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Dielectric properties of frozen tuna and analysis of defrosting using a radio-frequency system at low frequencies

Yvan Llave, Yuina Terada, Mika Fukuoka, Noboru Sakai *

Department of Food Science and Technology, Tokyo University of Marine Science and Technology, Konan 4-5-7, Minato-ku, Tokyo 108-8477, Japan

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ABSTRACT

Characterization of radio-frequency (RF) defrosting of tuna (*Thunnus maccoyii*) influenced by its dielectric properties (DPs) was investigated experimentally. DPs at 13.56 and 27.12 MHz of three ordinary muscles of tuna were evaluated from −20 to +10 °C using the parallel-plate measurement method with an impedance analyzer and a dielectric test fixture. In the range of −3 to +1 °C, dielectric constant (ε') values were significantly higher than at other measured temperatures. Higher DP values were found for tuna samples with higher moisture content, especially at lower frequencies. Samples were defrosted using a 13.56-MHz parallel-plate RF system. Greater uniformity of end-point temperature distribution of tuna muscle was obtained when the top electrode projection was similar in size to the sample, especially for samples with high-moisture content. Additionally, a threefold reduction in thawing time was obtained with the RF system compared with conventional thawing.

1. Introduction

Over the last ten years, demand for fresh and frozen tuna to prepare delicatessen products such as sushi or sashimi has soared in the Japanese market and worldwide. The ability to supply this fish to distant markets makes the trade in frozen tuna popular. In the frozen tuna industry, harvested tuna is typically kept in a deep-frozen state below −60 °C (Zhao et al., 1998) until transportation to local markets or processing factories in order to preserve its quality for prolonged periods of time (Santos-Yap, 1995).

To defrost frozen tuna, it may be thawed (temperature of the coldest spot being just above the product's freezing point) or tempered (temperature of the warmest spot being just below the product's freezing point). For processing purposes, tempering is usually performed for ease of handling. The typical target temperature range in industrial-scale defrosting of meat is −2 to −5 °C (Farag et al., 2009) because at these temperatures, meat products are highly amenable to mechanical chopping (James and James, 2002). Safe and efficient technologies to temper or thaw frozen blocks of tuna are under intensive development; the control of temperature during these processes is critical.

The tuna industry is always interested in faster and more compact systems while maintaining the high quality demanded by consumers. Alongside the traditional methods of defrosting (air or water defrosting at controlled temperatures), novel methods such as dielectric heating systems, e.g. microwave (MW) and radio frequency (RF), have been evaluated and developed. RF heating is an innovative dielectric technique that generates heat energy within the product. The US Federal Communications Commission (FCC) allocates bands at 13.56, 27.12, and 40.68 MHz in the RF range for industrial, scientific and medical (ISM) applications (Wang and Tang, 2001). RF heating is recognized as a method that enables rapid and uniform heating throughout a medium (Zhao, 2006), so it is attractive for the uniform defrosting of tuna in a short time.

RF heating is achieved through a combination of ionic displacement and dipole rotation. However at lower frequencies associated with RF, ionic displacement is the major contributor to the heating mechanism (Jones, 1992). Heating arises due to ionic displacement within the product leading to direct conversion of electric energy to heat within the product, a phenomenon often referred to as volumetric heating (Rowley, 2001). Dielectric properties (DPs) are physical properties that govern the interaction between RF radiation and food. Knowledge of such properties is necessary not only because they are important in their own right, but also because they affect physical treatments undertaken during processing (Zhang et al., 2004). Thus, the availability of the DPs of foods will be central to the development and industrial application of RF technology and, according to Jiao et al. (2014), may help to predict possible overheating of the samples and the temperature distribution in bulk foods. The DPs can be described by the dielectric

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* Corresponding author. Tel./fax: +81 3 5463 0622.
E-mail address: sakai@kaiyodai.ac.jp (N. Sakai).

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constant (ε'), the ability of the product to store electromagnetic energy, and the dielectric loss factor (ε''), its ability to dissipate the electromagnetic energy. A number of factors have been shown to affect the DPs of foodstuffs, such as temperature, frequency, chemical composition, and the state of moisture (frozen, free, or bound) as has been reported by Farag et al. (2008a, 2011), Jiao et al. (2014), Piyasena et al. (2003), Zhang et al. (2004, 2000), and Zhao (2006). However, limited data are available on the RF bands in the temperature range for thawing and tempering. A few early studies were conducted in this field in the 1940s and 1960s, as summarized by Farag et al. (2011), Piyasena et al. (2003), and Zhao et al. (2000). Most of them focused on the thawing of large blocks of food using high frequencies (35–40 MHz), with successful results compared with conventional methods. Pizza et al. (1997) evaluated the use of RF heating in the 10–300 MHz range. They claimed that RF heating does not substantially change the physicochemical properties of meat during thawing. Recently, Farag et al. (2008a,b, 2009, 2010, and 2011) evaluated the application of RF heating to the defrosting of frozen beef and its effect on quality parameters and DPs. However, no information is available on the DPs of frozen tuna at RF bands.

