Journal of Food Engineering 203 (2017) 16–24

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Correlating structural properties to sodium release of model solid lipoproteic colloids

Wan-Yuan Kuo, Youngsoo Lee*

Department of Food Science and Human Nutrition, University of Illinois at Urbana-Champaign, 382K, Agricultural Engineering and Sciences Building, 1304 W. Pennsylvania Ave., Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 26 September 2016
Received in revised form
5 January 2017
Accepted 25 January 2017
Available online 30 January 2017

Keywords:
Solid lipoproteic colloid
Sodium release
Porosity
Gyration radius of fat
Serum release
Texture

ABSTRACT

Effect of structure on sodium release of model solid lipoproteic colloids (SLCs) was investigated. The SLCs structures were varied by different levels of protein (8 and 16%, w/w), fat (0, 11, 22, and 33%, w/w), NaCl (1.5% and 3.5%, w/w), and homogenization pressure (14 and 55 MPa). Sodium release was measured while the SLCs were compressed in water. For SLCs with 1.5% and 3.5% NaCl, the porosity correlated positively with the maximum rate of sodium release. For the SLCs with 3.5% NaCl, the particle size of fat correlated negatively with the maximum concentration of released sodium and the area under the curve of sodium release profile. This study revealed that sodium release can be controlled via the convective transfer or diffusive transfer mechanisms by controlling the porosity and particle size of fat, respectively.

1. Introduction

Engineering food structure to improve the sensory and nutritional qualities of the products has become one of the featuring areas in food science and food industry (Aguilera, 2005; Knoop et al., 2013; Norton et al., 2014; Stieger, 2011). Enhancing sodium release via engineering food structure has been proposed as one key strategy to allow a reduction in sodium content in processed foods (Stieger and van de Velde, 2013; van de Velde and Adamse, 2013). Understanding the effect of food structure on the transport mechanisms of sodium can help tailoring the product formulation and process design for an efficient sodium delivery during mastication process.

Transport of sodium from porous food systems to the oral cavity can be achieved via convective and/or diffusive transfer (Geankoplis, 2003; Kuo and Lee, 2014a). In a convective transfer, sodium migrates with the fluid flowing from the food matrix into surroundings. Deformation of the food matrix due to oral processing can initiate outward fluid flow from the pores, resulting in serum release (van den Berg et al., 2007a). Sodium ions that are free of ionic interaction with the matrix are readily carried out by the serum. Previous studies showed the serum release of gels can be enhanced by increasing porosity, by forming a coarse-stranded network, or by forming a bicontinuous network of gels (van den Berg et al., 2007a, 2007b, 2008). Moreover, increasing serum release has been shown to enhance sodium release and saltiness perception (Stieger, 2011). However, the study by Stieger (2011) used model gels composed of proteins and polysaccharides. While many food products such as cheese and sausages contain emulsified fat, it has not been studied how the presence of fat can alter the serum release and sodium release. It has been demonstrated in meat products that a reduction of sodium by at least 15% was achieved by increasing the juiciness (van de Velde and Adamse, 2013). Still, the roles of fat particles in the above meat products were not examined.

While the driving force of convective transfer for sodium is the serum flow, the driving force for spontaneous diffusion of sodium is the concentration gradient of sodium across the food matrix and the surrounding oral cavity (Geankoplis, 2003; Kuo and Lee, 2014a). In model lipoproteic gel systems, decrease in particle size of fat caused increased extent of gel breakdown and thus increased surface area, allowing more sodium release (Boisard et al., 2013, 2014; de Loubens et al., 2011a, 2011b; Panouille et al., 2011). The above studies did not include the serum release of the gels. In another two studies on model lipoproteic gels, sodium release in mouth correlated positively with the water content of the gel (Lawrence et al.,

* Corresponding author.
E-mail addresses: wkuo7@illinois.edu (W.-Y. Kuo), leeys@illinois.edu (Y. Lee).

http://dx.doi.org/10.1016/j.jfoodeng.2017.01.025
0260-8774/

2012; Phan et al., 2008).

Porosity and particle size of fat are critical factors affecting sodium release of lipoproteic foods, yet never studied together in a model food system. It is essential to study the effect of various structural properties together in the same food matrix to understand the role of structure in sodium release. The objective of this study is to correlate the structural properties, including porosity and particle size of fat, to the *in vitro* sodium release properties collected during the compression of solid lipoproteic colloids (SLCs). The correlation of the structural properties to the temporal properties of sodium release further revealed the time-dependent variation of sodium transport mechanisms throughout the gel compression process. The results will enhance the understanding of the saltiness perception of lipoproteic products such as cheese and sausages, as well as developing prototypes for sodium reduction.

2. Material and methods

2.1. Preparation of solid lipoproteic colloids (SLCs)

The protocol for the preparation of the SLCs is detailed in previous literature (Kuo and Lee, 2014b; Kuo et al., 2016). Briefly, NaCl solutions containing whey protein isolate were homogenized with anhydrous milk fat using the APV 2-stage homogenizer (15 MR, SPX Flow Technology, Soeborg, Denmark), followed by heat-induced gelation by heating the emulsion at 90°C for 30 min to form the SLCs. The SLCs varied by the contents of protein (8 and 16%, w/w), fat (0, 11, 22, and 33%, w/w), NaCl (1.5 and 3.5%, w/w), and homogenization pressures (14 and 55 MPa). The SLCs are coded according to their formula and homogenization pressure as protein(%, w/w)-fat(%, w/w)-pressure(MPa).

