ISSN 1726-5479

SENSORS & TRANSDUCERS

12/12
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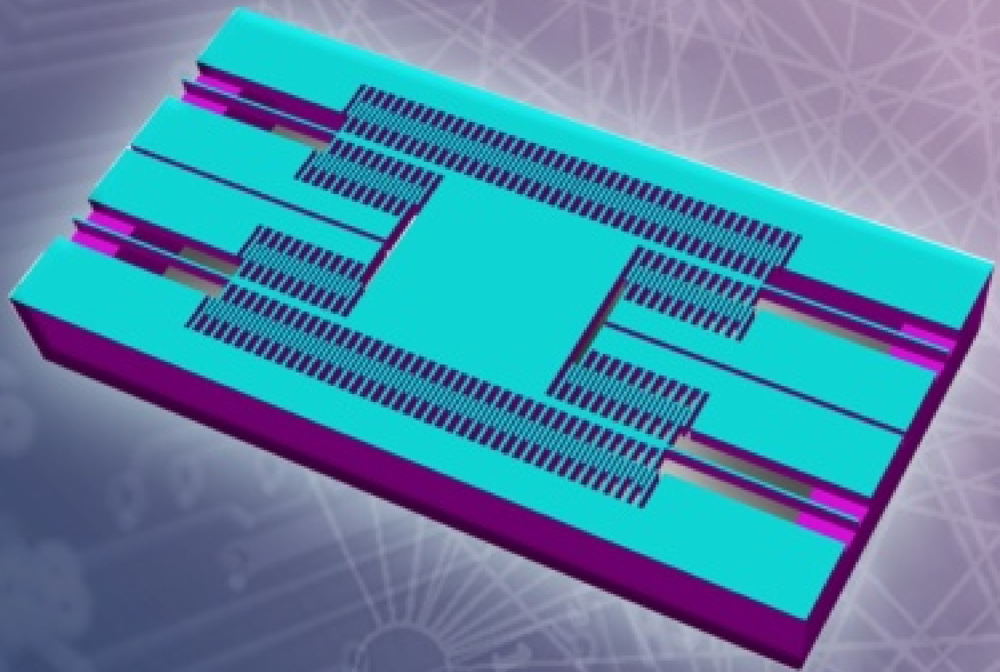

Sensors and Intelligent Systems

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 17, Special Issue
December 2012

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Contents

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Special Issue
December 2012

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ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 17, Special Issue, December 2012, pp. 247-256

Sensors & Transducers

ISSN 1726-5479

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Permittivity and Conductivity Dispersions of Properly and Non-properly Slaughtered Goat Meat

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Received: 29 September 2012 /Accepted: 29 October 2012 /Published: 18 December 2012

Abstract: Electrical properties of meat, such as permittivity and conductivity, depend on its constituents like blood, ions, and water molecules. These properties can be used as indicators to inspect the quality of meat. In this work, the permittivity (*ε'*) and the conductivity (*σ*) of meat obtained from properly and non-properly slaughtered goats were investigated over a frequency range of 50 Hz - 4 MHz and up to 168 hours of postmortem time. The results revealed that at frequencies below few kHz, a significant difference in the *ε'* between the two types of meat was found. The results also showed that the difference in the *ε'* and *σ* between the two types of meat can still be observed even after 7 days of postmortem time. The results suggest that it is possible to use *ε'* and *σ* to distinguish between the properly and the non-properly slaughtered goat meat. *Copyright © 2012 IFSA.*

Keywords: Meat, Permittivity, Conductivity, Frequency.

1. Introduction

Meat is a biological tissue that, upon consumption, supplies the human body with protein necessary for growth. Meat with high blood content, however, is considered unhealthy because the blood retained in the meat could potentially become a growth medium for hazardous microorganisms and bacteria [1], [2]. To obtain the healthy meat, it is recommended to drain out blood as much as possible from the animal during slaughter. Therefore, a proper animal slaughtering process that causes a rapid and thorough bleeding out must be used.

