Comparison of functional properties of 34% and 80% whey protein and milk serum protein concentrates

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ABSTRACT

This study compared the functional properties of serum protein concentrate (SPC) with whey protein concentrate (WPC) made from the same milk and with commercial WPC. The experimental SPC and WPC were produced at 34% or 80% protein from the same lot of milk. Protein contents of WPC and SPC were comparable; however, fat content was much lower in SPC compared with WPC and commercial WPC. The effect of drying methods (freeze vs. spray drying) was studied for 34% WPC and SPC. Few differences due to drying method were found in turbidity and gelation; however, drying method made a large difference in foam formation for WPC but not SPC. Between pH 3 and 7, SPC was found to have lower turbidity than WPC; however, protein solubility was similar between SPC and WPC. Foaming and gelation properties of SPC were better than those of WPC. Differences in functional properties may be explained by differences in composition and extent of denaturation or aggregation.

Key words: whey protein concentrate, serum protein concentrate, functional properties, microfiltration

INTRODUCTION

Whey, the liquid remaining after the coagulation of micellar caseins in cheese production or rennet casein production, is an important ingredient in the food industry. Whey proteins are produced as a co-product from the cheese and rennet casein industries. Sweet whey is obtained from the manufacture of cheese or rennet casein, whereas acid whey is from the production of acid casein (Mulvihill and Ennis, 2003), cottage cheese, and strained yogurts. Because whey proteins represent only 10% of the total solids of whey, several processes (e.g., UF-diafiltration, ion exchange, and ul-

tracentrifugation) have been developed to recover whey proteins in a more concentrated form. Different whey products are categorized based on their protein concentration, with whey protein concentrate (WPC) having 30 to 85% protein and whey protein isolate (WPI) containing >90% protein (Foegeding et al., 2011).

Commercial WPC are produced by UF-diafiltration. In UF, a pressurized solution flows over a porous membrane allowing the separation of protein and fat from lactose, minerals, and water under mild temperature and pH conditions (Mulvihill and Ennis, 2003). Because of problems associated with UF, such as membrane fouling, diafiltration (retentate dilution with water and repeated UF) is used to further remove lactose and minerals and thus, increasing the protein concentration (de la Fuente et al., 2002; Yee et al., 2007). The retentate is concentrated by evaporation and spray dried into powder.

Like all other membrane separation processes, microfiltration (MF) is a pressure-driven separation technique using membranes with pore-size diameters of 10 to 0.1 μm (Saboya and Maubois, 2000). The major breakthrough for MF in the dairy industry came after the development of new ceramic membranes with multichannel geometry and a highly permeable support as well as the concept of uniform and low transmembrane pressure (Sandblom, 1974; Gillot and Garcera, 1986; Saboya and Maubois, 2000). The applications of MF in the dairy industry are primarily the removal of microorganisms from skim milk, whey defatting, and casein enrichment (Saboya and Maubois, 2000). The MF permeate of cheese whey is lower in fat and microbial debris from starter culture than cheese whey, and also lower in annatto color if the cheese whey was from colored Cheddar (Saboya and Maubois, 2000).

Removal of fat and micellar caseins from milk results in milk serum proteins that are similar to the family of proteins found in cheese whey with the exception of the absence of the glycomacropeptide (GMP) fraction of κ -casein (Walstra et al., 1999). The difference in size between casein micelles (0.2 μm ; Dalgleish and

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Corredig, 2012) and serum proteins (0.01 μm for WPI; Roefs and de Kruif, 1994) allows the separation of these proteins using a ceramic membrane with a pore-size diameter of 0.1 μm (Saboya and Maubois, 2000). Permeate from MF of skim milk is clear and sterile, and it is an excellent starting material for production of serum protein concentrate (SPC) or isolates (Saboya and Maubois, 2000). Serum or whey proteins obtained by MF from raw milk have been referred to as native whey protein (Heino et al., 2007), milk microfiltrate protein (Britten and Pouliot, 1996; Maubois et al., 2001), virgin whey protein (Marcelo and Rizvi, 2008), and milk serum proteins (Nelson and Barbano, 2005).

Nelson and Barbano (2005) demonstrated the feasibility of removal of serum proteins from skim milk before Cheddar cheese making. A combination of MF and diafiltration with UF permeate was developed to remove 95% of serum proteins from milk before Cheddar cheese making without changing the mineral balance or NPN level in the aqueous phase of the milk. Because of differences in composition and processing effects, SPC from MF and WPC from cheese making could differ in functionality. Serum protein concentrates are not exposed to the enzymatic or chemical reactions of the cheese making process, thus potentially offering different levels of functional properties.