Nowadays, stationary or continuous RF systems are increasingly used in commercial processes to produce food products for retail market; however, the use of electrodes larger than the surface sizes of the samples has been observed. This practice overheats samples of small size, especially at their edges. Tiwari et al. (2011b) reported that non-uniform temperature distribution may cause quality loss due to over- or under-heating in different parts of a food product. Therefore, understanding the complex mechanism of RF heating of foods is essential to overcoming the major challenges of non-uniform heating and runaway heating. These cause overheating in corners, edges, and center parts, especially in foods of intermediate and high water content (Fu, 2004). While some recent papers have addressed RF heating uniformities (Alfaifi et al., 2014; Marra et al., 2007; Romano and Marra, 2008; Tiwari et al., 2011a,b), most of them are focused on low-moisture foods. Although the DPs of low-moisture foods are very similar to those of frozen foods, there is a lack of information about heating uniformity during defrosting of tuna assisted by RF heating. In this study, in order to examine the defrosting conditions, RF defrosting of tuna influenced by DPs was investigated experimentally. The main objective of this study was to evaluate the effect of temperature (−20 to +10 °C), frequency (13.56 and 27.12 MHz), and muscle composition on the DPs of three tuna muscles during defrosting. A secondary objective was to evaluate the defrosting performance of a 13.56-MHz RF system, using projections of top electrodes of different sizes, for samples with different compositions by examining temperature distribution within the samples. The RF system results were also compared to those of the conventional defrosting method.

2. Materials and methods

2.1. Fish sample handling and preparation

Frozen blocks (skinned and boned) of the cephalic parts of tuna (*Thunnus maccoyii*) were used (Fig. 1). Three ordinary muscles (OM) from this part were considered: the dorsal (DOM), lateral (LOM), and ventral (VOM). The frozen blocks were obtained from a Japanese frozen tuna manufacturer and stored at −60 °C. Sample size was adjusted using a meat band-saw cutting machine (LUXO S-II, LUXO Co., Ltd., Nagoya, Japan). Two block sizes were obtained (60 × 60 × 25 mm and 60 × 60 × 50 mm) for RF thawing evaluation while a cylindrical slice 50 mm in diameter (ϕ) and 6 mm thick was obtained for DP measurement. For the analysis of the DPs, it was crucial to ensure full contact between the electrode and the sample surface. To achieve this, samples with flat surfaces were essential. The top and bottom surfaces of the cut fish muscle samples were submitted to a fine-tuned roughness correction. To this end, samples were placed in a press prior to storage at −60 °C with an unadjusted load. This improved the smoothness of the surface without influencing the structure of the tuna samples.

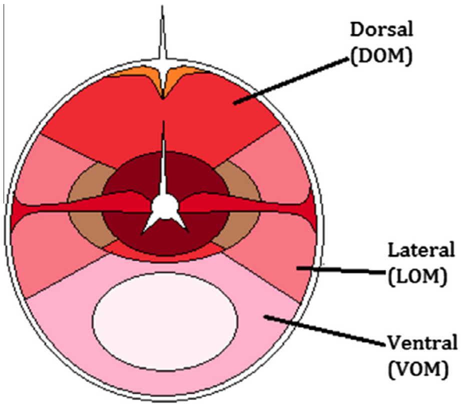

Fig. 1. Cephalic parts of the ordinary muscles of tuna used in this study.

2.2. Moisture and crude fat contents

The moisture and crude fat contents of the fish samples were quantified. Typical samples of each muscle type were ground with a mortar and pestle. Crude fat content was determined by the Soxhlet method using a 5-g portion of the ground sample (AOAC, 1995). Moisture content was determined on a wet basis by drying a 5-g portion of the ground sample at 105 °C to a constant weight (AOAC, 1995).

2.3. Temperature measurements

2.3.1. Measurement of internal temperature

For temperature control during RF thawing and tempering, two fiber-optic temperature sensors ($\phi = 1.6$ mm) attached to a temperature measuring system (FTC-DIN-ST-TH, Photon Control, BC, Canada) were inserted at the center (used as a target point in thawing experiments) and at a position near the upper surface (at a distance 5 × 5 × 5 mm from the corner) of the samples (used as a target point in tempering experiments). The sensors were inserted using a drill to ensure the precision of the hole positioning. A single fiber-optic sensor was also inserted for temperature recording during the measurement of DPs (2.5 × 10 mm from the outside). Since no significant differences ($p > 0.05$) were found between measurements of DPs with and without the fiber-optic sensor, it was decided that the sensor could be inserted for accurate recording of the temperature during the experiments.

2.3.2. Surface temperature measurement

The distribution of the surface temperature of the sample was determined immediately after thawing using an infrared (IR) camera (TH7102WV, NEC San-ei Instruments, Ltd., Tokyo, Japan) with an accuracy of ±2 °C. Moreover, to evaluate the defrosting performance at the interior, samples were immediately bisected vertically and a thermal image was recorded with an IR camera for one of the cut surfaces within 10 s to avoid the surface temperature increasing.