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# Electrical conductivity and ohmic thawing of frozen tuna at high frequencies

Lei Liu [a, b], Yvan Llave [a], Yinzhe Jin [c], Da-yu Zheng [b], Mika Fukuoka [a], Noboru Sakai [a, *]

[a] Department of Food Science and Technology, Tokyo University of Marine Science and Technology, Konan 4-5-7, Minato-ku, Tokyo 108-8477, Japan
[b] School of Energy and Civil Engineering, Harbin Commercial University, Xuehai Load 1, Harbin 150028, China
[c] College of Food Science and Technology, Shanghai Ocean University, China

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ABSTRACT

In this study, we examined ohmic thawing in frozen tuna muscle (*Thunnus maccoyii*), and how it is influenced by electrical conductivity (EC). The EC values of three tuna muscles (dorsal, lateral, and ventral) were measured between frequencies of 50 Hz and 20 kHz and temperatures of −30 °C to 20 °C. The effect of both parallel and series current direction and the presence of membranes in the tuna muscle, on EC were also evaluated. Increasing the frequency caused a drop in resistance and an increase in heating rate, thereby decreasing the thawing time of the frozen tuna muscles. The thawing time and EC were the longest and lowest for the muscle with the least moisture content and the highest fat content, and vice versa for the muscle with highest moisture content and least fat content. The use of a parallel electrical circuit and the removal of membranes from the muscle yielded higher EC values.


## 1. Introduction

Freezing has been used for thousands of years for long-term food preservation because it maintains product quality and provides a long shelf life. However, chemical, physical, and microbiological changes that occur during long thawing periods can result in the degradation of the product quality (Seyhun et al., 2014). Therefore, safe and efficient methods to rapidly thaw frozen foods are needed. In particular, the tuna industry is interested in fast, compact systems that maintain the high quality demanded by consumers (Llave et al., 2014).

There are many techniques for thawing frozen food products: thawing at room temperature, cold-storage thawing, warm salt-water thawing, static water thawing (Liu et al., 2010), microwave thawing (Liu and Sakai, 1999; Llave et al., 2016), radio-frequency thawing (Llave et al., 2014; Llave and Sakai, 2016), ohmic thawing (Bozkurt and Icier, 2012; Miao et al., 2007; Seyhun et al., 2013, 2014), pressure ohmic thawing (Min et al., 2016), high-pressure thawing (LeBail et al., 2002), high voltage electric field thawing (Mousakhani-Ganjeh et al., 2015, 2016), and acoustic thawing (Li and Sun, 2002).

Ohmic thawing is an electro-heating method that heats more uniformly than other electro-heating techniques. The rapid and relatively uniform heating of ohmic heating (OH) is achieved by the direct passage of electric current through the product (Marra, 2013). In addition, the processing time is substantially less than conventional heating, yielding higher product quality traits, including integrity, flavor, and nutrient retention (Li and Sun, 2002; Seyhun et al., 2013). This process uses the electrical resistance of the food being treated; electrical energy is dissipated as the current flows through the food, causing heat to be released (Joule effect). The amount of dissipated heat is directly related to the applied voltage and the EC of the product or product fraction (Ohm's law; Varguese et al., 2014).

For the ohmic thawing process to be successful, the rate of heat generation and overall EC of the food must be measured (Leizerson and Shimoni, 2005). The electrical properties of many food products have been investigated in recent years, including in chicken (Palaniappan and Sastry, 1991; Sarang et al., 2008), beef (Kim et al., 1996; Palaniappan and Sastry, 1991), pork (McKenna et al., 2006; Shirsat et al., 2004), and fish (Jin et al., 2015; Yongsawatdigul et al., 1995). The structure of the meat, including membrane direction, moisture content, fat content, and the type of meat, have all been shown to affect EC (Jin et al., 2015; Lyng, 2014; Sarang et al., 2008). To date, the EC values of frozen tuna have not been reported.

* Corresponding author.
*E-mail address:* sakai@kaiyodai.ac.jp (N. Sakai).

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While there have not been a large number of studies examining ohmic thawing and tempering, several studies have been recently summarized by Lyng (2014) and Seyhun et al. (2014). In addition, Duygu and Ümit (2015) reported that using OH to thaw frozen meat results in less weight loss and a shorter thawing time, as compared with conventional thawing methods. Min et al. (2016) showed that pressure ohmic thawing (POT), a technique that utilizes the synergy of high-pressure thawing and ohmic thawing, is faster than conventional, ohmic, or pressure-assisted thawing alone, and does not affect meat quality at 40 V $cm^{-1}$ and 200 MPa. Seyhun et al. (2013), using high frequency (10–30 kHz) OH to temper frozen potato puree samples, found that temperature differences within the sample could be minimized by using a 0.50% salt solution and a frequency of 10 kHz. In this study, we examine an OH system, using high frequencies, and its effectiveness in the thawing process.

As described, there have been several studies examining the EC of frozen foods, and the capability of OH to rapidly and safely thaw these foods; however, these studies represent only a small fraction of the research needed to determine the overall efficacy of OH. Therefore, this study represents a part of an ongoing project designed to evaluate the effectiveness of using OH to thaw frozen foods, not only quickly but also safely and without reducing quality. Here, we evaluate the thawing performance of OH by examining electrical current flow in both parallel and series directions, and determining the time-temperature profiles in three different tuna muscles. We examine several factors that influence EC while using OH to thaw frozen tuna muscles. These factors include frequency, temperature, the chemical composition of the muscle, the direction of the electric current in relation to the muscle orientation, and the presence or absence of membranes in the muscle. In addition, we evaluate the EC of the tuna muscles, in both parallel and series current directions, using two approaches. In the first approach, impedance and resistances measurements using an LCR meter were used to estimate the EC values. In the second approach, voltage and current were measured, followed by the calculation of LI/AV taking into consideration the influence of membranes.