Whey proteins have many functional characteristics, including solubility, gelation, emulsification, and foaming. A few studies investigated the functional properties of microfiltered whey proteins compared with commercial products (Britten and Pouliot, 1996; Heino et al., 2007; Marcelo and Rizvi, 2008) but not when proteins were made from the same lot of milk.

Previous work (Evans et al., 2009, 2010) compared composition, sensory, and volatile components of 34% and 80% WPC and SPC made from the same lots of milk in 3 replications. Few sensory flavor differences were found in 34% WPC and SPC for both freeze-dried and spray-dried powders, despite differences in appearance and composition (Evans et al., 2009). Comparison of 80% WPC and SPC rehydrated powders yielded higher concentrations of lipid oxidation products and greater numbers of oxidation products in WPC (Evans et al., 2010). Comparison of 80% WPC and SPC with commercially produced products found higher levels of lipid oxidation products in commercial WPC products (Evans et al., 2010). Overall, flavor profiles and intensities of pilot plant-produced WPC and SPC were very similar for both 34% and 80% protein powders. Both pilot plant and commercially produced WPC had higher oxidized flavor compared with SPC, most likely because of the enzymatic and chemical reactions taking place in the cheese making process that preceded WPC production and the higher fat content of the WPC.

This paper is the third in a series with the goal of comparing quality characteristics and functional properties of SPC and WPC (34 and 80% protein) made from the same lot of milk. In addition to comparing pilot plant-produced SPC and WPC, commercial WPC made by 6 different companies were used as a second level of comparison for some properties. Solubility, turbidity, foaming, and gelation properties of 10% (wt/vol) protein suspensions were compared. The effects of spray and freeze drying were also examined.

MATERIALS AND METHODS

Materials

The SPC and WPC samples were made at Cornell University (Ithaca, NY). One lot of whole raw milk from the Cornell University dairy farm was divided into 2 portions. One portion was used to make Cheddar cheese and produce 34% WPC. Before cheese making, the whole milk was pasteurized at 72°C for 16 s. Once drained from the curds, the whey was pasteurized at 72°C for 16 s, before concentration via UF (Evans et al., 2009). The other portion of raw milk was centrifuged at 4°C to separate cream and skim milk, followed by skim milk pasteurization at 72°C for 16 s, and then used to produce 34% and 80% SPC. Production of SPC and WPC was replicated 3 times with different lots of milk. Commercial WPC (34% protein) samples were obtained from 6 different companies and analyzed under the same conditions for comparison with the samples produced in this study. Details of SPC and WPC production can be found in Evans et al. (2009, 2010).

Chemical Analyses

The WPC and SPC samples were analyzed for fat, total N, and NPN content using ether extraction (AOAC International, 2000; method 989.05, 33.2.26), Kjeldahl (AOAC International, 2000; method 991.20; 33.2.11), and Kjeldahl (AOAC International, 2000; method 991.21; 33.2.12), respectively. The GMP content (which is soluble in 12% TCA) of WPC was calculated as a difference in NPN content between WPC and SPC powders on a dry basis. Contents of Ca, P, K, and Na were determined using a standard dry ash method with inductively coupled plasma optical emission spectroscopy (ICP-OES) at the Department of Soil Science, North Carolina State University (Raleigh).

Solution Preparation

Samples of WPC or SPC (10% wt/vol protein) were hydrated in deionized water (80% of total volume) with

stirring for 6 h at room temperature ($22 \pm 2^\circ\text{C}$). The solutions were kept overnight at 4°C and were brought up to 25°C the next day. Then, the solutions were adjusted to experimental pH conditions (± 0.05) with 1 *N* HCl or NaOH before adjusting to final volume.

pH-Sensitive Solubility

Solution pH was adjusted to 3, 4, 5, 6, or 7. Samples were centrifuged at $10,000 \times g$ for 15 min in a Beckman Microfuge 11 (Beckman, Fullerton, CA). The dispersed protein concentration was determined before and after centrifugation using the bicinchoninic assay (Pierce, Rockford, IL). The amount of protein solubility was reported as percentage proteins left in the supernatant after centrifugation compared with that before centrifugation. The experiments were repeated at least twice and average values were calculated.

Turbidity Measurement

The degree of protein aggregation was estimated by measuring the turbidity of solutions and gels in a 2100AN turbidity meter (Hach Co., Loveland, CO) and reported as nephelometric turbidity units (NTU).

Foam Generation

Solution pH was adjusted to pH 7. A KitchenAid Ultra Power Mixer (KitchenAid, Benton Harbor, MI) with a 4.3-L stationary bowl and rotating beaters was used to generate foams. Two hundred milliliters of protein solution was measured, weighed, and added to the mixing bowl. The solution was whipped for 20 min at a speed setting of 8 (planetary rpm of 225 and beater rpm of 737). After foam generation was complete, the beaters were gently lifted out of the foam.

