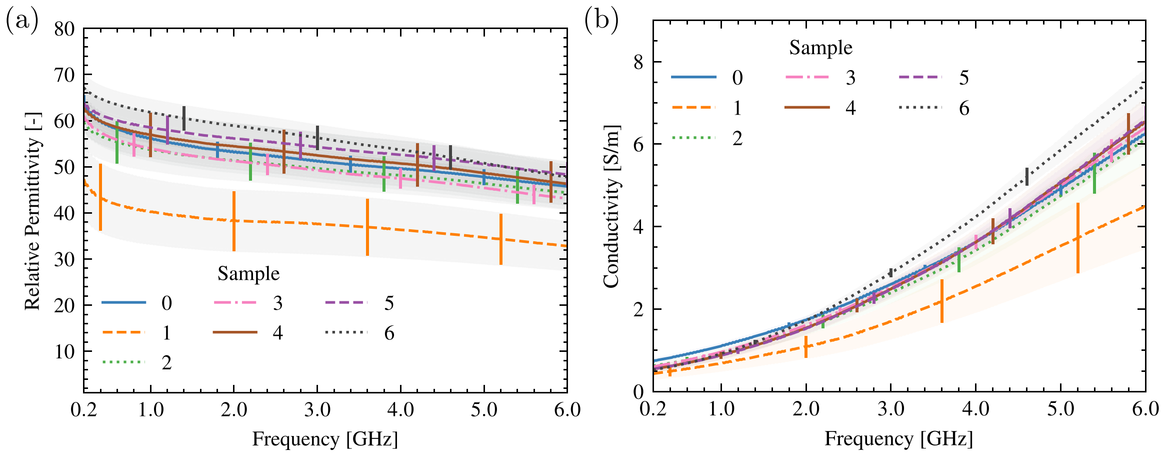

FIGURE 7 | Mean (a) relative permittivity and (b) conductivity of each ground beef sample at baseline hydration. Shaded regions and error bars represent standard deviation.

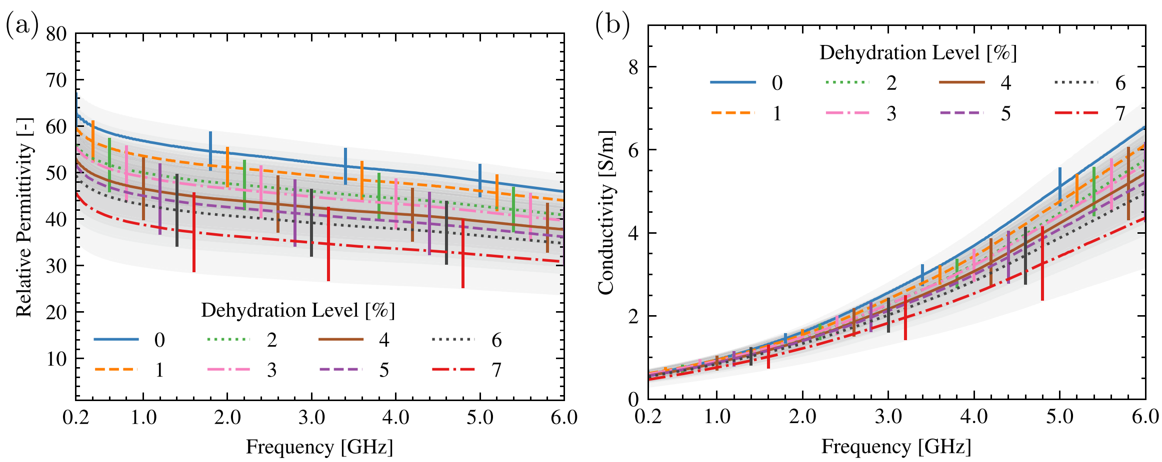

FIGURE 8 | Mean (a) relative permittivity and (b) conductivity of all ground beef samples (excluding Sample 1) at each dehydration level. Shaded regions and error bars represent standard deviation.

TABLE 5 | Linear mixed-effects model of dehydration, frequency, and their interaction on relative permittivity.