Heart beat is one of the many factors that affect the rapid bleeding process. It is high when the animal is directly slaughtered by sticking and exsanguinations method, whereas it is low when the animal is stunned before being slaughtered by the same sticking and exsanguinations method. The stunning process has three main categories namely electrical, mechanical and pneumatics. Upon application of these techniques, the animal may become unconscious, fall into deep state of unconsciousness or in the worst case scenario die. Within these states of unconsciousness, the heart is not beating as strong as when the animal is conscious. Therefore, significant difference in terms of blood volume retained in the carcasses is expected. Meat obtained by this or similar process is considered as meat from non-properly slaughtered animal.

This paper aims to differentiate properly and non-properly slaughtered goat meat obtained from the extreme cases of conscious and dead goats, respectively. Firstly, the permittivity and conductivity dispersions of meat are highlighted. Then, the changes in permittivity and conductivity during meat ageing are investigated after 12 hours, 3 days and 7 days of postmortem time. Lastly, based on the results, a frequency range is proposed to distinguish between the two types of goat meat.

2. Electrical Properties of Meat

2.1 Permittivity and conductivity of meat

The electrical properties of meat can be represented in terms of dielectric permittivity and conductivity [3]. Dielectric permittivity describes the behavior of a dielectric material under an applied electric field. This dielectric permittivity is usually relative to the permittivity of free space. Mathematically, relative dielectric permittivity is a dimensionless and complex quantity, which can be represented by equation (1) [4].

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon^{''}, \tag{1}$$

In this equation, the real part *ε'* refers to the dielectric constant or the relative permittivity, which is a measure of the material's capacitance and ability to store electrical energy when an external electric field is applied. The imaginary part *ε"* refers to the loss factor associated with the energy absorption [5].

As for conductivity, it is also a complex quantity, which can be represented by equation (2) [6].

$$\sigma^{*} = \sigma + j\omega\varepsilon_{0}\varepsilon, \tag{2}$$

In this equation, σ refers to the electrical conductivity, which is a measure of the material's ability to transport charges when an external electric field is applied [7]. The ε refers to the dielectric permittivity. ω is the angular frequency and ε_o is the permittivity of free space (8.85×10^{-12} F/m) [8].

The permittivity and the conductivity are influenced by many factors such as the frequency of the applied electric field, the surrounding temperature, and the moisture content [9, 10]. For the frequency-dependent, these electrical properties of meat exhibit three main dispersions denoted as α, β and γ. The α dispersion is seen at a frequency range from few Hz up to few kHz and it is mainly attributed to the distribution of the ions. The β dispersion arises at MHz frequencies as a result of Maxwell Wagner effect where the polarization of cell interfaces occurs. The γ dispersion exists at GHz frequencies, and it is mainly due to the dipolar polarization of water molecules [8, 11]. Understanding these parameters is important for interpreting the results of the work presented afterwards.

2.2. Model of Meat Structure

Meat is composed of many constituents such as connective tissues, muscle fibers, water molecules, metal ions, proteins and macromolecules like organelles. This anisotropy in the composition of meat causes a non-ideal electrical response of meat when subjected to an external electric field [12]. To illustrate this, meat tissue is typically modeled as an array of cells surrounded by insulating cellular membranes [13] as shown in Fig. 1. The cellular membrane isolates the intracellular fluids or the conductive interiors of the cell from the extracellular fluids. At low frequencies (below few kHz), when an external electric field is applied, the cellular membrane alters the current path or the ions passage from extracellular fluids to the intracellular fluids causing a counter-ion phenomenon along the cellular membrane [7, 14]. This is expected to increase the ε' and decrease the σ of meat. However, with increasing frequency, the current paths become aligned to the applied electric field and pass through the cellular membrane and the intracellular fluids. As a result, ions exchange between the intra and the extra-cellular fluids can now take place. This phenomenon leads to a higher σ and a lower ε'.