Foam Yield Stress Measurement

Yield stress was measured utilizing vane rheometry, according to the method of Pernell et al. (2000). A vane (10 mm in diameter and 40 mm in length) was attached to a Brookfield 25xLVTDV-ICP viscometer (Brookfield Engineering, Middleboro, MA). Immediately after foam generation, the vane attachment was gently lowered into the foam until the top edge was level with the foam surface. The vane was rotated at a speed of 0.3 rpm and the maximum torque (%) was recorded. Yield stress was calculated utilizing maximum torque and vane dimensions according to the following equation:

$$\tau = \frac{M_0}{\left(\frac{h}{d} + \frac{1}{6}\right)\left(\frac{\pi d^3}{2}\right)},$$

where τ is the yield stress, M_0 is the maximum torque, h is the height of the vane, and d is the diameter of the vane. The vane was then gently lifted out and the process was repeated for a total of 3 yield stress measurements throughout the bowl. These 3 measurements were averaged to form 1 data point, and the treatments were repeated in duplicate. All 3 measurements per bowl were completed within 5 min of foam generation.

Foam Overrun

Immediately after yield stress measurements, foam overrun was measured based on the method of Phillips et al. (1987). Foam was gently scooped into a standard weight boat (100 mL) and leveled off using a rubber spatula. Weight of the foam was recorded and this process repeated for 10 measurements per bowl. Overrun measurements were completed within 15 min of whipping. The average of 10 foam weights, along with the initial weight of the protein solution, was used for the calculation of overrun according to the following equation: Overrun (%) = [(wt. of 100 mL of solution – wt. of 100 mL of foam)/wt. of 100 mL of foam] $\times$ 100%. Overrun measurements were completed in duplicate.

Foam Stability/Drainage Time (Half-Life Time)

The foam stability was assessed by recording the length of time required for half the foam mass to drain, based on the method of Phillips et al. (1987). A mixing bowl with a 6-mm-diameter hole was used for stability measurements. The hole was covered with tape during whipping and placed on a ring stand directly over a scale immediately after foam generation. The tape was removed and the time for half the liquid mass to drain into a weigh boat was recorded. Foam stability measurements were measured in duplicate for each treatment. Greater stability was reflected by slower draining, hence a longer drainage time.

Gelation Properties

Solutions were adjusted to pH 7.0. Sodium chloride (100 mM; Sigma Chemical Co.) was added to a portion of the solutions. The solutions were poured into glass tubes (19 mm internal diameter) coated with Sigmacote (Sigma Chemical Co.). Gels were formed in a water bath at 90°C for 30 min and cooled at $23^\circ\text{C} \pm 1^\circ\text{C}$. Fracture stress (strength) and fracture strain (deformability) of the gels were determined by twisting gel samples until fracture. Gels were cut into cylinders (29 mm in height), and each end was glued to plastic disks using cyanoacrylate glue. The cylinders were ground into capstan shapes with a center diameter of

Table 1. Mean ($n = 3$) composition (% by weight) of serum protein concentrate (SPC), pilot-plant whey protein concentrate (WPC), or commercially produced whey protein concentrate (WPC34-1 to 34-6 and WPC80-1 to 80-5) calculated on a dry basis

Product	Protein	Fat	Glycomacropeptide
34% protein WPC ¹			
SPC34	35.3 ^{cd}	0.25 ^e	0.00 ^a
WPC34	34.4 ^d	1.93 ^f	1.45 ^b
WPC34-1	39.1 ^a	3.41 ^{ab}	
WPC34-2	36.2 ^{bc}	3.52 ^a	
WPC34-3	36.5 ^{bc}	3.23 ^{abc}	
WPC34-4	36.8 ^a	2.81 ^{cd}	
WPC34-5	35.6 ^{bcd}	3.03 ^{bc}	
WPC34-6	36.3 ^{bc}	2.50 ^d	
80% protein WPC ²			
SPC80	77.9 ^a	0.53 ^b	0.00 ^b
WPC80	72.2 ^b	8.12 ^a	4.88 ^a
WPC80-1	81.0 ^a	5.19 ^b	
WPC80-2	79.9 ^{ab}	4.51 ^b	
WPC80-3	80.1 ^a	8.02 ^a	
WPC80-4	78.8 ^{ab}	7.02 ^{ab}	
WPC80-5	81.4 ^a	5.31 ^b	

^{a-f}Means in the same column within each type of WPC, either 34 or 80% protein, not sharing a common superscript are different ($P < 0.05$).

