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ORIGINAL ARTICLE

Effect of marination in gravy on the radio frequency and microwave processing properties of beef

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Abstract Dielectric properties (the dielectric constant (ε′) and the dielectric loss factor (ε″)) and the penetration depth of raw eye of round beef *Semitendinosus* muscle, raw beef marinated in gravy, raw beef cooked in gravy, and gravy alone were determined as a function of the temperature (20–130 °C) and frequency (27–1,800 MHz). Both ε′ and ε″ values increased as the temperature increased at low frequencies (27 and 40 MHz). At high frequencies (915 and 1,800 MHz), ε′ showed a 50 % decrease while ε″ increased nearly three fold with increasing temperature in the range from 20 to 130 °C. ε′ increased gradually while ε″ increased five fold when the temperature increased from 20 to 130 °C. Both ε′ and ε″ of all samples decreased with increase in frequency. Marinating the beef in gravy dramatically increased the ε″ values, particularly at the lower frequencies. Power penetration depth of all samples decreased with increase temperature and frequency. These results are expected to provide useful data for modeling dielectric heating processes of marinated muscle food.

Keywords Microwave · Radio frequency · Dielectric properties · Penetration depth · Beef · Gravy · Marinating

Introduction

Introduction of novel alternative processing technologies and processes to preserve foods including meat products is one of the most challenging areas in food science. Electromagnetic radiation, namely radio frequency (RF) (3 kHz and 300 MHz) and microwave (MW) (0.3 GHz and 300 GHz) dielectric heating present several advantages compared to conventional heating such as reduced process time with improved quality of the final product (Coronel et al. 2008; Decareau 1985; Schiffmann 1986; Zhao et al. 2000).

Several factors can affect the heating uniformity of food processed using dielectric heating methods (microwaves and radio frequency). These generally include: product geometry, thermal, physical, and dielectric properties, and processing parameters such as frequency, temperature, power applied and treatment time (Schiffmann 1986). The dielectric properties (dielectric constant (ε′) and dielectric loss factor (ε″)) describe the behavior of a material when subjected to an electromagnetic field (Hasted et al. 1948). Therefore, dielectric properties are important in product development, food process engineering, in the design of equipment for heating purpose (Decareau 1985; Schiffmann 1986), and in choosing appropriate materials for containers and packaging (Tang 2005). ε′ is a measure of the ability of a material to store electrical energy. ε″ is a measure of a material's ability to convert electrical energy to heat (Hasted et al. 1948). The magnitude of these properties is important in determining the penetration depth of microwave power and power absorption rate during thawing or heating (Nelson 1973).

Two important mechanisms are responsible for dielectric heating in foods; dipole-dipole interactions and ionic interactions (Decareau 1985). With dipole-dipole interactions, the rapidly alternating electric field causes the oscillation of the dipoles of the molecules (i.e. water) in the food. The electromagnetic energy at this frequency disrupts the hydrogen bonds associated with the dipole rotation of polar

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molecules. With ionic interactions, the electric field induces the migration of ions (Decareau 1985). Both mechanisms create friction between adjacent molecules, as polar molecules align themselves within the electromagnetic field and as ions move within the electric field.

Dielectric properties of several food products have been reported (Coronel et al. 2008; Guan et al. 2004; Kent 1987; Tinga and Nelson 1973; Wang et al. 2003). Predictive models for dielectric heating properties have been developed based upon food composition (Mudgett et al. 1977; Ohlsson et al. 1974; Sipahioglu et al. 2003; Sun et al. 1995; Tulasidas et al. 1995). These models usually account for water and its physical state, salt, fat, carbohydrate, and protein levels; however, the importance of the interaction of each of these constituents as they relate to the dielectric behavior of a food product is not well understood. The ionic strength of the material, mostly a factor of salt content, has a significant effect on dielectric properties (Bengtsson and Risman 1971; Kent 1987; Guan et al. 2004).

Beef is the most frequently consumed meat in the United States (USDA, ERS 2005) and marinating a meat product or serving meat in a sauce or gravy are popular prepared and ready-to-eat foods. Marinating meat products involves incorporation of a number of possible components including spices, salts, sugars, fat, and acid into the muscle tissue. Marinating often improves the cooking yield, juiciness, and tenderness since the water holding capacity of the meat is often increased (Onenc et al. 2004). Also, adding a sauce or marinade improves the flavor, appearance, color attributes and texture of microwave cooked meat products.