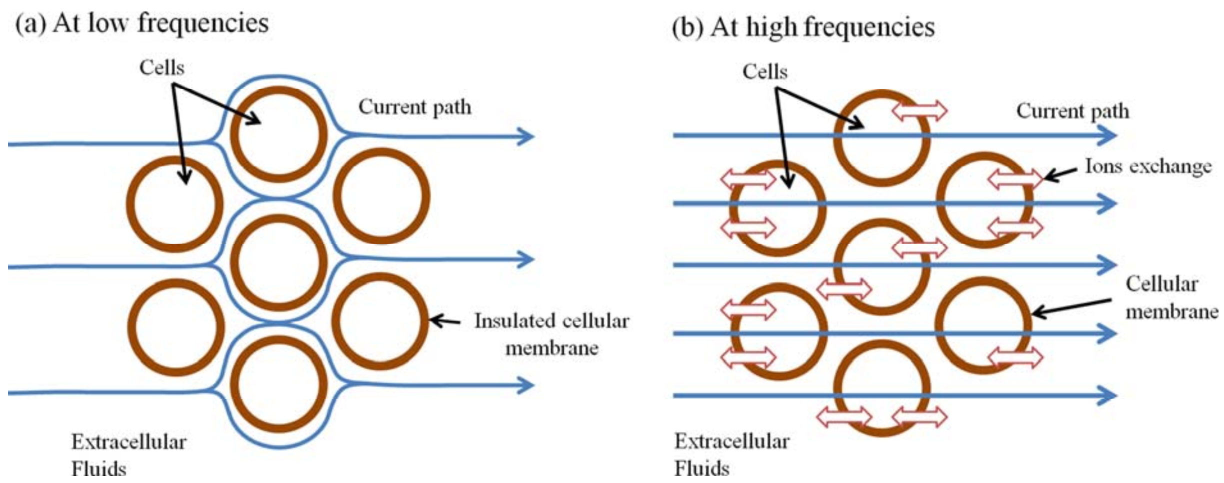

Fig. 1. Model of meat structure depicting the (a) altered current path at low frequencies, and (b) aligned current path at high frequencies.

3. Materials and Methods

3.1. Raw Material

Feral goats of similar age and from one same farm were selected and delivered to a Veterinary Research Institute. The goats were weighed and then prepared for slaughtering. Some goats were slaughtered properly according to the Islamic method by cutting the two jugular veins and arteries using a sharp knife. The other goats were put to death first by inhaling diethyl ether followed immediately by cutting the two jugular veins and arteries using also a sharp knife. After the slaughter, the goats were weighed again in order to determine the percentage of blood loss. The goat meat obtained from the Islamic method was labeled as the properly slaughtered goat meat while the latter one was labeled as the non-properly slaughtered goat meat.

The labeled raw meat was then packed in plastic zip-lock bags. The bags were placed inside two thermally insulated boxes filled with ice cubes in order to preserve the freshness of the raw meat. Lastly, the boxes were delivered to our laboratory.

3.2. Meat Samples Preparation

Slices of meat without fat and bone were prepared from the hind limb part. They were then labeled and placed again in plastic zip-lock bags before storing them in a freezer. Prior to conducting any measurements, the slices were thawed for 2 hours to ensure that they are at the same 23 ^oC ambient temperature. After that, the meat slices were cut into samples with a thickness of 5.5 mm to minimize the electrode polarization effect [15]. To reduce the influence of fiber orientations during measurements, the samples were cut in a fixed perpendicular direction of the muscle fibers to the applied electric field [16].

3.3. Measurement Technique

The equipments used in this work consist of an Agilent 4294 Impedance Analyzer connected to an Agilent 16451B parallel plate dielectric fixture with a 5 mm guarded electrode (see Fig. 2).

Fig. 2. Equipment used for measuring the permittivity and the conductivity of meat, which consists of Agilent 4294 impedance analyzer connected with Agilent 16451B dielectric fixture.

Prior to any measurement, a standard calibration of open and short compensation was performed [17]. Then, the sample of meat was put between the two parallel plates. A good contact between the electrodes and the sample was carefully made as required in the contacting electrode measurement technique [17]. The measurements were done over a frequency range from 50 Hz up to 4 MHz at a constant temperature of 23 ^oC. In this work, the quantities measured from the impedance analyzer were capacitance and conductance. The measured capacitance was then used to calculate the relative permittivity using equation (3).

$$\varepsilon' = \frac{T_m C_p}{\pi (d/2)^2 \varepsilon_0}, \quad (3)$$

In this equation, ε' refers to the relative permittivity, T_m refers to the thickness of the sample under test, C_p refers to the parallel capacitance, d refers to the diameter of the guarded electrode, and ε_o refers to the permittivity of free space. For the measured conductance, it was also used to calculate the conductivity using equation (4).

$$\sigma = \frac{T_m G}{\pi (d/2)^2}, \tag{4}$$

In equation (4), σ refers to the conductivity, T_m refers to the thickness of the sample under test, G refers to the conductance and d refers to the diameter of the guarded electrode.