¹Evans et al. (2009).

²Evans et al. (2010).

10 mm using a precision milling machine (model GC-TG92 US, Gel Consultants, Raleigh, NC). Gels were vertically mounted and twisted to fracture at 0.405 rpm on a Haake VT 550 rheometer (Haake, Karlsruhe, Germany). At least 6 gels were tested for each replication of each treatment. Fracture stress and fracture strain were calculated from the torque and angular displacements according to the method of Diehl et al. (1980).

Statistical Analysis

Significance differences ($P < 0.05$) were determined by ANOVA using the Proc GLM procedures of SAS (version 9.1, SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Proximate analysis results of 34 and 80% protein SPC (**SPC34**, **SPC80**), WPC (**WPC34**, **WPC80**), and commercial WPC (**cWPC**) are listed in Tables 1 and 2 (Evans et al., 2009, 2010). Percentage protein was comparable across all samples; however, the amount of fat was significantly lower in SPC samples, as seen by other investigators (Heino et al., 2007; Marcelo and Rizvi, 2008). Mineral compositions of experimental SPC and WPC were generally similar and in the same range as those of cWPC samples.

Effect of pH on Turbidity and Solubility of Unheated Protein

The most striking difference between SPC34 and WPC34 was solution clarity (Table 3). All experimental

WPC34 and commercial WPC (cWPC34) between pH 3 and 7 were very turbid and had turbidity values out of range of the instrument's sensitivity. This could be caused by the higher amount of lipid or the presence of large aggregates in WPC. Aggregates could have been protein alone or a mixture of proteins and other compounds. In a survey of commercially produced 34 and 80% WPC, aggregated protein was found to account for between 10 and 29% of the total protein in the powder (Roufik et al., 2005). Regardless of drying treatment, SPC34 was most turbid at pH 3 and 4. Increasing pH led to a decrease in turbidity, with the freeze-dried SPC being less turbid than spray-dried SPC at the same pH. The largest difference in turbidity between drying treatments was seen at pH 5, with spray-dried SPC having 10 times the turbidity of freeze-dried SPC. The heat from spray drying could lead to protein denaturation and aggregation during processing, and protein aggregates would cause a higher turbidity at pH 5.

Solubility of SPC34 and WPC34 solutions at varying pH is shown in Figure 1. Solubility of both SPC and WPC was found to be lower at pH 3. Drying method had no effect on solubility of both proteins at the same pH. Surprisingly, we found no significant difference ($P \geq 0.05$) among SPC and WPC at all pH values. Solubility of cWPC34 (WPC34-1 to WPC34-6) ranged from 49.8 ± 3.8 to 89.1 ± 11.8 and from 76.7 ± 5.8 to $96.2 \pm 2.4\%$ at pH 3 and 7, respectively (Figure 2). This indicated the large variability among commercial products regarding (1) the amount of denatured or aggregated protein, and (2) electrostatic stability of proteins as affected by mineral content. These 2 factors are major

Table 2. Mean ($n = 3$) mineral composition (% by weight) of 34% or 80% protein serum protein concentrate (SPC), pilot-plant whey protein concentrate (WPC), or commercially produced whey protein concentrate (WPC34-1 to 34-6 and WPC80-1 to 80-5) calculated on a dry basis

Product	Ca	Na	K	P
34% protein WPC ¹				
SPC34	0.44 ^d	0.43 ^b	1.88 ^{bc}	0.56 ^d
WPC34	0.54 ^c	0.44 ^b	1.91 ^b	0.62 ^c
WPC34-1	0.40 ^d	0.44 ^b	1.71 ^{cd}	0.55 ^d
WPC34-2	0.59 ^b	0.89 ^a	1.73 ^{bcd}	0.64 ^{bc}
WPC34-3	0.69 ^a	0.47 ^b	2.11 ^a	0.66 ^c
WPC34-4	0.66 ^a	0.42 ^b	2.04 ^a	0.88 ^a
WPC34-5	0.45 ^{cd}	0.48 ^b	1.66 ^d	0.55 ^d
WPC34-6	0.66 ^a	0.54 ^b	1.75 ^{bc}	0.69 ^b
80% protein WPC ²				
SPC80	0.40 ^b	0.19 ^{cd}	0.87 ^a	0.30 ^c
WPC80	0.47 ^a	0.17 ^{de}	0.77 ^b	0.35 ^{bc}
WPC80-1	0.48 ^a	0.24 ^b	0.57 ^{ca}	0.36 ^{bc}
WPC80-2	0.52 ^a	0.12 ^f	0.49 ^{cd}	0.37 ^b
WPC80-3	0.40 ^b	0.22 ^{bc}	0.47 ^d	0.47 ^a
WPC80-4	0.35 ^b	0.14 ^{ef}	0.50 ^{cd}	0.33 ^{bc}
WPC80-5	0.29 ^c	0.32 ^a	0.53 ^{cd}	0.31 ^{bc}

^{a-f}Means in the same column within each type of WPC, either 34 or 80% protein, not sharing a common superscript are different ($P < 0.05$).