Zhang et al. (2004) studied the dielectric properties of two comminuted meat products (pork based luncheon meat and white pork meat pudding) with a number of non-meat ingredients such as salt, starch, and onion over the temperature range 5–85 °C at both RF and MW frequencies. The final concentration of salt was 1.2 % for pork luncheon meat and 2.3 % for white pudding samples (Zhang et al. 2004). In an earlier work, Ohlsson et al. (1974) investigated the dielectric properties of raw beef, gravy (1.5 % salt (w/w)), and codfish at 450 and 900 MHz between 20 and 60 °C. They observed that gravy had a higher ε'' than raw beef samples. Bengtsson and Risman (1971) found that when 1 % salt was added to gravy, ε' changed very little, while ε'' increased about 20 %. For example, ε' increases with moisture content for most foods (Calay et al. 1995; Sun et al. 1995; To et al. 1974). However, studies report different trends for ε''. ε'' of most foods increases with temperature, which may cause thermal runway and reduce heating uniformity during processing. It is critical to design RF/MW processing systems with uniform electric energy in packaged foods to prevent thermal runway.

Meats served or cooked in gravy or sauces are popular processed foods and come in many varieties of preparation. They are used widely in food service and by consumers at home. However, there is little reliable information available in the literature regarding the dielectric properties of these heterogeneous foods. It is possible that the behavior of such foods during dielectric heating may be significantly different than the muscle tissue alone. Therefore, it is important to measure the dielectric properties of prepared ready-to-cook meat entrees if safe dielectric heating procedures are to be modeled or developed. Although, there have been some studies on RF and MW pasteurization and sterilization, more studies need to be done if acceptance of these methods by the Food and Drug Administration (FDA) is to receive broader approval. The FDA requires that a processor be able to accurately determine the cold spot in packaged foods as a means of ensuring that the applied for pasteurization or sterilization process is adequate and effective. Design of new thermal processing methods and protocols require accurate measure of dielectric properties and these data are not available. Further, computer simulation is an effective tool for studying influence of various parameters on heating uniformity in RF and MW heating of products. But, accurate computer simulations for dielectric heating processes will not be possible unless accurate dielectric property data exists as functions of temperature, composition, and electromagnetic wave frequencies (Zhao et al. 2000; Wang et al. 2008). Because of the interest in having better quality shelf stable muscle foods, this study is focusing on dielectric properties of beef and marinated beef products. The objective of this study was to determine the changes in the dielectric properties of eye of round beef in gravy as affected by temperature, frequency, and the marinating process. Based on these results the general heating time can be used to estimate the general heating performance of marinated meat products in gravy and lead to development of improved dielectric heating processing procedures for safer and more convenient meat products without the loss of nutritive values.

Materials and methods

Sample preparation

The eye of round beef (*Semitendinosus muscle)* cut from Angus beef cattle was obtained fresh (within two weeks post slaughter) from a local custom slaughterhouse (Moscow, ID). First, all visible fat on the outer surface of the cut was removed. Then samples of the beef muscle (19 g; 22 mm diameter, 45 mm long) were cut into cylinders to form a sample plug with the same dimensions as the sample cell to improve contact with the probe during dielectric property measurements as described by Basaran-Akgul et al. (2008), and then sliced into small cylindrical pieces (22 mm diameter, 15 mm long) making the samples the same diameter as the sample cell of the dielectric properties determination setup.

Marinating

Prepared beef cylinders (75 % moisture, 1.48 % salt, 2.24 % fat (w/w) were mixed with liquid gravy (70 % moisture, 2.5 % salt, 4 % fat (w/w)) which was prepared from commercially available dry mix product as described by the producer (Beef Gravy; Safeway, Inc. Pleasanton, CA). The marinated samples (60 g beef in 100 g liquid gravy) were stored at 4 °C for 18 h before determination of dielectric properties. The cooked beef samples were prepared using some of the marinated samples (i.e. 60 g beef in 100 g gravy) placed in small sealed plastic bags which were cooked (boiled) by immersing them in hot water at 75 °C for 20 min.

Measurements of dielectric properties

The dielectric properties measurement system used in this study consisted of an Agilent (formerly Hewlett Packard) 4291B Impedance Analyzer with a calibration kit (Agilent Technologies, Palo Alto, CA, USA), a custom-built test cell, a VWR Model 1157 programmable circulator (VWR Science Products, West Chester, PA, USA), and the dielectric probe included in the Hewlett Packard 85070B Dielectric Probe Kit. Measurements were conducted every 10 °C in the temperature range of 20 to 130 °C which covers typical conditions used in commercial pasteurization and sterilization processes and 121.1 °C is commonly used as a reference temperature in thermal process calculations in food engineering (Teixeira 1992; Toledo 1991) for all samples (raw beef, marinated beef, beef cooked in gravy, and gravy alone) at 201 discrete frequencies between 27 to 1,800 MHz (the upper limit of the impedance analyzer). The dielectric property values were reported at 27, 40, 915 MHz which are allocated by the US Federal Communications Commission (FCC) for industrial, scientific, and medical ISM applications (Rowley 2001). The data at 1,800 MHz, the upper limit of the impedance analyzer, were also reported here. The upper frequency (1,800 MHz) is close to another FCC allocated frequency 2,450 MHz, mainly used in domestic MW ovens. Two different lots of eye of round cut beef were used, and for each cut, three replicate samples were taken for measurement. The detailed information on procedure for calibration of the system and measurement the dielectric properties were conducted as described in Basaran-Akgul et al. (2008).

