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Dielectric properties of myofibrillar protein dispersions from Alaska Pollock (*Theragra chalcogramma*) as a function of concentration, temperature, and NaCl concentration

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ABSTRACT

The open-ended coaxial probe technique was used to study the effects of frequency (500–2500 MHz), temperature (20–90 °C), concentrations of myofibrillar protein (0.5, 1.5, and 2.5 mg/mL) and NaCl (0.3, 0.45, and 0.6 M) on the dielectric properties of myofibrillar protein. Models describing the behavior of the dielectric constant (ε'), loss factor (ε'') were developed. ε' decreased as frequency, temperature, and NaCl concentration increased, whereas ε'' decreased with increasing frequency but increased with increasing temperature and NaCl concentration. Minor differences in the effects of myofibrillar protein concentrations were observed; the trend of ε' changes agreed with viscosity changes, namely the maximum value of ε' and viscosity were achieved when the myofibrillar protein concentration was 1.5 mg/mL, followed by concentration of 0.5 and 2.5 mg/mL. The penetration depth was estimated under various conditions and decreased with frequency, temperature, and NaCl concentration increasing but increased with myofibrillar protein concentration increasing.

1. Introduction

Surimi, a concentrate of salt-soluble myofibrillar proteins, is an intermediate foodstuff producing various texturized products (Debusca et al., 2013; Zhang et al., 2015a,b). Currently, the demand for surimi products has increased owing to the increase of population and the continuous improvements of people's living standards. Surimi-based products have become increasingly popular because of their unique textural properties and high nutritional value due to their high-protein, low-fat content and tender texture (Shi et al., 2014). It is known that the functional and textural characteristics of surimi-based products critically depend on the gel-forming ability of myofibrillar protein (Ruan et al., 2014; Zhou et al., 2014a). Myofibrillar protein contains myosin, actin, actomyosin, tropomyosin, and troponin and has the ability to form a stable three-dimensional gel network via unfolding, aggregation, and crosslinking when subjected to heat. The ionic strength is an important factor that influences protein behavior during cooking, affecting the physical and chemical properties of the protein, such as thermal denaturation and rheological properties (Ni et al., 2014; Xiong et al., 2009; Zhou et al., 2014b). It is known that the gelation properties and extraction of myofibrillar protein differ with the source of the protein (with different fish species). In addition, the extraction of myofibrillar protein depends on a number of factors such as pH, ionic strength, ion species, and polyphosphates.

Microwave heating is widely used in the food industry for its relatively short heating time due to its ability to generate volumetric heating within food materials (Fu et al., 2012). Currently, an increasing number of studies has focused on microwave radiation effects on the protein structure and function. Shazman et al. (2007) built a system which allowed the output of high microwave energy and good temperature control to study the influence of microwave radiation on five systems, including the Maillard reaction, protein denaturation, mutagenesis of bacteria, glucose mutarotation, and saturation solubility of sodium chloride protein denaturation. Overall, the results of their study were insufficient to support the hypothesis of athermal effects induced by microwave radiation. The microwave heating rate depends on the dielectric properties of the material. Currently, a very limited amount of published information related to the dielectric properties of fish protein at microwave frequencies is available. The dielectric properties of food materials have been considered to be the major factors contributing to the interactions between microwaves and food (Ahmed et al., 2008). Furthermore, the dielectric properties are important criteria for selecting proper model foods for microwave

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heating because they determine how the microwave energy is absorbed, transmitted, reflected, or concentrated inside a food material (Datta, 2001). The dielectric properties are normally described by the relative permittivity (ε^*) (Sosa-Morales et al., 2010): $\varepsilon^* = \varepsilon' - j\varepsilon''$, where $j = \sqrt{-1}$, the real part ε' is the dielectric constant, and the imaginary part ε'' is the dielectric loss factor. ε' indicates the ability of a material to store electric energy when subjected to an electromagnetic field, and ε'' reflects the ability of a material to convert electromagnetic energy into thermal energy. The dielectric properties of a material can also be used to estimate the thermal energy converted from electric energy at microwave frequencies. If the heat loss is negligible, the increase in the temperature (ΔT) of the material can be calculated from (Nelson and Datta, 2001)

$$Q = \rho Cp\frac{\Delta T}{\Delta t} = 2\pi f\varepsilon_0\varepsilon'' E^2$$

where Cp is the specific heat of the material [J/(kg °C)], ρ is the density of the material (kg/m^3), Δt is the change in time (s), ε_0 (8.8542×10^{-12} F/m) is the permittivity of free space or vacuum, E is the strength of the electric field (V/m), and f is the frequency (Hz).

There are many factors that influence the dielectric properties of a given food, including the frequency, temperature, moisture content, salts, and other food constituents (Okiror and Jones, 2012; Tang, 2005). However, water is the major component of food with regard to heating by electromagnetic energy. Salt is typically added during the formulation of surimi products such as imitation products and kamaboko for extracting fish myofibrillar protein, resulting in good texture and sensory properties. However, in low-salt products, the complete solubilization or dissociation of myofibrillar proteins was not achieved, and the interaction among myofibrillar proteins was insufficient which most likely contributed to the coarse structure with lower gel strength, lower water-holding capability (WHC), and higher cook loss (Fu et al., 2012). Namely, the salt concentration affects the amount of extracted surimi protein, and therefore, has an effect on the gel properties (Fu et al., 2012; Pedro and Nunes, 2007; Tahergorabi and Jaczynski, 2012) and dielectric properties.