¹Evans et al. (2009).

²Evans et al. (2010).

contributors to protein solubility (de Wit and van Kessel, 1996).

Spray- and freeze-dried treatments for 34% concentrate samples showed little difference in measured functional properties due to drying treatment; therefore, freeze-dried samples were not examined for 80% concentrate samples. Additionally, spray drying is the industry standard. Turbidity of spray-dried SPC80 and WPC80 is shown in Table 3. Similar to WPC34, all WPC80 samples were more turbid than SPC80; however, the turbidity of the WPC80 samples was within the sensitivity of the instrument. The highest turbidity was

seen at pH 4.0 in both SPC80 and WPC80. All cWPC samples were very turbid and could not be measured as they were out of range of the instrument.

Both SPC80 and WPC80 were highly soluble at all pH values with 89.6% solubility and above (data not shown). We observed no significant difference between SPC and WPC at all pH values. Solubility of cWPC was compared with that of SPC and WPC at pH 3 or 7. Solubility of SPC80 and WPC80 samples produced in this study was comparable to that of commercial products (Figure 3), all of which were very soluble. Some solubility values were above the maximum value

Table 3. Comparison of turbidity values for 34% and 80% protein serum protein concentrates (SPC) and whey protein concentrate (WPC) powders

pH	34% protein		80% protein	
	Drying treatment	Turbidity ¹	Protein treatment	Turbidity
3	SPC/Freeze	OR	SPC	452.0
	SPC/Spray	OR	WPC	4,672.0
4	SPC/Freeze	OR	SPC	4,201.0
	SPC/Spray	OR	WPC	6,000.0
5	SPC/Freeze	90.3	SPC	2,164.0
	SPC/Spray	1,178.0	WPC	5,187.0
6	SPC/Freeze	36.7	SPC	14.8
	SPC/Spray	46.4	WPC	4,888.0
7	SPC/Freeze	30.4	SPC	10.6
	SPC/Spray	48.5	WPC	4,380.0

¹Values reported in nephelometric turbidity units (NTU). Turbidity of experimental and commercial 34% protein WPC and 80% protein commercial WPC were out of range (OR) for the instrument. Values listed in the 80% protein column in the table are experimentally produced WPC and SPC. The values that are OR are commercially produced 80% protein WPC and all 34% protein WPC and these values are not shown in the table.

Figure 1. Comparison of serum protein concentrate (SPC) or whey protein concentrate (WPC) pH-sensitive protein solubility; ● = 34% protein, freeze-dried SPC; ■ = 34% protein, spray-dried SPC; ○ = 34% protein, freeze-dried WPC; □ = 34% protein, spray-dried WPC. Error bars represent 1 SD.

of 100% and this was due to the inherent variability of the analysis, as actual values >100% are not possible.

Overall, WPC were more turbid than SPC but their solubility was not different across pH values. Highest turbidity was found around pH 4 and 5 for SPC80 and WPC80. It was surprising to observe the high turbidity and low solubility of SPC34 at pH 3. Typically, the lowest solubility of whey protein is reported to be around pH 4.5 (Pelegre and Gasparetto, 2005).

Figure 2. Comparison of spray-dried 34% protein whey (WPC) and serum (SPC) protein concentrate; ● = pH 3; □ = pH 7. The SPC and WPC were made in a pilot plant; WPC34-1 to WPC34-6 were all made commercially. Error bars represent 1 SD.

Figure 3. Comparison of spray-dried 80% protein whey (WPC) and serum (SPC) protein concentrate; ● = pH 3; □ = pH 7. The SPC and WPC were made in a pilot plant; WPC80-1 to WPC80-5 were all made commercially. Error bars represent 1 SD.

Foaming Properties and Foam Stability

Foaming properties of 34% and 80% protein whey protein ingredients were compared. Freeze-dried WPC34 did not form a foam stable enough for analysis compared with spray-dried WPC34, which did. Little difference was observed in foaming properties of SPC34 solutions made with spray- and freeze-dried powders. One of the main differences in the composition of SPC34 and WPC34 is the amount of fat present (Table 1). Although not investigated, a plausible reason for the difference in foaming properties due to drying technique could be increased availability of lipid, or a lipid complex, that more readily ruptures the air–water interfacial film.

