J. Dairy Sci. 101:1–13
https://doi.org/10.3168/jds.2017-14103
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Effect of high-pressure-jet processing on the viscosity and foaming properties of pasteurized whole milk

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ABSTRACT

The processing of milk using high-pressure technologies has been shown to dissociate casein micelles, denature whey proteins, and change the appearance and rheological properties of milk. A novel high-pressure processing technology called high-pressure-jet (HPJ) processing is currently being investigated for use in the food industry. Few studies have evaluated the effects of HPJ technology on dairy foods. The present study investigated the physicochemical and foaming properties of homogenized pasteurized whole milk processed at pressures from 0 to 500 MPa using HPJ processing. The apparent particle size exhibited a monomodal distribution in whole milk samples processed up to 125 MPa and a bimodal distribution for samples processed at 250, 375, and 500 MPa. The viscosity increased from approximately 2 to 5 mPa·s when whole milk was processed using HPJ at 375 MPa, and foam expansion increased from approximately 80 to 140% after processing at >125 MPa. Foam stability was limited to pressures in the 375 to 500 MPa range. We hypothesized that the increase in apparent particle size was due to the dissociation of casein micelles into surface-active casein protein monomers, and the formation of casein–casein and casein–fat particles. Ultracentrifugation of samples into 3 milk fractions (supernatant, serum, and precipitate), and subsequent fat and protein analysis on the 3 fractions, showed that a strong interaction between casein proteins and fat triglycerides occurred, evidenced by the increase in fat content associated with the precipitate fraction with increasing pressure. This suggests that stable casein–fat aggregates are formed when whole milk is processed using HPJ at pressure >125 MPa.

Key words: high-pressure jet, whole milk, foaming, creaming

INTRODUCTION

Most research conducted on high pressure involves high-pressure processing, microfluidization, or high-pressure homogenization (Tobin et al., 2015; Voigt et al., 2015). High-pressure processing (**HPP**) has been commercialized in the food industry by utilizing high hydrostatic pressure for nonthermal pasteurization (i.e., to inactivate foodborne pathogens; Feijoo et al., 1997; Mussa and Ramaswamy, 1997; Hayes et al., 2005) and to prevent quality loss (i.e., polyphenol oxidase inactivation in avocado; Palou et al., 1999). The capabilities of HPP are limited because it is a batch process, and industries that process fluid and semi-solid foods prefer continuous processing for increased efficiency. Microfluidization utilizes pressure to push fluids into 2 opposing channels where the liquids impinge, followed by a decrease in pressure, which causes turbulence, resulting in droplet disruption (Tobin et al., 2015). Advantages of using microfluidization include low maintenance, because there are no moving parts in the interaction chamber, and the ability to produce fine emulsions with narrower particle size distribution. Limitations include pressure ranges from 20 to 275 MPa and possible increase of fat globule size and coalescence due to "over-processing" at higher pressures, which also occur during HPP (Jafari et al., 2007). High-pressure homogenization (**HPH**) is a continuous process that utilizes a pump to push fluids through a ball-seat or needle-seat shear-resistant valve at pressures up to 400 MPa. The act of forcing fluids through the resistant valve creates a combination of physical phenomena including high hydrostatic pressure, shear, turbulence, cavitation, impingement, and temperature (Paquin, 1999). These physical phenomena cause physicochemical changes to foods processed using HPH.

Advances in material science and engineering have enabled high-pressure jet (**HPJ**) technology to achieve processing pressures up to 600 MPa. The HPJ is equipped with a diamond, sapphire, or ruby nozzle (75 to 400 μm in diameter) to restrict the flow into a jet stream. Similarly to HPH, physical phenomena in-