Calculation of penetration depth

Power penetration depth can be calculated according to following equation (Buffler 1993).

$$d_p = \frac{c}{2\sqrt{2}\pi f\left\{\varepsilon'_r\left[\sqrt{1+\left(\frac{\varepsilon''_r}{\varepsilon'_r}\right)^2}-1\right]\right\}^{\frac{1}{2}}}$$

dp: power penetration depth (cm), $\boldsymbol{c}$ is the speed of light in free space (2.998×10^8 m/s), $\boldsymbol{f}$ is the frequency (Hz), $\boldsymbol{\varepsilon'}$ is the dielectric constant, and $\boldsymbol{\varepsilon''}$ is the dielectric loss factor.

Data analysis

The data analysis was conducted using Statistical Analysis System (1999). Analysis of variance using PROC MIXED repeated analysis method was performed to determine the individual effects of frequency, temperature, marinating on the measured dielectric properties of the samples with significance set at $P<0.05$.

Results and discussion

ε' and ε'' values at RF and MW frequencies for raw beef, gravy, raw beef marinated in gravy, and cooked beef marinated in gravy are summarized in Table 1. The ε' and ε'' of the samples increased with increasing temperature both at RF and MW frequencies and decreased with increasing frequency especially at high temperatures. This indicated that run away heating is very likely to occur at RF range while it is not as likely at MW frequency range. The ionic conductivity plays a significant role in dissipating electromagnetic fields at RF (Guan et al. 2004), and it increases sharply with increasing temperature. As a result, ε'' of samples such as gravy, marinated beef and beef cooked in gravy samples increased as temperature increased at RF. ε' for all samples remained relatively stable between 20 and 50 °C. Above this temperature for marinated beef in gravy, ε' increased steadily up to 80 °C, then from 80 °C to 130 °C ($P<0.05$) remained stable at RF frequency. At high temperatures denaturation of protein causes to a release of water and shrinkage which is assumed to be a reason for significant changes in the dielectric properties of beef (Nelson and Datta 2001). Dielectric properties of marinated beef gradually decreased with increasing frequency but increased with temperature at RF. It also was observed that all the samples followed the same general trend of decreasing for ε' and increasing ε'' with increasing temperature at MW (Fig. 1). At all MW frequencies ε' values for gravy marinated beef samples also tended to decrease gradually with increasing temperature (Fig. 1a). However, mean values at 915 and

Table 1 Dielectric constant (ε′) and dielectric loss factors (ε″) (mean ± SD, *N*=3) for two different lots of eye of round beef samples at different frequencies over the temperature range from 20 to 130 °C