All SPC34 samples formed foams with high overrun (Figure 4). The overrun of freeze- and spray-dried SPC34 did not differ significantly, but spray-dried WPC34 produced significantly less overrun than SPC ($P \leq 0.01$). Only 2 out of 6 of cWPC34 formed foams, indicating a high degree of variability among commercial samples. The lack of foaming in WPC is most likely due to the presence of antifoaming agents (emulsions with hydrophobic particles) rather than the inability of the whey proteins to form an interfacial film (Karakashev and Grozdanova, 2012). The level of overrun from cWPC was comparable to that of SPC.

Yield stress is a measurement that relates to the firmness of the foam. For example, when whipping egg white foams, the desired end point is indicated by a visible level of firmness in the foam (e.g., stiff peak stage). Both freeze-dried and spray-dried SPC34, as well as 2 cWPC34, produced foams with high yield stress, which

was significantly higher than foams formed with spray-dried WPC34. Drainage time is used as a measure of foam stability, with longer drainage time indicating more stable foam. Trends in drainage time for SPC34 and WPC34 were very similar to those observed for yield stress (Figure 4); however, foams from cWPC were much more stable.

Foaming properties of spray-dried 80% WPC are shown in Figure 5. Only SPC80 and 3 out of 5 cWPC samples formed foams. Overrun of foams from SPC80 was higher than those from cWPC80 samples. Yield stress and drainage time of foams made from SPC80 were comparable to those of commercial samples. In both 34 and 80% protein powders, SPC showed better

Figure 4. Comparison of spray-dried 34% protein whey (WPC) and serum (SPC) protein concentrate at pH 7. The SPC and WPC were made in a pilot plant; WPC34-1 to WPC34-6 were all made commercially. Error bars represent 1 SD. ^{a-c}Significant differences are between those proteins that formed foams, $P > 0.01$.

Figure 5. Comparison of spray-dried 80% protein whey (WPC) and serum (SPC) protein concentrate at pH 7. The SPC and WPC were made in a pilot plant; WPC80-1 to WPC80-5 were all made commercially. Error bars represent 1 SD. ^{a-c}Significant differences are between those proteins that formed foams, $P > 0.01$.

foaming properties and foam stability than WPC. Better foaming properties of SPC may be explained by the lower fat content (Table 1). Similarly, SPC from milk microfiltration, with a decrease fat content compared with WPC, has been shown to exhibit increased overrun, foam firmness, and foam stability (Britten and Pouliot, 1996; Heino et al., 2007). The negative effect of

fat content on foaming capacity and foam stability has been reported (Karleskind et al., 1995). In addition, the presence of other minor constituents in WPC may lead to differences in foaming properties. Whey protein concentrate from cheese whey was reported to contain surface-active compounds, such as phospholipids and lipoproteins (Joseph and Mangino, 1988), which can

Table 4. Stress and strain at fracture of gels made with 34% serum protein concentrate (SPC) or whey protein concentrates (WPC)¹

Sample	NaCl (mM)	Fracture stress (kPa)	Fracture strain
SPC34			
Freeze-dried	0	16.4 ± 3.3 ^{ab}	1.20 ± 0.11 ^a
Spray-dried	0	15.9 ± 2.6 ^b	1.13 ± 0.08 ^a
Freeze-dried	100	19.2 ± 4.8 ^a	1.28 ± 0.17 ^{ab}
Spray-dried	100	17.2 ± 2.1 ^{ab}	1.25 ± 0.05 ^a
WPC34			
Freeze-dried	0	12.1 ± 2.8 ^c	1.51 ± 0.21 ^b
Spray-dried	0	10.6 ± 2.0 ^c	1.38 ± 0.12 ^b
Freeze-dried	100	7.8 ± 1.4 ^d	1.64 ± 0.13 ^{bc}
Spray-dried	100	8.4 ± 1.7 ^d	1.57 ± 0.08 ^{bc}

^{a-d}Values with different letters in the same column are significantly different ($P \leq 0.05$).

¹Data represent mean ± SD of at least 2 replications.

act as foam-suppressing agents (Heino et al., 2007). As was seen with the commercial WPC34 (Table 1 and Figure 4), fat content alone does not predict foaming.

Gelation Properties

Fracture properties of gels were determined as an indication of texture-forming ability. Higher fracture stress indicates a stronger gel, whereas higher fracture strain indicates a more deformable gel. Fracture properties of gels made from SPC34 and WPC34 are shown in Table 4. Gels made from SPC34 were consistently stronger (higher fracture stress) than gels made with WPC34, whereas WPC34 gels tended to be more deformable (higher fracture strain). Adding 100 mM NaCl to SPC34 gels had no effect, whereas it decreased the strength (fracture stress) and slightly increased the deformability (fracture strain) of WPC34 gels.

