



One-directional modelling to assess the mechanistic actions of power ultrasound on NaCl diffusion in pork

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ABSTRACT

A one-directional modelling method for the assessment of the influence of power ultrasound (US) (4–19 W cm^{−2}, 25–40 min) on NaCl diffusion in pork is presented. In doing so, the mechanistic actions of US salting in meat are elucidated. Temperature controls (4–21 °C) were generated according to each US treatment. NaCl concentration profiles were fitted to Fick's second law, generating the effective NaCl diffusion coefficient (D_{eff}). D_{eff} ranged from 1.34×10^{-10} to 4.01×10^{-10} m² s^{−1}, which is in agreement with the literature. The average D_{eff} was higher at increased temperature ($p < 0.05$) and US intensity ($p < 0.01$) and a lower D_{eff} was found with longer US treatment time as an effect of structural changes in the meat ($p < 0.05$). The D_{eff} was higher at all US intensities than the corresponding temperature control indicating that mass transfer is accelerated by US mechanisms, such as cavitation, independent of temperature effects. This study provides further information on the mechanistic actions of ultrasonic enhanced mass transfer and further proves the potential of power US for the accelerated salting of pork.

1. Introduction

Meat is commonly preserved by the addition of NaCl. This ingredient also leads to structural modifications within the meat matrix which affects flavour, juiciness and texture [1]. For effective curing, NaCl must diffuse into the meat matrix and reach an equilibrium concentration throughout. According to Thorarinsdottir et al. [2] meat is composed of a liquid phase which acts as a solvent for salt ions and soluble proteins and a solid phase which can be considered as porous, capillary and colloidal. Depending on the NaCl concentration, microstructural changes such as fibre swelling or shrinkage occur within the solid phase [3]. During myofibrillar swelling, unfolding and expansion of the filament lattice leads to reorganisation of water from extra-myofibrillar to intra-myofibrillar locations [4].

Due to these structural changes, the transport phenomenon within meat is very complex. Pressure changes due to swelling/expansion can cause convection to occur. Muscle cells are semi-permeable so mass transfer due to osmosis may also occur. Furthermore, meat is anisotropic, adding to the complexity [5]. However, diffusion is generally accepted as being the most important of the mass transfer processes

occurring in meat during curing [2]. Diffusion is driven by concentration gradients whereby ions move from a region of high concentration to one of lower concentration. Although it is difficult to account for all modes of transport phenomena in meat, Fick's second law of diffusion is commonly used [6,7] as it allows for quantification of diffusion of a solute as a function of time and position and generates the NaCl diffusion coefficient (D_e). Fickian models have been successful in understanding diffusion in meat as affected by pH, fibre direction [8,9], temperature and NaCl concentration [6,10].

Although information has been gained on the factors affecting the rate of NaCl diffusion in meat, traditional meat curing remains a slow process. The evolving meat industry would benefit from a novel technology which could enhance diffusion rates and potentially improve the quality of products. Power ultrasound (US) has been shown to increase NaCl mass transfer in meat [7,11,12]. Power US, which works at frequencies between 20 and 100 kHz can have destructive physical and chemical effects on a medium [13], as an oscillating sound wave travels through a medium, the rarefaction cycle induces stretching and this can cause microscopic gas bubbles of certain radii to increase in size. However, during the compression cycle, extreme pressures are exerted

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Nomenclature

C	instantaneous NaCl concentration in the meat aqueous phase ($\text{kg}_{\text{NaCl}} \text{kg}_{\text{NaCl} + \text{water}}^{-1} \text{d.m.}$)
C_s	NaCl content of the brine ($\text{kg}_{\text{NaCl}} \text{kg}_{\text{NaCl} + \text{water}}^{-1}$)
C_o	initial NaCl of the meat sample ($\text{kg}_{\text{NaCl}} \text{kg}_{\text{NaCl} + \text{water}}^{-1} \text{d.m.}$)
dt/dT	temperature change ($^{\circ}\text{C}$)

$D_{s,\text{eff}}$	effective NaCl diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
m	mass (kg)
t	time (s)
x	distance (m) from the surface
ΔJ	quantity of heat energy gained (J)
γ	specific heat capacity ($\text{J kg}^{-1} ^{\circ}\text{C}^{-1}$)

onto the microbubble until it becomes unstable and implodes. When the bubble collapses, high-speed liquid jets and shock-waves propagate in the same direction as the acoustic wave. The micro-jets can penetrate biological tissue causing damage and increasing diffusion. Prior to implosion, the pulsating action of the bubble creates acoustic-streaming, ensuring constant movement of ions, further enhancing mass transfer [13].