## 2. Materials and methods

### 2.1. Preparation of tuna muscles

Skinned and boned flesh blocks of the cephalic parts of tuna (*Thunnus maccoyii*) were used in our experiments (Fig. 1A). Three ordinary muscles were considered: dorsal, lateral and ventral. The blocks were purchased at the Tsukiji fish market (Tokyo, Japan) in a state of *rigor mortis*. 20 mm per side cube samples were prepared using a meat band-saw cutting machine (LUXO S-II, LUXO Co., Ltd., Japan). Samples were deep frozen in an air blast freezer (KQF-5AL, Air Operation Technologies, Inc., Japan) and stored at −60 °C (NF-400SF3, Nihon Freezer Co. Ltd., Japan) until used. Prior to testing, samples were tempered in a freezer (CR-221BSE, TOSHIBA, Japan) at −30 °C for no more than 12 h. This temperature was used as the starting point for the EC measurements and OH experiments. The moisture and crude fat content of each sample (in wb), measured as described by Llave et al. (2014), are summarized in Table 1. Table 1 also shows the membrane thickness of the three muscles and further explained in Section 2.6. The weight loss ratio was calculated from the weights before and after thawing.

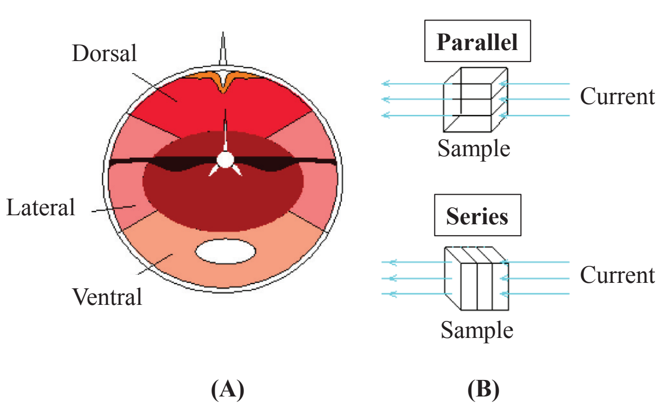


**Fig. 1.** (A) Cephalic muscles of tuna used in this study. (B) Current directions and muscle orientations for EC measurements.

### 2.2. Experimental thawing of tuna muscles using an OH system

The static OH system used in this study consisted of a cube shaped polystyrene chamber (20 mm per side), with 7 mm thick walls, to hold the sample, an alternating current power supply, and a control panel for controlling the voltage. A constant voltage of 200 V was applied to the electrodes using a voltage regulated Joule heating machine (FJB-5.5, Frontier Engineering Co. Ltd., Japan), at a frequency of 20 kHz. A schematic diagram of the OH circuit is shown in Fig. 2. Also shown in Fig. 2, is an LCR meter (HiTESTER 3532-50, HIOKI Co. Ltd., Japan) used to directly measure the impedance ($Z$), reactance ($X$), and resistance ($R_s$ and $R_p$) for our first approach of EC estimation as explained in Section 2.4. All experiments were performed in a single stage, starting from the initial frozen state at −30 °C, continuing until the temperature at the center of the tuna sample reached 20 °C. This was considered the end of the thawing and heating process, and the total OH time was determined at this point. The final temperature was decided in this study at 20 °C because it is frequently identified as a room temperature. The results represent the average of five samples.

**Table 1**
Crude fat, moisture content, and membrane thickness of tuna muscles.

| | Dorsal[a] | Lateral[a] | Ventral[a] |
|---|---|---|---|
| Moisture (%) | 70.05 ± 0.63 | 67.30 ± 0.43 | 54.78 ± 0.72 |
| Crude fat (%) | 0.96 ± 0.12 | 9.56 ± 1.41 | 30.21 ± 1.6 |
| Membrane thickness (mm) | 1.10 ± 0.1 | 1.50 ± 0.1 | 1.99 ± 0.2 |

[a] Mean ± standard deviation ($n = 5$).

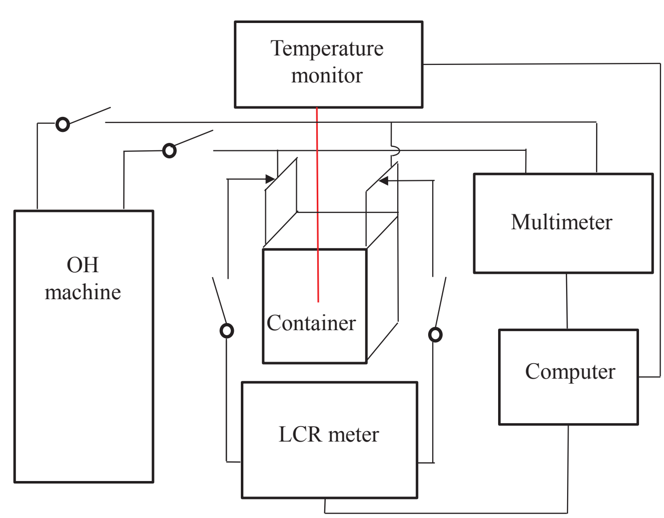


**Fig. 2.** Schematic of the experimental setup for OH and EC measurements.