4. Results and Discussion

Blood loss for both types of goat meat was determined by calculating the difference in the goat's weight before and after slaughter. The average percentage of blood loss obtained from the properly slaughtered goats was 6.29 %, whereas from the non-properly slaughtered goats was 1.37 %. The 4.92 % difference in blood loss shows that there is a significant difference in the blood volume between the properly and the non-properly slaughtered goat meat which would contribute to the permittivity and conductivity dispersions for both types of goat meat [18].

Figs. 3 and 4 show the relative permittivity and conductivity dispersions of goat meat measured after 12 hours, 3 days and 7 days of postmortem time, respectively. In general, the permittivity and conductivity dispersions obtained in this work are in agreement with the permittivity and conductivity dispersions published in ref. [16] for pork and [19] for beef.

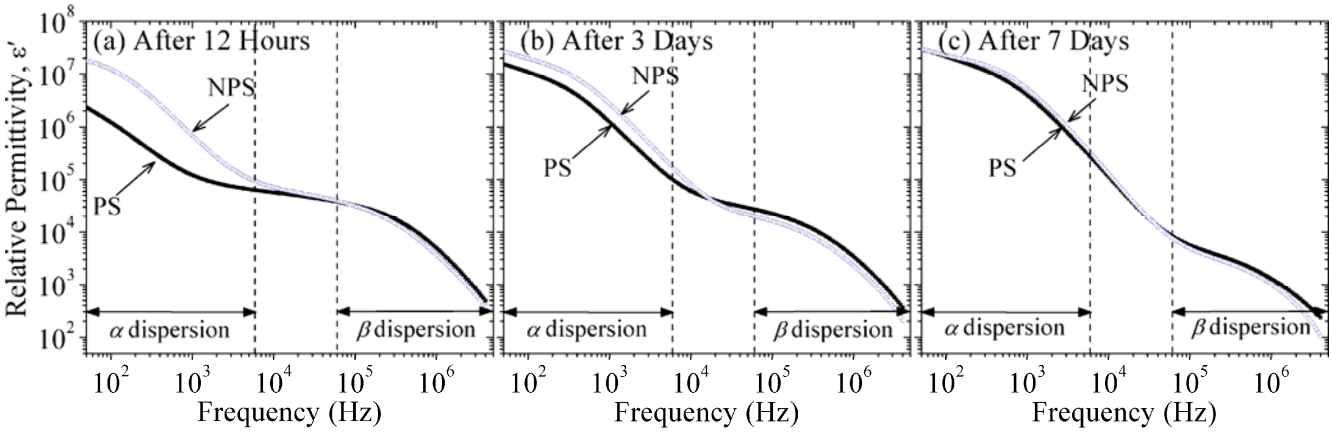

Fig. 3. Permittivity dispersion of properly slaughtered (PS) and non-properly slaughtered (NPS) goat meat measured after (a) 12 hours, (b) 3 days and (c) 7 days of postmortem time.