	T °C		27 MHz	40 MHz	915 MHz	1,800 MHz
Raw beef	20	ε′	92.2±1.75	85.0±0.98	58.6±0.82	55.3±0.98
		ε″	440.5±20.49	301.1±13.17	22.4±0.13	17.5±0.11
	60	ε′	107.6±2.05	95.1±0.80	51.2±1.56	48.2±1.40
		ε″	676.6±48.26	463.6±31.32	30.0±1.04	19.2±0.79
	100	ε′	99.8±9.51	86.8±7.38	37.1±2.56	33.4±2.32
		ε″	519.9±62.40	471.3±32.03	26.6±2.72	18.0±1.67
	121	ε′	105.0±9.92	91.0±7.17	37.7±2.58	33.5±2.29
		ε″	674.6±137.67	463.7±93.21	31.5±4.87	24.2±9.77
	130	ε′	103.9±10.21	89.9±7.55	38.3±1.66	33.9±1.50
		ε″	731.1±177.65	501.3±120.16	34.3±6.17	21.0±3.33
Gravy	20	ε′	101.2±2.61	90.3±1.84	71.7±0.28	69.6±1.04
		ε″	1270.8±61.47	855.4±41.60	45.0±2.62	29.8±1.84
	60	ε′	110.4±1.53	89.4±1.97	63.1±0.24	61.6±0.41
		ε″	2434.8±63.33	1640.8±42.15	77.0±1.68	43.2±1.49
	100	ε′	124.6±6.85	91.0±6.02	54.8±1.04	52.0±0.57
		ε″	3722.3±68.43	2507.4±41.01	113.0±1.40	64.7±1.26
	121	ε′	132.8±9.20	92.7±7.64	51.0±1.35	50.3±0.56
		ε″	4356.9±57.86	2932.4±36.50	130.9±0.89	68.9±1.08
	130	ε′	140.0±7.23	93.3±9.18	49.6±0.96	48.9±0.30
		ε″	4541.7±720.71	3123.6±25.46	138.8±0.02	72.5±0.51
Beef marinated in gravy	20	ε′	109.1±1.61	96.3±0.73	62.3±3.59	66.3±3.78
		ε″	789.1±59.52	537.1±39.46	36.5±3.14	20.1±2.43
	60	ε′	130.1±5.73	108.6±4.84	58.9±6.93	63.5±7.96
		ε″	1433.6±337.08	973.1±223.31	54.6±8.39	30.2±2.04
	100	ε′	145.7±11.62	116.6±0.45	50.2±9.04	50.8±10.28
		ε″	1933.3±472.35	1313.8±189.26	69.7±37.60	42.1±20.18
	121	ε′	147.1±8.23	115.4±4.50	47.3±5.68	46.9±6.35
		ε″	2215.2±613.89	1503.6±184.30	74.9±36.66	41.9±19.24
	130	ε′	151.0±8.31	117.1±5.52	47.3±4.95	45.0±3.36
		ε″	2424.4±698.70	1645.1±242.15	80.7±37.88	44.6±18.37
Beef cooked in gravy	20	ε′	75.7±11.67	68.0±9.35	42.4±1.43	40.5±1.91
		ε″	503.9±149.52	344.3±99.19	21.3±2.90	14.7±1.28
	60	ε′	88.8±26.80	76.6±22.12	38.8±2.22	36.7±1.25
		ε″	915.5±170.90	623.2±113.13	34.4±2.16	20.0±0.69
	100	ε′	102.5±31.59	85.7±26.55	37.6±1.50	34.7±0.30
		ε″	1432.2±382.39	972.2±254.69	51.4±7.54	28.5±3.29
	121	ε′	109.1±33.31	89.3±29.00	36.5±2.70	33.2±1.27
		ε″	1653.3±432.52	1121.4±288.45	58.7±8.65	32.4±3.74
	130	ε′	113.7±35.22	93.0±30.59	36.7±3.00	33.3±1.51
		ε″	1825.5±438.54	1239.3±295.44	64.3±8.92	35.4±3.77

T Temperature

1,800 MHz for ε′ and ε″ were significantly different ($P<0.05$) (Table 1). The increase in ionic conductance as a result of salt in gravy appears to be the principal reason for the differences in dielectric properties of marinated beef samples.

Frequency dependence of dielectric properties

Overall, both ε′ and ε″ were influenced by frequency, especially at high temperatures. For example, in the studied frequency range, ε′ and ε″ of samples decreased with