Fick's law has been used to understand the effect of US on mass transfer in apples [14,15] and cheese [16]. The effect of US on mass transfer in meat has also been reported [7,12,17] with variable results. The potential benefits of US in meat processing are well documented [18] but the mechanisms by which US contributes to mass transfer are yet to be proven. Power US dissipates heat energy within a liquid medium as long as the rate of heat generation exceeds the rate of heat removal [13]. Indeed, a combination of temperature and US has been shown to influence the diffusion coefficient in cheese [16] and chick-peas [19]. Furthermore, several authors have shown that the NaCl diffusion coefficient in food matrices increases with increasing temperature [20,21]. The research of Siró et al. [7] suggested that NaCl diffusion in meat increases linearly when US intensities of $2\text{--}4 \text{ W cm}^{-2}$ are applied. Ozuna et al. [17] also reported increased NaCl diffusion when US (40 kHz; 37 W L^{-1} ; 15–120 min) was applied to various NaCl concentrations (50, 100, 150, 200, 240 and 280 g L^{-1} NaCl) during meat salting. However, Cárcel et al. [11] suggested that a minimum US intensity of 51 W cm^{-2} is required before the overall NaCl concentration increases in pork. The existence of an US intensity threshold was in agreement with Ojha et al. [12] who reported a small effect of US on mass transfer at low intensity (9 W cm^{-2}) but a significant effect at a higher intensity (54.9 W cm^{-2}).

This study aims to assist in understanding the mechanistic actions of US on the effective NaCl diffusion coefficient ($D_{s,\text{eff}}$) in pork by applying a unidirectional diffusion model to a range of US treatments while isolating temperature effects with corresponding temperature controls. In turn, the physical and chemical effects of US on mass transfer can be further elucidated, independent of temperature.

2. Materials and methods

2.1. Raw material sampling

Pork *M. longissimus thoracis et lumborum* (LTL) muscles were obtained at 72 h post-mortem from a commercial slaughterhouse. The pH was measured by direct insertion of a pH electrode EC2010-11 (Refex sensors Ltd., Westport, Co. Mayo, Ireland) with a meter (Ion 6 Acorn Series, Oakton, IL, USA) and only muscles of pH 5.5–5.8 were used. All visible connective tissue was removed from the muscle and cylindrical samples ($35 \phi \times 50 \text{ mm}$, $50 \pm 0.5 \text{ g}$) were generated from the lean tissue. Location within the muscle was randomised with respect to treatment to allow for sampling effects. A new muscle was used for each repetition of the experiment. A total of 3 repetitions were carried out for each treatment. The samples were inserted into a specially designed diffusion cell ($34 \phi \times 160 \text{ mm}$). It is known that NaCl diffusion in meat is affected by fibre direction [9], therefore the fibre direction was maintained parallel to the main axis of the cylinder for all treatments. A stopper was placed into the bottom of the cell and a brine solution ($5.7\% \text{ w w}^{-1}$ NaCl; 65 ml) was placed into the open end of the tube

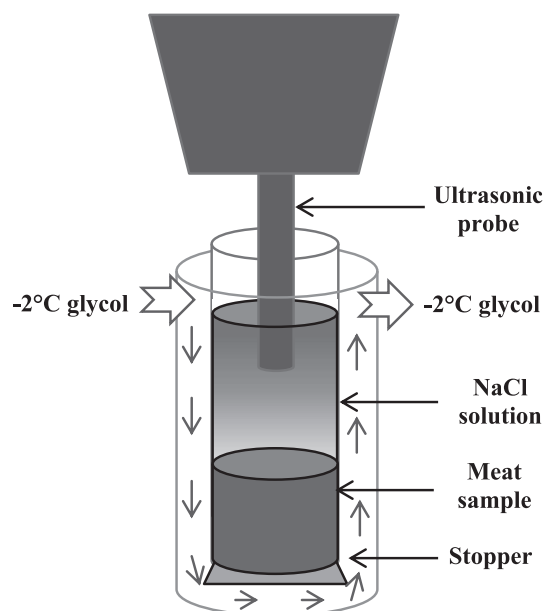


Fig. 1. Experimental set-up for ultrasonic treatments.

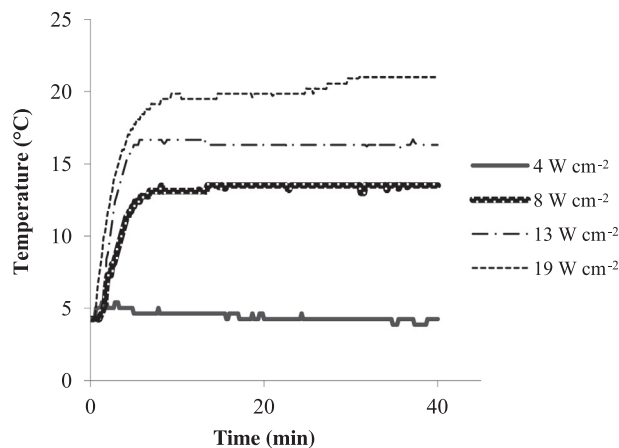


Fig. 2. The temperature rises occurring in the treatment vessel at different ultrasonic intensities applied for 40 min.

such that it came in contact with the exposed meat surface (Fig. 1). The diffusion cell was placed into a jacketed beaker and a glycol coolant was circulated (-2°C , 5 L min^{-1}) to control temperature rises, which were dependent on the US intensity applied (Fig. 2).

2.2. Treatment

The ultrasonic treatment was administered by a 20 kHz, 550 W ultrasonic probe (XL2020, Heat Systems, Misonix Inc., Farmingdale, NY, USA). The power output of an US probe can be affected by many factors such as temperature, viscosity and vessel geometry [22], therefore measurement of the acoustic field is necessary. Calorimetry is the measurement of the temperature rise in the first moments of sonication.

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