The SPC and WPC gels made with 80% protein powders were much weaker than those made from 34% protein powders. Without NaCl addition, gels were too weak and lost water such that testing was prevented. Addition of 100 mM NaCl increased the firmness of SPC80 gels and allowed them to be tested; however, gels were weak with fracture stress of 7.96 ± 1.80 kPa and fracture strain of 1.14 ± 0.13 . Increased fracture stress of WPI gels with the addition of 25 to 75 mM NaCl was reported by Kuhn and Foegeding (1991). Gels made with WPC80 were still too weak to be tested. A significant difference in the amount of calcium in both 34 and 80% powders, with WPC being higher than SPC, could explain the difference in gel strength (Table 2). A higher concentration of calcium, as seen in WPC powders, favors lower fracture stress (Kuhn and Foegeding, 1991) and could explain the lower fracture stress of WPC seen here.

Overall, SPC formed stronger gels than WPC. Similar results were reported by Britten and Pouliot (1996) and Heino et al. (2007). Strengths of gels made from

SPC were higher than that from traditionally made WPC. The lowered gel strength of WPC may be explained by higher fat content (Morr and Ha, 1993), the larger the extent of heat denaturation (Mangino et al., 1987), as well as the presence of GMP. Only a few studies have been done on the effect of GMP on functional properties of whey protein products (Thorma-Worringer et al., 2006). A comparison of the gel strength and water-holding capacity of commercial WPC from rennet cheese whey and acid whey (which does not contain GMP) found the gel strength of WPC from rennet cheese whey to be 4.5 times lower than that of WPC from acid whey, which had decreased water-holding capacity (Veith and Reynolds, 2004).

CONCLUSIONS

Although manufactured from the same milk under similar conditions, 34% and 80% protein SPC and WPC were different in composition and functional properties. Whey protein concentrate had higher fat and contained GMP, whereas SPC did not contain GMP. Unheated WPC were much more turbid than unheated SPC. Both 34% protein WPC and SPC were significantly less soluble at pH 3, whereas WPC80 and SPC80 were highly soluble at all pH values (3–7). Serum protein concentrate had better foaming properties than WPC, as shown by higher overrun and yield stress. Freeze-dried WPC34 and spray-dried WPC80 did not form foams. Both 34 and 80% protein SPC formed better heat-induced gels than did WPC. Generally, SPC exhibited better functional properties. Differences in functional properties may be explained by the differences in composition, particularly fat, and the extent of denaturation and protein aggregation.