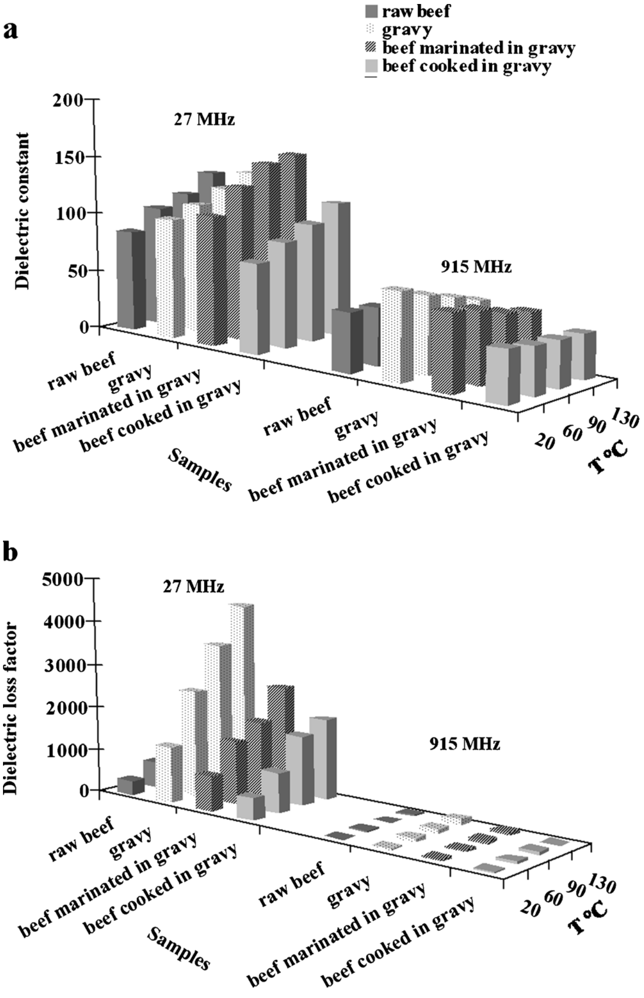

Fig. 1 Dielectric constant (ε') (**a**) and Dielectric loss factor (ε'') (**b**) for two different beef lots of eye of round at temperatures ranging from 20 to 130 °C and frequencies of 27 and 915 MHz

increase in frequency at high temperatures (Table 1). At elevated temperatures, the effect of frequency on the permittivity was much more pronounced than at 20 °C. When the frequency increased from 27 to 1,800 MHz, ε' of marinated beef samples decreased from 109.07 to 66.26 at 20 °C, but from 151.04 to 45.01 at 130 °C; ε'' decreased from 789.07 to 20.09 at 20 °C, but from 2424.42 to 44.05 at 130 °C. The trends observed in this work can be again attributed to the fact that the dielectric property values, in particular ε'', at low frequencies are influenced by ionic conductivity. The ionic conductivity in turn increases with temperature (Wang et al. 2008). In general, trends previously reported for dielectric properties as a function of frequency (Kent et al. 2001; Ohlsson et al. 1974; Wang et al. 2003) are supported by this study. Furthermore, the results of beef samples were similar to values reported by others (Brunton et al. 2006; Wang et al. 2012), However, they were not agree with comminuted meat products (pork based luncheon meat and white pork meat pudding with a number of non-meat ingredients such as salt, starch, and onion) (Zhang et al. 2004) in the same frequency range.

Temperature dependence of dielectric properties

To better understand the relationships between permittivity, marinating, and temperature, the $\varepsilon'$and ε'' at 27 and 915 MHz were plotted versus temperature ranging from 20 to 130 °C for all samples (Fig. 1). Both ε' and ε'' increased with marinating at each temperature. Figure 1 also shows that both ε' and ε'' increased with increasing temperature at RF. When the temperature was raised from 20 to 130 °C, ε' at 27 MHz increased from 92.23 to 103.88 and ε'' increased from 440.53 to 731.12 for raw beef samples, while ε' increased from 109.07 to 151.04, and ε'' increased from 789.07 to 2424.42 for marinated beef samples. ε'' of all samples increased 2–4 fold at 27 and 40 MHz as temperature increased from 20 to 130 °C, whereas the values of ε'' increased approximately 2–3-fold at 915 and 1,800 MHz for the same temperature rise. ε'' of marinated beef in gravy samples was about two times as much as the other food components for all frequencies. ε'' values of marinated beef and gravy alone samples increased sharply at 27 and 40 MHz with the increase of temperature, meanwhile, ε'' increased slightly at 915 and 1,800 MHz due to the opposing effects of ionic conductivity and dipole rotation of free water. The results indicated that run away heating (synergy of temperature and loss factor) is very likely to occur in the RF range while it is not likely in the MW frequency range.

Similar results were obtained by Wang et al. (2012) for meatballs where ε' of beef meatballs increased steadily as the temperature increased at RF frequencies (27 and 40 MHz) until 100 °C, while it decreased with increasing temperature at MW frequencies (915 and 1,800 MHz). Similar trends were also observed in the dielectric properties of salmon fillets (Wang et al. 2008). It is difficult to directly compare the results for this study to the others in the literature because of differences in samples and frequency range used. However, the range of values obtained in this study for the beef samples are comparable with those reported for turkey (Sipahioglu et al. 2003), beef (Bircan and Barringer 2002), beef and turkey (To et al. 1974) and pork (Brunton et al. 2005). The results of this study showed that increasing temperature (20 to 130 °C) increased ε' (Fig. 1a) at RF and decreased at MW. This is in agreement with most of the literature for food samples, which indicates that ε' decreases with temperature at MW (Brunton et al. 2005; Bircan and Barringer 2002; Coronel et al. 2008; Ohlsson et al. 1974; Fasina et al. 2003).