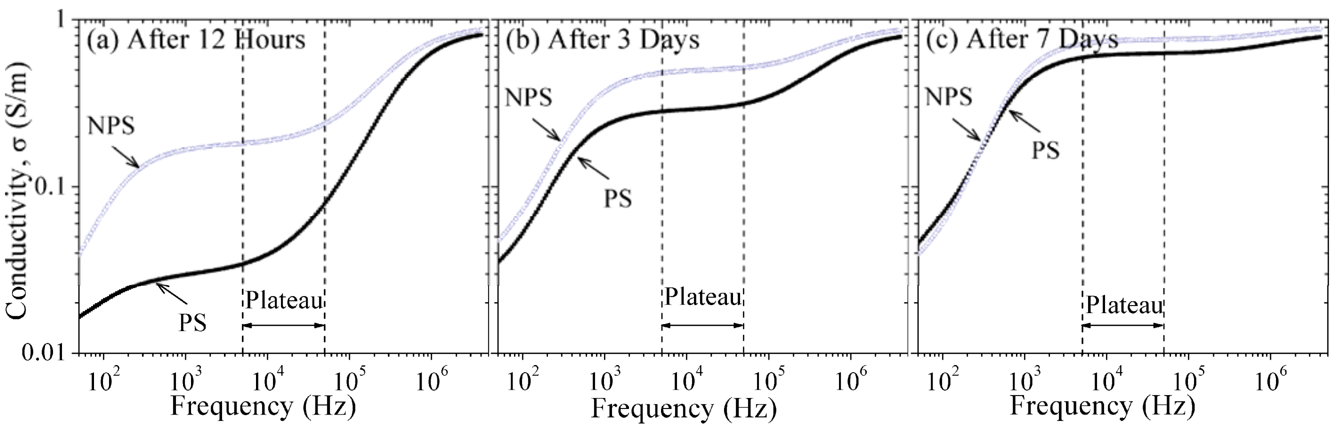

Fig. 4. Conductivity dispersion of properly slaughtered (PS) and non-properly slaughtered (NPS) goat meat measured after (a) 12 hours, (b) 3 days and (c) 7 days of postmortem time.

4.1. Permittivity Dispersion of Goat Meat

The α and β dispersions of both types of goat meat are shown in Fig. 3.

In Fig. 3 (a), after 12 hours of postmortem time, the non-properly slaughtered goat meat shows higher relative permittivity at α dispersion as compared to the properly slaughtered one. This increment in the relative permittivity is attributed to the distribution of the ions along the cells membrane [16] which leads to an increase in the capacitance of the membrane, and hence an increase in the overall permittivity. Since the non-properly slaughtered goat meat contains more blood volume as compared to the properly slaughtered one, it has more ionic content. As a result, the non-properly slaughtered goat meat shows higher relative permittivity than the properly slaughtered goat meat.

On the contrary, at β dispersion, the properly slaughtered goat meat shows higher relative permittivity as compared to the non-properly slaughtered one. This dispersive behavior of the relative permittivity at this region arises mainly as a result of Maxwell Wagner phenomenon associated with the interfacial polarization of cells membrane [20, 21]. In this dispersion region, as frequency increases, the ions tend to penetrate to the conductive intracellular fluids [22] causing an increase in the overall conductivity of meat [23], and hence, a decrease in permittivity. Since the non-properly slaughtered goat meat contains more ionic content, therefore, it shows higher conductivity and lower relative permittivity than the properly slaughtered goat meat. However, the difference in the relative permittivity was gradually lost for both types of goat meat as the frequency and the postmortem time increased. This can be clearly seen in Fig. 3 (b) and (c) and will be discussed in section 4.3.

4.2. Conductivity Dispersion of Goat Meat

Fig. 4 (a), (b) and (c) shows the conductivity dispersions of the properly and non-properly slaughtered goat meat measured after 12 hours, 3 days and 7 days of postmortem time, respectively. In this figure, a relatively flat plateau of conductivity dispersion at a central frequency of 10^4 Hz with a bandwidth of $\pm 5\times10^4$ Hz is observed. This bandwidth is believed to be the band where neither α nor β dispersion dominates. The central frequency defined here together with the associated bandwidth will be used as the basis for the ensuing observation and discussion.

In Fig. 4 (a), the conductivity of the non-properly slaughtered goat meat is consistently higher than that of the properly slaughtered goat meat regardless of the frequency applied. The difference in conductivity ($\Delta\sigma$) between the two types of goat meat seems to be relatively constant. For instance, at 5×10^3, 10^4 and 5×10^4 Hz, $\Delta\sigma$ is found to be 0.1478, 0.1499 and 0.1593 S/m, respectively. In Fig. 4 (b), a similar conductivity dispersion as in Fig. 4 (a) is observed, although the overall conductivity for both samples has increased. The $\Delta\sigma$ at 5×10^3, 10^4 and 5×10^4 Hz are found to be relatively constant at 0.198, 0.2050 and 0.2020 S/m, respectively. In Fig. 4 (c), again similar conductivity dispersion as in Fig. 4 (a) and (b) is observed, although this time the overall conductivity for both samples has increased significantly. The $\Delta\sigma$ at 5×10^3, 10^4 and 5×10^4 Hz, in this case, are found to be 0.1223, 0.1279 and 0.1303 S/m, respectively. This consistent difference in conductivity suggests that the distinction between the properly and non-properly slaughtered goat meat can be made within this predefined bandwidth. The instrument used, however, must be accurate up to 3 significant figures.