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Received November 6, 2017.
Accepted January 8, 2018.
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cluding high hydrostatic pressure, turbulence, cavitation, and temperature occur in the HPJ nozzle. Studies conducted on raw and pasteurized skim and whole milk systems using HPH showed significant changes in fat globule and casein micelle size depending on pressures applied. Studies have reported a reduction in apparent particle size of fat globules at pressures between 200 and 250 MPa (Hayes and Kelly, 2003; Thiebaud et al., 2003; Hayes et al., 2005). At pressures $\geq$250 MPa, an increase in fat globule size has been observed, possibly due to clustering and coalescence of newly formed fat globules (Thiebaud et al., 2003; Pereda et al., 2007). Casein micelles processed under HPH are disrupted and decrease in size at pressures of 100 to 200 MPa, whereas micelle size appears to increase at pressure between 200 and 350 MPa (Hayes and Kelly, 2003; Sandra and Dalgleish, 2005; Roach and Harte, 2008; Lodaite et al., 2009). High-pressure homogenization at >350 MPa without cooling induces whey protein denaturation due to a shear-induced increase in temperature. The increase in temperature creates complexes between denatured β-LG and casein micelles, causing an increase in apparent casein micelle size (Hayes et al., 2005; Zobrist et al., 2005; Pereda et al., 2007). The extent of whey protein denaturation depends on the efficiency of the heat exchanger to cool the sample.

Pasteurized skim milk processed with HPJ from 0 to 500 MPa (in 100-MPa increments) exhibited significant changes in apparent particle size and increases in apparent viscosity and rennet coagulation time, as well as improved foaming and emulsifying properties (Harte et al., 2016; Mohan et al., 2016). The increased foamability and emulsifying properties were due to partial disruption of casein micelles, causing an increase of protein adsorption to the interface and partially heat-induced whey protein denaturation (Harte et al., 2016).

High-pressure-jet processing of pasteurized skim milk has led to modified functionality of casein micelles, creating the potential to use HPJ processing for novel dairy food applications. However, dairy foods are complex systems in which interactions of multiple components such as milk fat and proteins contribute to the structure and integrity. Therefore, investigating simpler systems such as pasteurized whole milk will aid in further understanding of HPJ processing capabilities for the food industry.

We hypothesized that dissociation of casein micelles by HPJ processing of whole milk will lead to improved foamability by creating stable casein–fat aggregates. Therefore, the objective of this study was to investigate the effect of HPJ processing on the physicochemical and foaming properties of pasteurized whole milk.

MATERIALS AND METHODS

HPJ Processing of Pasteurized Whole Milk

Pasteurized and homogenized whole milk was purchased from the Penn State Berkey Creamery (University Park, PA). The milk was kept at 4°C before HPJ processing from 125 to 500 MPa in 125-MPa increments using a Hyperjet 94i-S pump system (Flow Internationals Corp., Kent, WA). The control sample (0 MPa gauge pressure) was not subject to HPJ processing. The milk was forced through a 10-μm-diameter diamond nozzle. A custom-made tubular heat exchanger (**HE#1**, Figure 1; outer tube diameter of 7.6 cm and inner tube diameter 5.1 cm, with a height of 122 cm) connected to a temperature-controlled water bath was placed before the nozzle and was used to maintain temperature of the milk at 55°C or 5°C. A second heat exchanger (**HE#2**, Figure 1; outer tube diameter of 7.6 cm and inner tube diameter 5.7 cm, with a height of 152.4 cm) was placed after the nozzle to contain and cool the HPJ-processed milk. Cooled water (2–4°C) provided by the Department of Food Science pilot plant was pumped through HE#2 to rapidly cool the HPJ-processed milk. A hose was connected to the bottom of HE#2 to collect the milk. Three thermocouples were placed on the system: before the first heat exchanger (**TC#1**), before the nozzle (**TC#2**) to indirectly monitor temperature of the milk, and to directly measure exit temperature of the samples (**TC#3**; Figure 1). The flow rate was determined by measuring the time required to collect a known volume of milk. After the samples were processed, the pump was cleaned with domestic water, a neutral detergent (Soft Clean No. 379, Hydrite, Brookfield, WI), and food-grade sanitizer (XY, EcoLab, St. Paul, MN), and rinsed with domestic water. The HPJ-processed milks were stored at 4°C and analyzed within 5 d.

Apparent Particle Size and Fat Globule Size

Apparent particle size distribution of HPJ-processed milks was determined by static light scattering using a Horiba LA-920 particle size analyzer (Horiba Scientific, Edison, NJ). The milk fat refractive index was 1.14, which was calculated as the refractive index of the particle (1.52 for milk fat) divided by the refractive index of the diluent (1.33 for water). The HPJ-processed milks were transferred into the particle size analyzer until transmittance equilibrated between 70 and 90% and further analyzed for volume-surface mean diameter ($\boldsymbol{d_{4,3}}$).

Apparent fat globule size was measured using the method of Huppertz et al. (2011). Briefly, samples were

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