The temperature at which ε' increase occurred appears to be close to the denaturation temperature for collagen as predicted by Zhang et al. (2004), Bircan and Barringer (2002) Brunton et al. (2005). A rapid release of fluid leading to increased fluid mobility within the muscle is associated with collagen denaturation. Since ε′ at MW frequencies relate to the mobility of water (Roebuck and Goldblith 1972), this may explain why a sharp rise occurs at denaturation temperature. The rise in ε″ with increasing temperature was observed especially at 27 and 40 MHz in the samples tested. The ε″ values for the marinated beef were much higher than raw beef and cooked beef samples approaching in value to the gravy alone. In this study, ε″ increased with increasing temperature up to 60 °C for marinated beef samples and then decreased between 60 and 70 °C. At 70 °C ε″ began to increase again. Zhang et al. (2004) also observed similar results that ε″ increased steadily between the temperature range of 5–50 °C. This phenomenon is most likely due to the increase in ionic mobility, which increases with temperature. Similarly, Li and Barringer (1997) observed a sharp increase in ε″ around 70 °C for ham containing salt, which was attributed to protein denaturation. During dielectric measurements on meat samples, Bircan and Barringer (2002) observed a similar decrease in ε′ and increase in ε″ at denaturation temperatures range (70–80 °C) and MW frequencies (915 and 2,450 MHz). Brunton et al. (2005) also observed a similar trend for ε′ of pork meat at MW frequencies (300, 915, 2,450, and 3,000 MHz) at 66 °C. Collagen is the major connective tissue protein present in meats and collagen fibers begin to shrink at around 64 °C with complete denaturation usually being complete at around 70 °C (Rochdi et al. 1985). However, prolonged heating of meat above 70 °C will eventually produce a reduction in shear value and this is believed to be due to the cleavage of peptide bonds in the collagen (Sims and Bailey 1992). In the majority of muscle protein systems examined, actin proteins are the most heat stable and begin to denature at temperatures above 71 °C with denaturation complete in most instances at 83 °C (Barbut and Findlay 1991). Rochdi et al. (1985) reported that when collagen fibers are restrained during heating the temperature at which denaturation is completed could increase to 80–85 °C. Therefore, it must also be considered that the temperature can modify the heated product so that dielectric properties not only change with the temperature but also the type of product.

Effect of marination on dielectric properties

ε″ of marinated beef in gravy samples increased more with temperature from 20 to 130 °C 3-fold at RF and 2-fold at MW frequencies in general (Fig. 1b). The more dissolved ions in gravy, the greater the ionic loss component of ε″, and the greater the increase which was expected since the ionic loss increases with temperature (Mudgett 1995). The values of dielectric properties of marinated beef in gravy were found to be between those of its constituents, lower than those of gravy but higher than those of raw beef and beef cooked in gravy. This was due to both the water and ion content of marinated beef in gravy were between those of its constituent. Similar results were observed by other researchers for increased ionic components for different food components (Bengtsson and Risman 1971; Houben et al. 1991; Sipahioglu et al. 2003). Bengtsson and Risman (1971) found that when 1 % salt was added to a gravy, ε'_r changed very little, while ε''_r increased by about 20 % because of the contribution from electric conductivity to the effective loss factor. Houben et al. (1991) studied the effect of salt content on ham samples. ε″ showed an increase by a factor of 1.5 to 2.0 at target temperatures between 15 °C and 80 °C. In another study, Kirmaci and Singh (2012) studied the dielectric properties of marinated chicken breast meat at RF and found that the addition of salt due to marination changed ε′ very little while ε″ increased by 2-fold. The ionic loss component plays a significant role in dissipating electromagnetic fields at RF/MW frequencies, ε″ of most biomaterials increases with increasing temperature due to increased ionic conductivity (Decareau 1985; Guan et al. 2004; Tang 2005). As a result, ε″ of marinated beef samples increased sharply as temperature increased.

In addition, a decrease in ε′ and an increase in ε″ with temperature were observed for all the samples at MW (Fig. 1b). These observations were similar to previous published data at various frequencies (Fasina et al. 2003; Kent 1987; Ohlsson et al. 1974; Sun et al. 1995). The decrease in ε′ of samples with increasing frequency at a given temperature agrees with the results reported by To et al. (1974) for beef and turkey products at MW (300, 915, and 2,450 MHz). For beef products, both ε′ and ε″ increased with decreasing frequency at constant temperature; however, ε′ decreased while ε″ increased with increasing temperature at constant frequency. This was confirmed by this study. However, van Dyke et al. (1969) reported an increase in ε'_r with temperature (1 to 80 °C) at 915 MHz on reconstituted beef samples.