2.2. Structural, textural and sodium release properties of the SLCs

The protocols for acquiring the structural, textural and sodium release properties of the SLCs are detailed in previous literature (Kuo and Lee, 2014b; Kuo et al., 2016) unless additionally specified.

The images of the SLC internal structure were captured using an environmental scanning electron microscope (ESEM) with a field emission electron gun (FEI Co., Hillsboro, Oreg., U.S.A.) (Kuo and Lee, 2014b). The samples were freshly prepared and observed at the 1 Torr wet mode of the ESEM which allows characterizations of high-moisture samples without the need of prior drying (Donald, 2003). The pores of the gel on the ESEM photos were identified using image analysis with the method described by Kuo and Lee (2014b). The porosity was calculated as the volume fraction of the pores relative to the total volume of the gel (Ryukhtin et al., 2003), assuming the pores are spherical. The gyration radius of fat particles ($r_{g,f}$) in the SLCs was determined using the Bonse-Hart double-crystal ultra-small-angle X-ray scattering (USAXS) instrument operated by ChemMatCARS at the Advanced Photon Source, Argonne National Laboratory (Argonne, IL, USA) (Kuo et al., 2016).

The textural properties, including serum release, maximum stress ($stress_{max}$), and strain at maximum stress ($strain_{max}$) were measured by a compression test using a texture analyzer (TA-XT2i, Texture Technologies Corp., Scarsdale, N.Y., U.S.A.) (Kuo and Lee, 2014b).

The *in vitro* sodium release properties of the SLCs were determined by compressing the SLC in water using a texture analyzer (TA-XT2i, Texture Technologies Corp., Scarsdale, N.Y., U.S.A.), while recording the conductivity of the water using a conductivity probe (Orion DuraProbe 4-Electrode Conductivity Cells 013005MD) connected with an Orion VERSA STAR Multiparameter Benchtop Meter (Thermo Fisher Scientific Inc., Waltham, Mass, U.S.A.). The parameters extracted from the curve of sodium release included the maximum rate of sodium release (R_{max}), the maximum concentration of released sodium (C_{max}), and the area under the curve (AUC) of sodium release (Kuo and Lee, 2014b).

2.3. Statistical analyses

Analysis of variance (ANOVA) on each group of the SLCs with a constant level of NaCl was performed using SAS Software (SAS 9.3, SAS Inst., Inc., Cary, N.C., U.S.A.). The proc glm and the LSMEANS with the adjusted Tukey test were used to analyze the difference between the sample means.

Linear correlation, partial least square (PLS), and cluster analyses on each group of the SLCs with the same level of NaCl were performed using OriginPro 2015 (OriginLab Corporation, Northampton, MA, USA). These three analyses were performed on all the SLC samples, and also on only the fat-containing SLCs.

In the linear correlation, the treatment variables were correlated to the measured variables. The treatment variables in the linear correlation included the contents (w/w) of protein (P%), fat (F%) and water (W%), the weight ratios of fat to protein (F/P), fat to water (F/W), protein to water (P/W), fat to solids (F/S), and homogenization pressure of the SLCs.

In the PLS analysis, the treatment and measured variables with significant and representative correlations were used as the X and Y variables, respectively. For each Y-score PLS graph, cluster analysis with Euclidean distance and Ward's method was performed based on the Y-score variables.

3. Results and discussion

3.1. Effect of the treatments on the porosity of the SLCs

Our previous studies have explored the microstructure of the SLCs using ESEM and USAXS (Kuo and Lee, 2014b; Kuo et al., 2016). The SLCs are composed of a continuous protein network with varying average pore size (0.4–2.3 μm, data not shown) and porosity depending on the formulation and treatment (Kuo and Lee, 2014b). Protein aggregates with sizes below a hundred nanometers were the basic subunits of the SLC protein network (Kuo et al., 2016). For the fat-containing SLCs, spherical fat particles were homogeneously distributed within the protein network structure. The protein-fat interaction of the SLCs with 1.5% NaCl was relatively stronger than in the SLCs with 3.5% NaCl, from which the fat particles were more easily observed under the ESEM (Kuo et al., 2016).

Varying treatments including compositions and homogenization pressure to prepare SLCs affected structural, textural, and sodium release properties (Tables 1–3). For the SLCs with 1.5% NaCl, the porosity correlated positively with the W% and negatively with the F/S (Table 4). Similar trends were found in the SLCs with 3.5% NaCl, with higher levels of significance and greater values of the correlation coefficients than the SLCs with 1.5% NaCl. This stronger dependence of porosity on the formula in the SLCs with 3.5% NaCl compared to those with 1.5% NaCl is further presented in the PLS graphs of the two sample groups (Fig. 1(a) and (b)). The positive correlation between the porosity and the W% reflected the nature of porosity – originating from the voids filled with fluids in water-based gel network (van den Berg et al., 2007a, 2007b). Hence, increased water content of the gel generally leads to increased porosity (Kuo and Lee, 2014b). However, in the SLC systems, the porosity correlated stronger with the F/S ratio than with the water content. When comparing the selected samples with similar water contents, the effect of F/S ratio on porosity can be clearly seen. For example, the water contents of samples 8-33-14 and 16-22-14 are