	Fixed effect	Standard error	95% confidence interval	*p*-value
Overall mean, μ (–)	4.08	0.03	4.02–4.14	< 0.001
Dehydration, β_0 ($\%^{-1}$)	−0.052	0.000	−0.053–−0.052	< 0.001
Frequency, β_1 (GHz^{-1})	−0.0411	0.0003	−0.0418–−0.0405	< 0.001
Interaction, β_2 ($(\%\cdot\mathrm{GHz})^{-1}$)	−0.00086	0.00008	−0.00101–−0.00071	< 0.001

4 | Discussion

Using the LMM, the sample means, independent of dispersion or dehydration, show considerable difference as seen in Figure 9. Thus, it is important to characterize ground beef samples before use. Less variation between samples could be achieved with more careful control of the sample composition, time since death, and processing, however, this is not possible with the more readily available commercial samples that are typically used for phantoms. Although there is considerable variation in baseline properties, the statistical model controls for the variation between samples and the expected change in properties found here can be generalized to other similar samples.

The LMM shows that dehydration has a significant ($p < 0.05$) effect on both permittivity and conductivity. Both permittivity and conductivity decrease as dehydration occurs. The effect of dehydration on permittivity (5.1%–5.6%) and on conductivity (3.2%–5.7%) are similar as shown in Figure 10 and Tables 5 and 6. The sensitivity of conductivity to dehydration is strongly frequency dependent as shown in Figure 10 and Table 6. A similar frequency dependency was seen in theoretical and simulation work (Garrett and Fear 2019).

In Bengtsson and Risman (1971), the properties of various meat products are measured and compared with their total water content at 2.8 GHz. A change of 3.2% and 2.9% per percent

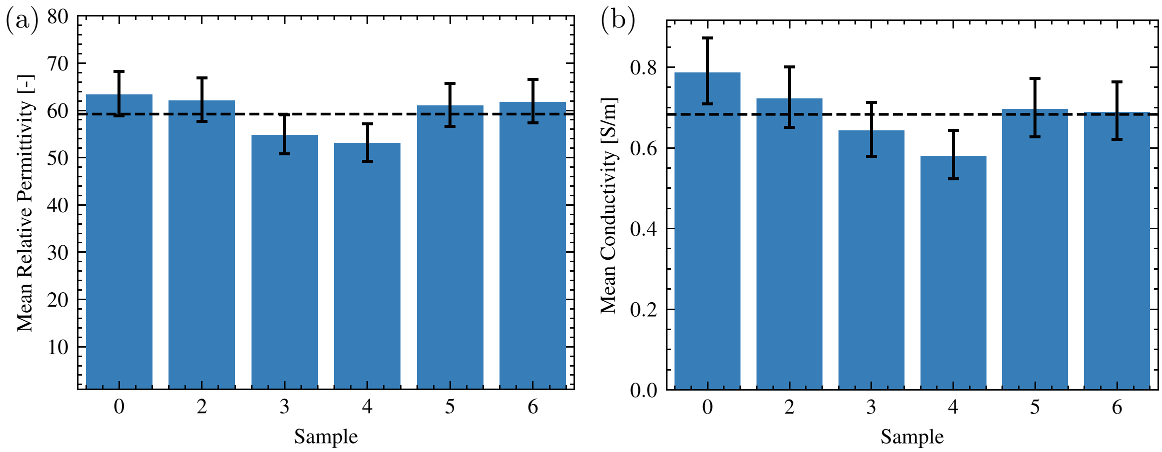

FIGURE 9 | Ground beef sample random effects and overall mean ($e^{\mu}e^{S_m}$) for (a) relative permittivity and (b) conductivity. Error bars represent random effect standard deviation. Dashed line indicates overall mean (e^{μ}).