In Fig. 4 (a), (b) and (c), the changes in conductivity with time are clearly observed after 12 hours, 3 and 7 days. Such variation in conductivity with postmortem time is due to the distribution of the ions and the degradation of cells membrane during meat ageing [16]. To explain this variation in the conductivity of meat, the same meat model described earlier is also considered. When the meat tissue is subjected to an external electric field, the cellular membrane blocks the current flow from the extracellular fluids to the intracellular fluids causing the current to flow around the cells [23]. This leads to an increase in the ionic content of the extracellular electrolyte, and hence, an increase in the conductivity. Therefore, at low frequencies (few Hz – few kHz), the conductivity of meat is dominated by the ionic conductivity of the extracellular fluids [6]. Since the non-properly slaughtered goat meat contains more blood content as compared to the properly slaughtered one, it has more ions, hence more electrolytes. Consequently, the non-properly slaughtered goat meat shows higher conductivity than the properly slaughtered one. However, it is important to point out that as frequency increases, the membrane resistance is shorted out by the membrane capacitance, and as a result, the cellular membrane tends to lose its insulating properties [23, 24]. This allows the current to flow through the interiors of the cells (see Fig. 1 (b)) causing an increase in the conductivity of meat. Therefore, at higher frequencies, particularly from few kHz up to few MHz, the conductivity of meat is dominated by the conductivity of both extracellular fluids and the interiors of the cells.

4.3. Time-dependent Permittivity and Conductivity of Goat Meat

As observed in sections 4.1 and 4.2, the permittivity and conductivity of properly and non-properly slaughtered goat meat change gradually with increasing postmortem time. In fact, after a certain period of time, these properties of properly slaughtered goat meat become almost the same as the non-properly slaughtered one. For instance, the relative permittivity at α dispersion tends to increase with increasing postmortem time, whereas at β dispersion, the relative permittivity for both types of goat meat tends to decrease with increasing postmortem time. For conductivity, it gradually increases with increasing frequency and postmortem time. These changes in the relative permittivity and the conductivity of goat meat are attributed to the gradual deterioration of cells structure and the degradation of the cellular membrane due to the meat ageing process. As postmortem time progresses, cellular membrane degrades and becomes more permeable to the intracellular fluids [19]. Consequently, the insulating properties of the membrane disappear causing an exchange between the extracellular fluids and the interior of the cells [16, 22, 25], (see Fig. 5).

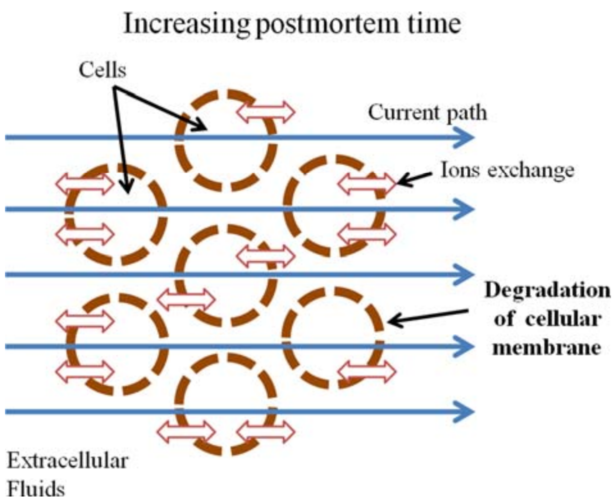

Fig. 5. Model of meat structure illustrating the degradation of the cellular membrane as postmortem time increases.

A more frequent measurement of the permittivity and conductivity as a function of time was carried out in order to investigate the consistency of $\Delta\varepsilon'$ (difference in permittivity) and $\Delta\sigma$ (difference in conductivity). In this case, both the relative permittivity and the conductivity of goat meat were measured at a 24 hour interval at fixed frequencies of 10^3 Hz for permittivity and 10^4 Hz for conductivity. The outcome of such measurement was plotted in Fig. 6 and it shows that the non-properly slaughtered goat meat clearly has higher relative permittivity and conductivity as compared to the properly slaughtered goat meat, irrespective of the postmortem time.