The changes in the dielectric properties of numerous food products when subjected to an electromagnetic field are still the subject of multiple studies, but little is known about the changes in fish myofibrillar protein when subjected to an electromagnetic field. The objectives of the current study were (1) measuring the dielectric properties of myofibrillar protein within a temperature range of 20–90 °C over 500–2500 MHz; (2) studying the effects of the concentrations of myofibrillar protein (0.5, 1.5, and 2.5 mg/mL) and NaCl (0.3, 0.45, and 0.6 M) on the dielectric properties of myofibrillar protein; (3) investigating the microwave penetration depths for myofibrillar protein; and (4) measuring the viscosity of different concentrations of myofibrillar protein formulations.

2. Materials and methods

2.1. Materials

Frozen Alaska Pollock surimi (grade AAA) was purchased from JINCAN Foods Co., Ltd., Qingdao, Shandong, China. The surimi was kept at −20 °C until use. All of the chemicals used were of analytical grade and were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.2. Preparation of myofibrillar protein

To prepare myofibrillar protein, frozen surimi weighing 250 g was partially thawed at 4 °C for 4 h and then cut into small pieces (approximately 3-cm cubes). The frozen surimi cubes were chopped at a speed of 1500 rpm for 4 min in a Stephan vertical vacuum cutter (Model UM 5, Stephan Machinery Co., Hameln, Germany). The double-walled chopping bowl was continuously circulated with a cooling medium (ethanol: water, 95:5) to maintain the sample below 4 °C during chopping.

After thawing, the surimi was homogenized with five volumes (w/v) of cold 20 mM Tris-maleate (pH 7.0) containing 50 mM NaCl using an electronic stirrer (JJ-1, Guohua, Changzhou, China) for 5 min. The homogenate was centrifuged at 8910g using an Anke GL-20G-II centrifuge (Anting Scientific Instrument Factory, Shanghai, China) for 10 min at 4 °C; the precipitate was washed twice by suspension in five volumes of the same buffer (cold 20 mM Tris-maleate containing 50 mM NaCl, pH 7.0) following centrifugation as described above. The resultant pellet was resuspended in three volumes of 0.6 M NaCl–20 mM Tris-maleate and centrifuged at 11,000g for 20 min at 4 °C. The supernatant was filtered through three layers of cheese cloth to remove connective tissue, and ten volumes of cold distilled water (4 °C) were added to precipitate myofibrillar protein. The precipitate was collected by centrifugation at 11,000g for 10 min at 4 °C and stored on ice to be used within 18 h. A myofibrillar protein dispersion was created by using the required volume of the selected concentration of NaCl (0.3, 0.45, and 0.6 M) and maintained at the refrigeration temperature (4 °C) for maximum hydration for 2 h.

2.3. Determination of the myofibrillar protein content

The protein concentration of the myofibrillar precipitates was measured by the Biuret method (Gornall et al., 1949) using bovine serum albumin (BSA) as a standard. Each sample was prepared in triplicate. Briefly, 1 mL of each solution was diluted to 2 mL using distilled water, combined with 4 mL of Biuret reagent, and then maintained at room temperature for 30 min. The absorbance was measured at 540 nm using a UV 751 GD spectrophotometer (Shengfang Analytic Instruments Co., Ltd., Qingdao, China).

BSA was used to prepare the protein solutions and was reacted with 4 mL of Biuret reagent at room temperature for 30 min. The absorbance was measured at 540 nm, and a standard curve was constructed to calculate the myofibrillar protein content by plotting the absorbance versus the BSA concentration. All the results were obtained from at least triplicate measurements.

2.4. Determination of the dielectric properties

The dielectric properties of myofibrillar protein were measured using an open-ended coaxial probe (Hewlett Packard Corp., Santa Clara, CA, USA) connected to an 8714ET network analyzer (Agilent Technologies, Palo Alto, CA, USA). Before the measurements, the impedance analyzer was warmed up for at least 30 min, following the manufacturer's recommendations to obtain precise results, and measurements were obtained. The instrument was calibrated by measuring the properties of air, a short circuit, and ultrapure water (25 °C). Once the calibration was performed, deionized water was measured again to check its validity. The dielectric properties (ε' and ε'') were determined over a frequency range of 500–2500 MHz (a total of 85 trigger points) for temperatures ranging 20–90 °C in 10 °C increments. All the results were obtained from at least triplicate measurements.

2.5. Determination of the power penetration depth

An important concept in dielectric heating is the power penetration depth, which is defined as the depth at which the microwave power decreases to $1/e$ ($e = 2.718$) or 36.8% of the initial power entering the surface of a sample (Zhang et al., 2015c).