There has been limited research conducted on marinated samples. Tanaka et al. (1999) demonstrated that while ε′ decreased with increasing temperature for marinated chicken breast placed in 0 %, 0.5 %, and 1 % salt solutions at both 915 and 2,450 MHz, ε″ increased with increasing temperature at 915 MHz, but at 2,450 MHz dielectric loss factors decreased from 0 to 35 °C and then increased from 35 to 70 °C. Although not same frequencies were used, Ohlsson et al. (1974) stated that the risk may be larger for run-away heating at 450 and 900 MHz than in samples treated at a higher frequency, for example 2,800 MHz. Researchers also reported that the risk for run away heating increases rapidly with increasing salt content (Ohlsson et al. 1974; van Dyke et al. 1969). Based on these observations, beef in gravy may be at greater risk for run away heating compared to samples without gravy because of the effect of temperature on increase in ε″ (Fig. 1b) and to a lesser extent, a decrease in ε′

(Fig. 1a). Lyng et al. (2005) studied the dielectric properties in different types of meat and the ingredients commonly used in meat products and they reported that ingredients such as salt, phosphate and nitrite increased ε″. Addition to these, it was reported that salt and sugar in solution reduce ε′ and increase ε″ at MW (2,450 MHz) (Calay et al. 1995). Zheng et al. (1998) reported dielectric properties at 915 MHz and 2.45 GHz on raw non-marinated and marinated catfish and shrimp at temperatures from about 10 to 90 °C. The composition of the marinade was not provided but the marinade formula consisted of salt, dextrose, sodium phosphates, black pepper, spice extracts, and lemon oil. Measurements showed that marination increased both ε′ and ε″. However in this study, ε′ decreased with increasing temperature and frequency (Fig. 1a) whereas ε″ increased with temperature (Fig. 1b).

Penetration depth

Penetration depth for all samples was calculated from the measured ε′ and ε″. Penetration depths calculated from the measured dielectric properties of raw eye of round beef, raw beef marinated in gravy, raw beef cooked in gravy, and gravy alone samples are listed in Table 2 at four specific frequencies over the temperature range from 20 to 130 °C. Penetration depths for all samples (Table 2) decreased with increasing temperature and frequency. Power penetration depths of all samples decreased by approximately 40–65 % as temperature increased from 20 to 130 °C at all frequencies. At each temperature, the penetration depth at RF frequencies (27 and 40 MHz) was much greater than that of microwave frequencies (915 and 1,800 MHz). Penetration depth at RF and MW frequencies for marinated beef in gravy was lower than for cooked beef in gravy and raw beef samples because of higher ε″ values. The marinated samples in this study could have a higher dielectric loss factor due to the presence of ionic compounds in gravy such as salt which alters the penetration pattern of RF and MW that may cause a different rates in heating. The lower the frequency, the deeper the energy can penetrate into the samples. These results suggested that more energy was dissipated in the surface layers of marinated foods because of the higher salt content which affects the ionic response to the electromagnetic wave.

The data for penetration depth in Table 2 shows an increase in heating for the all of the samples with decreasing frequency. Another trend observed is that, for the raw beef sample, the penetration depth slightly increased up to a temperature of 90 °C while for certain frequencies the penetration depth started decreasing after 90 °C for raw beef. This may be due to protein denaturation process at this temperature in raw beef. The penetration depth decreased for gravy alone, cooked beef in gravy, and raw marinated beef in gravy samples with increasing temperature.

Table 2 Penetration depths (mm) (mean ± STD, $N=3$) for two different beef lots of eye of round at temperatures ranging from 20 to 130 °C