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REFERENCES

- AOAC International. 2000. Official Methods of Analysis. 17th ed. AOAC International, Gaithersburg, MD.
- Britten, M., and Y. Pouliot. 1996. Characterization of whey protein isolate obtained from milk microfiltration permeate. *Lait* 76:255–265.
- Dalgleish, D. G., and M. Corredig. 2012. The structure of the casein micelle of milk and its changes during processing. *Annu. Rev. Food Sci. Technol.* 3:449–467.
- de la Fuente, M. A., Y. Hemar, M. Tamehana, P. A. Munro, and H. Singh. 2002. Process-induced changes in whey proteins during the manufacture of whey protein concentrates. *Int. Dairy J.* 12:361–369.
- de Wit, J., and T. van Kessel. 1996. Effects of ionic strength on the solubility of whey protein products. A colloidal chemistry approach. *Food Hydrocolloids* 10:143–149.
- Diehl, K. C., D. D. Hamann, and J. K. Whitfield. 1980. Structural failure in selected raw fruits and vegetables. *J. Texture Stud.* 10:371–400.
- Evans, J., J. Zulewska, M. Newbold, M. A. Drake, and D. M. Barbano. 2009. Comparison of composition, sensory, and volatile components of thirty-four percent whey protein and milk serum protein concentrates. *J. Dairy Sci.* 92:4773–4791.
- Evans, J., J. Zulewska, M. Newbold, M. A. Drake, and D. M. Barbano. 2010. Comparison of composition and sensory properties of 80% whey protein and milk serum protein concentrates. *J. Dairy Sci.* 93:1824–1843.
- Foegeding, E. A., P. Luck, and B. Vardhanabhuti. 2011. Whey protein products. Pages 873–878 in *The Encyclopedia of Dairy Sciences*. 2nd ed. J. Fuquay, P. Fox, and P. McSweeney, ed. Academic Press, Oxford, UK.
- Gillot, J., and D. Garcera. 1986. Ceraver: Nouveaux médias filtrants céramiques. *Lait* 1007:23–24.
- Heino, A. T., J. O. Uusi-Rauva, P. R. Rantamäki, and O. Tossavainen. 2007. Functional properties of native and cheese whey protein concentrate powders. *Int. J. Dairy Technol.* 60:277–285.
- Joseph, M. S. B., and M. E. Mangino. 1988. The effects of milk fat globule membrane protein on the foaming and gelation properties of β -lactoglobulin solutions and whey protein concentrates. *Aust. J. Dairy Technol.* 43:9–11.
- Karakashev, S. I., and M. V. Grozdanova. 2012. Foams and antifoams. *Adv. Colloid Interface Sci.* 176–177:1–17.
- Karleskind, D., I. Laye, F. I. Mei, and C. V. Morr. 1995. Foaming properties of lipid-reduced and calcium-reduced whey protein concentrates. *J. Food Sci.* 60:738–741.
- Kuhn, P., and E. A. Foegeding. 1991. Factors influencing whey protein gel rheology: Dialysis and calcium chelation. *J. Food Sci.* 56:789–791.
- Mangino, M. E., S. W. Liao, W. J. Harper, C. V. Morr, and J. G. Zadow. 1987. The effects of heating during processing on the functionality of whey protein concentrates. *J. Food Sci.* 53:1522–1524.
- Marcelo, P. A., and S. S. H. Rizvi. 2008. Physicochemical properties of liquid virgin whey protein isolate. *Int. Dairy J.* 18:236–246.
- Maubois, J. L., J. Fauquant, M. H. Famelart, and F. Caussin. 2001. Milk microfiltrate, a convenient starting material for fractionation of whey proteins and derivatives. Pages 59–72 in *The Importance of Whey and Whey Components in Food and Nutrition*, Proc. 3rd Int. Whey Conf. P. Jelen, ed. Behr's Verlag, Hamburg, Germany.
- Morr, C. V., and E. Y. W. Ha. 1993. Whey protein concentrates and isolates: Processing and functional properties. *Crit. Rev. Food Sci. Nutr.* 33:431–476.
- Mulvihill, D. M., and M. P. Ennis. 2003. Functional milk proteins: Production and utilisation. Pages 1175–1228 in *Advanced Dairy Chemistry*. Vol. 1, Part B. P. F. Fox and P. L. H. McSweeney, ed. Kluwer Academic Publishers, New York, NY.
- Nelson, B. K., and D. M. Barbano. 2005. A microfiltration process to maximize removal of serum proteins from skim milk before cheese making. *J. Dairy Sci.* 88:1891–1900.
- Pelegri, D. H. G., and C. A. Gasparetto. 2005. Whey proteins solubility as function of temperature and pH. *Lebenson. Wiss. Technol.* 38:77–80.
- Pernell, C. W., E. A. Foegeding, and C. R. Daubert. 2000. Measurement of the yield stress of protein foams by vane rheometry. *J. Food Sci.* 65:110–114.
- Phillips, L. G., Z. Haque, and J. E. Kinsella. 1987. A method for the measurement of foam formation and stability. *J. Food Sci.* 52:1074–1077.
- Roefs, S. P. F. M., and K. G. de Kruif. 1994. A model for the denaturation and aggregation of β -lactoglobulin. *Eur. J. Biochem.* 226:883–889.
- Roufik, S., P. Paquine, and M. Britten. 2005. Use of high-performance size exclusion chromatography to characterize protein aggregation in commercial whey protein concentrates. *Int. Dairy J.* 15:231–241.
- Saboya, L. V., and J. L. Maubois. 2000. Current developments of microfiltration technology in the dairy industry. *Lait* 80:541–553.
- Sandblom, R. M., inventor. 1974. Filtering process. Swedish Patent No. 74.16.257.
- Thorma-Worringer, C., J. Sorenson, and R. Lopez-Fandino. 2006. Health effects and technological features of caseinomacropeptide. *Int. Dairy J.* 16:1324–1333.
- Veith, P. D., and E. Reynolds. 2004. Production of a high gel strength whey protein concentrate from cheese whey. *J. Dairy Sci.* 87:831–840.
- Walstra, P., T. J. Geurts, A. Jellema, A. Noomen, and M. A. J. S. van Boekel. 1999. *Dairy Technology: Principles of Milk Properties and Processes*. Marcel Dekker Inc., New York, NY.
- Yee, K. W. K., D. E. Wiley, and J. Bao. 2007. Whey protein concentrate production by continuous ultrafiltration: Operability under constant operating conditions. *J. Membr. Sci.* 290:125–137.