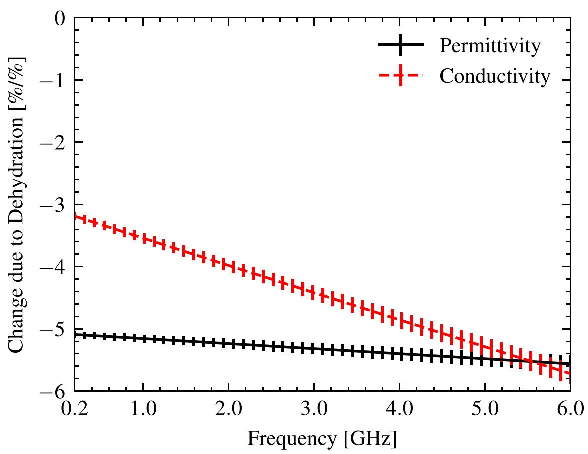

FIGURE 10 | Sensitivity of permittivity and conductivity to a percent change in weight due to water loss. Error bars represent the 95% confidence interval.

change in water content was measured in permittivity and conductivity, respectively. For a more accurate comparison, the percent differences in water content are converted to the equivalent percent change in weight assuming a nominal mass fraction of 0.74 for muscle (Duck 2013). Due to a percent change in weight, this translates to a change in permittivity of 4.3% and a change in conductivity of 3.8%. This change is similar to the 5.1%–5.6% change in permittivity and 3.2%–5.7% change in conductivity reported here.

In Pollacco et al. (2018), average property changes in excised mouse muscle tissue over 0.5–50 GHz are reported for weight changes between 0% and 10% where the exact weight changes are not reported. Changes of at least 0.1% (permittivity) and 0.5% (conductivity) are noted for ex vivo samples between the initial measurement and after 0%–10% weight change. Although these values are an order of magnitude different from the results shown here, the ambiguity in the reported weight changes make the comparison imperfect. The higher frequency range used also measures different dielectric phenomena, namely the predominate effect is that of free water rather than the effect of bound water at lower frequencies, which results in markedly different dispersion characteristics.

In Garrett and Fear (2019), the bulk properties of forearm models (comprised of skin, muscle, fat, blood, and bone tissue) are perturbed based on their nominal water content in simulation between 2 and 12 GHz. Sensitivity of 2.0% and < 0.3% are reported for permittivity and conductivity, respectively. These lower sensitivities may be attributed to the relatively high proportions of low water-content tissue (i.e., fat and bone) in the model used.

The statistical model outlined here is widely applicable when measuring the dielectric properties of tissue samples. It is well known that biological samples exhibit large within-sample and between-sample variations, thus, in general, a number of samples should be reported for any biological tissue measurements. The variation in the measured results must also be taken into account when exploring the impact of a variable of interest. When combined with a systematic measurement procedure, the model presented here provides a robust and informative method for exploring many research questions.

5 | Conclusion

The dielectric properties at microwave frequencies of commercially purchased extra lean ground beef samples were systematically analyzed at physiologically relevant dehydration levels of 0.0%–7.0% by weight in 1.0% increments. There was considerable variation within the samples because of their heterogeneous composition, and between samples because of differences in sample preparation that cannot be controlled for in commercial samples. An LMM was used to control for the substantial within- and between-sample variation. Using this model, the effect of dehydration on sample dielectric properties was isolated from confounding factors such as baseline properties and frequency dispersion. This statistical model can be used to augment existing dielectric measurement frameworks.

The analysis showed that dehydration resulted in significant decreases in the permittivity and conductivity. Due to a 1.0% decrease in weight due to water loss, permittivity decreased by 5.1%–5.6% and conductivity decreased by 3.2%–5.7%.

TABLE 6 | Linear mixed-effects model of dehydration, frequency, and their interaction on conductivity.

	Fixed effect	Standard error	95% confidence interval	p-value
Overall mean, μ (–)	−0.381	0.042	−0.471 to −0.292	< 0.001
Dehydration, β_0 ($\%^{-1}$)	−0.032	0.000	−0.032 to −0.031	< 0.001
Frequency, β_1 (GHz^{-1})	0.406	0.000	0.405–0.407	< 0.001
Interaction, β_2 ($(\%\cdot\mathrm{GHz})^{-1}$)	−0.0046	0.0001	−0.0048 to −0.0044	< 0.001

The changes in the dielectric properties of muscle tissue due to changes in water content reported here demonstrate the feasibility of detecting changes in hydration in humans and animals using microwave sensing techniques.

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Conflicts of Interest

The authors declare no conflicts of interest.

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