	T °C	27 MHz	40 MHz	915 MHz	1,800 MHz
Raw beef	20	50.9±0.75	42.6±0.60	13.3±0.20	9.9±0.16
	40	52.0±0.75	43.4±0.60	12.9±0.14	9.8±0.15
	60	49.6±2.08	41.3±1.72	11.7±0.50	9.0±0.39
	80	56.7±4.44	47.2±3.68	12.7±0.67	9.6±0.41
	100	60.3±1.42	49.2±1.86	12.6±0.00	9.4±0.12
	121	52.0±2.85	43.2±2.38	10.6±0.43	6.7±1.14
	130	49.6±6.50	41.2±5.46	10.2±1.47	7.7±1.02
Gravy	20	36.5±0.92	30.4±0.78	10.3±0.54	7.6±0.40
	40	28.9±2.08	23.9±1.78	7.2±0.81	5.9±0.63
	60	25.9±0.36	21.4±0.30	6.1±0.12	5.1±0.15
	80	23.0±0.30	18.9±0.25	5.9±0.08	4.2±0.10
	100	20.8±0.22	17.2±0.17	4.4±0.06	3.6±0.08
	121	19.2±0.15	15.8±0.12	3.9±0.04	3.2±0.05
	130	20.3±0.70	15.3±0.09	3.7±0.01	3.0±0.02
Beef marinated in gravy	20	47.7±2.10	39.9±1.75	11.8±0.65	11.0±1.60
	40	42.5±1.17	35.3±0.95	10.3±0.14	9.8±1.60
	60	35.0±4.59	29.0±3.79	8.0±0.73	7.2±0.06
	80	36.4±1.31	30.1±2.43	7.5±2.02	6.7±2.19
	100	35.0±1.32	28.4±2.75	6.9±2.69	5.6±1.98
	121	31.3±1.19	25.9±1.97	6.3±2.23	5.1±1.83
	130	29.6±1.81	24.4±2.82	5.9±1.99	4.7±1.56
Beef cooked in gravy	20	59.5±1.35	49.7±2.66	16.6±1.90	11.8±1.71
	40	52.2±3.33	43.4±2.53	13.1±1.33	10.3±0.50
	60	42.9±3.15	35.5±2.36	10.1±0.58	8.2±0.11
	80	37.1±3.85	28.8±2.91	8.2±0.80	6.8±0.49
	100	34.0±3.43	28.0±2.54	7.2±0.49	5.9±0.32
	121	31.5±2.88	26.0±2.09	6.4±0.53	5.1±0.36
	130	30.0±2.24	24.7±2.57	6.0±0.27	4.7±0.12

T Temperature

In another study on penetration depth Al-Holy et al. (2005) determined the dielectric properties of salted roe products (0.2–3.3 % salt) at 27 and 915 MHz from 20–80 °C and found that ε′ and ε″ increased with increasing temperature and frequency. The penetration depth dropped as salt concentration and temperature increased. Zheng et al. (1998) determined the penetration depth for marinated shrimp and catfish at MW frequency (915 and 2,450 MHz). They observed that marination increased ε″ and decreased penetration depth of the MW radiation into the shrimp and catfish samples due to addition of salt and possibly other marinade components. The temperature difference from surface to the center of marinated seafood samples was greater than for non-marinated samples, which indicates a concentration of the electromagnetic energy of the marinade at the product surface. They also stated that the penetration depths of the MW radiation for all samples decreased with increasing temperature (Zheng et al. 1998), in support of the results presented in Table 2. Lyng et al. (2005) studied the effects of ingredients that used in marinating the lean meat products stated that higher absorption of power near the surface and a lower penetration depth of MW than non-marinated products. Kirmaci and Singh (2012) presented that fresh chicken breast meat had greater penetration depth of RF than the marinated chicken breast meat.

The results in this study supported by other studies in the literature in which temperature and composition dependence of ε′ and ε″ for beef products have been determined (Bircan and Barringer 2002; Brunton et al. 2005; Byrne et al. 2010; Ohlsson et al. 1974). As reported for other foods and agricultural materials (Al-Holy et al. 2005; Lyng et al. 2005; Ohlsson et al. 1974; Wang et al. 2003) the penetration depth was always greater at 27 MHz in comparison to 1,800 MHz (Table 2). The marinated beef in gravy had a higher ε″ due to the presence of ionic compounds such as salt which altered the penetration depth of RF and MW. At RF (27 and 40 MHz), the penetration depth decreased with temperature, while at MW (915 and 1,800 MHz) temperature only slightly affected the penetration depth.

Conclusion

Knowing how the dielectric properties of foods vary with composition, temperature, and frequency is important. Dielectric properties raw eye of round beef *Semitendinosus* muscle, raw beef marinated in gravy, raw beef cooked in gravy, and gravy alone samples as a function of marinating, frequency, and temperature were measured and the penetration depth of the samples were calculated. ε′and ε″ were significantly affected by temperature (20–130 °C), frequency (27–1,800 MHz), and marinating. Both ε′ and ε″ of the samples decreased with increase in frequency over the detected frequency range from 27 to 1,800 MHz. Marinating the beef samples increased ε″ and decreased penetration depth of the radio frequency and microwave radiation of beef due to an increase in ionic strength from the addition of gravy. A comparison between frequencies (RF and MW) showed an increase in ε′ and ε″ with an increase in temperature (except ε′, which decreased at MW frequencies) and decrease in frequency, resulting in considerably smaller differences in penetration depth. At any temperature, penetration depth was always greater at RF (27 and 40 MHz) in comparison to MW (915 and 1,800 MHz). The results of this study can be used to estimate the general heating performance of marinated meat products in gravy in a dielectric field as a function of power level, product thickness, frequency and time-temperature progression. The dielectric properties measured in this study are important parameters for designing dielectric heating system for processing marinated beef products.

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