It is also noted that both the relative permittivity and the conductivity of the non-properly slaughtered goat meat increase monotonously with increasing postmortem time. On the contrary, the relative permittivity and conductivity of the properly slaughtered goat meat fluctuate significantly. This inconsistency is perhaps because of the disturbance that happened to the extracellular fluids of meat tissue due to the significant amount of blood drained out during slaughter.

Fig. 6 (a) shows that there is ~ 10^6 difference in the relative permittivity between the two types of goat meat whereas Fig. 6 (b) shows only ~ 0.1 difference in conductivity between the two types of goat meat. The significant difference in permittivity suggests that measuring the relative permittivity at *α* dispersion seems to be a better option for distinguishing the two types of goat meat.

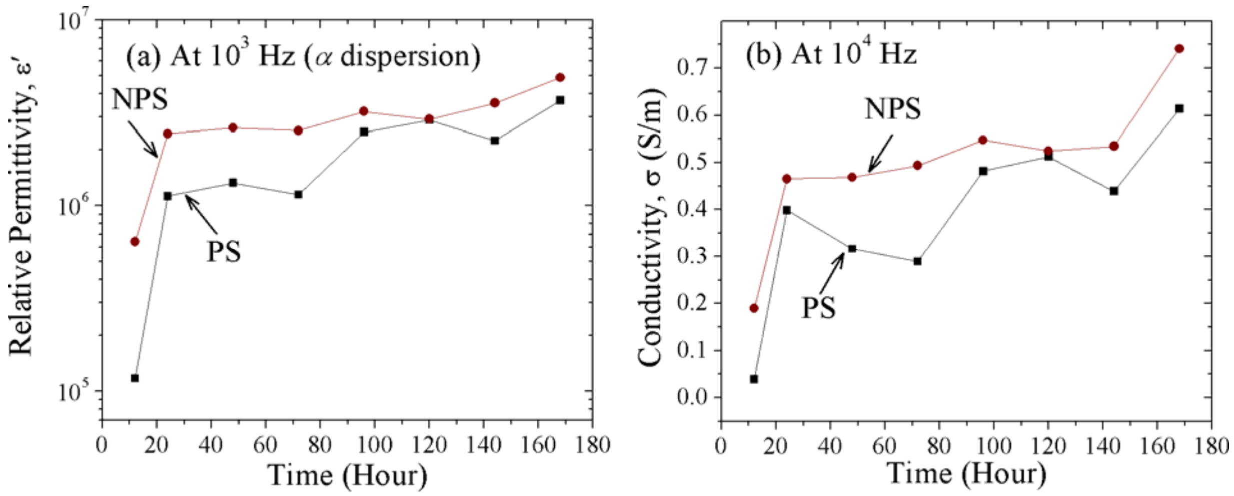

Fig. 6. Permittivity and Conductivity of properly slaughtered (PS) and non-properly slaughtered (NPS) goat meat plotted as a function of postmortem time at (a) 10^3 Hz and (b) 10^4 Hz.

5. Conclusion

Relative permittivity and conductivity of properly and non-properly slaughtered goat meat were measured over a frequency range from 50 Hz up to 4 MHz using a two parallel plate sensor connected with an impedance analyzer. The permittivity and conductivity as a function of postmortem time were also investigated at a constant temperature of 23 ^oC. The results showed that the relative permittivity and the conductivity of both types of goat meat depend very much on the frequency and the postmortem time. It was also found that even after 7 days of postmortem time, a difference in both the relative permittivity and the conductivity between the two types of goat meat could still be observed. Such a difference, however, was much higher in the case of the relative permittivity as compared to the conductivity. The results obtained suggest that the relative permittivity at *α* dispersion is a better option for distinguishing between the properly and the non-properly slaughtered goat meat.

Acknowledgements

The author would like to acknowledge the Ministry of Science, Technology & Innovation of Malaysia (MOSTI) for funding this work. Special thanks to Dr. Ramlan Mohamed and Dr. Norazura A. Hamid from the Veterinary Research Institute (VRI), Ipoh, for their valuable input and cooperation.

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