Instability and Partial Coalescence in Whippable Dairy Emulsions

H. D. GOFF
Department of Food Science,
University of Guelph,
Guelph, ON, Canada N1G 2W1

ABSTRACT

Dairy emulsions must be stabilized by an adsorbed layer to prevent flocculation or phase separation during quiescent storage. In the production of products such as whipped cream and ice cream, however, a controlled destabilization or partial coalescence of the emulsion is needed during further processing to develop an internal structure of agglomerated fat, which favorably alters the texture and physical appearance of the product. Several requirements must be met to induce partial coalescence, including a partially crystalline emulsion (implying refrigerated temperatures for milk fat), a weak adsorbed layer, and usually the presence of air, agitation, or both. Milk fat that is homogenized in the presence of a blend of caseins and whey proteins normally produces an emulsion that is too stable to undergo partial coalescence. Thus, small molecule surfactants (e.g., monoglycerides, diglycerides, and polysorbates) are added to protein-stabilized emulsions to promote partial coalescence by displacing proteins from the surface, resulting in a reduced surface concentration. However, it may be possible to control the adsorbed protein layer, hence promoting partial coalescence without the use of such surfactants, by selectively homogenizing the emulsion in the presence of only those milk proteins that would produce an interfacial layer that would be weak yet sufficient to maintain stability of the emulsion during storage but not sufficient to maintain stability during a whipping process.
(**Key words**: milk fat, emulsions, coalescence, fat destabilization)

Abbreviation key: **WPI** = whey protein isolate.

INTRODUCTION

Emulsions are thermodynamically unstable systems, and movement toward equilibrium causes a reduction or loss of the dispersed state. The adsorption of amphiphilic molecules to the surface, creating a membrane around the fat globule, creates a form of kinetic stability, slowing the rate at which the emulsion moves toward equilibrium. Dairy products containing milk fat are usually emulsions that have been stabilized through further phase disruption (e.g., homogenization) and membrane adsorption. Emulsion instability is sought, however, in butter manufacture and in developing structure in whipped cream and ice cream. The process of controlled partial coalescence of such emulsions during whipping and air incorporation leads to the formation of complex structures described both as protein-stabilized emulsions and fat-stabilized foams. This process has been studied by several researchers for whipped cream (2, 14, 15, 16, 44, 45, 48, 49, 55) and ice cream (6, 7, 33, 35, 37, 38, 40, 42). Partial coalescence is also responsible for structure formation in a variety of whipped nondairy dessert toppings (5, 17, 41). This paper briefly reviews the types of instability that are possible in dairy emulsions and then focuses on partial coalescence and structure formation in whipped cream and ice cream. Finally, the experimental results that were obtained by manipulation of the fat membrane to affect the process of partial coalescence are described.

COMPLEX EMULSIONS AND FOAMS

Emulsion Stabilization

Emulsions are inherently unstable. The interfacial tension or surface free energy between fat and water surfaces is high. Rearrangements lower the free energy as a thermodynamic system moves toward equilibrium by reducing the surface area. At equilibrium, minimum free energy, minimum surface area, and two distinct layers, fat and water, would exist (54). Two distinct types of instability are found. Coalescence refers to a decrease in the number and an increase in the size of individual globules. Flocculation is a clustering of individual globules into a coherent unit in which the size and identity of individual globules are retained. There are several

Received July 16, 1996.
Accepted April 23, 1997.

mechanisms for flocculation, including, for example, a cluster formed as a result of shared protein adsorption between two or more globules (bridging flocculation). Homogenization clusters would be an example of this mechanism. Calcium ions can also destabilize emulsions by flocculation through changes to the state of protein aggregation when the emulsion has been stabilized by protein (1). Flocculation is sometimes a precursor for coalescence. In addition, density differences between the fat and water phases result in a driving force for the fat phase to rise, a process known as creaming (55). Creaming is a function of globule size, and flocculation or coalescence lead to faster rates of creaming. Thus, creaming and coalescence are inevitable in emulsions, and both lead to loss of the dispersed state.

However, amphiphilic molecules play an important role in emulsions (43). Proteins with hydrophobic regions or mono- and diglycerides are examples of such molecules, as they contain segments that prefer solution into an aqueous environment and segments that prefer solution into a nonpolar environment (4, 50, 51). During the homogenization of a fat into a solution in the presence of amphiphilic molecules, a membrane quickly forms around the fat globule. This membrane acts to lower the interfacial tension (surface free energy) between oil and water and, depending on the amount of surfactant adsorbed, can increase the density of the fat globule (20, 54). Both mechanisms have a stabilizing effect, slowing the rate of creaming and coalescence that may have otherwise occurred.

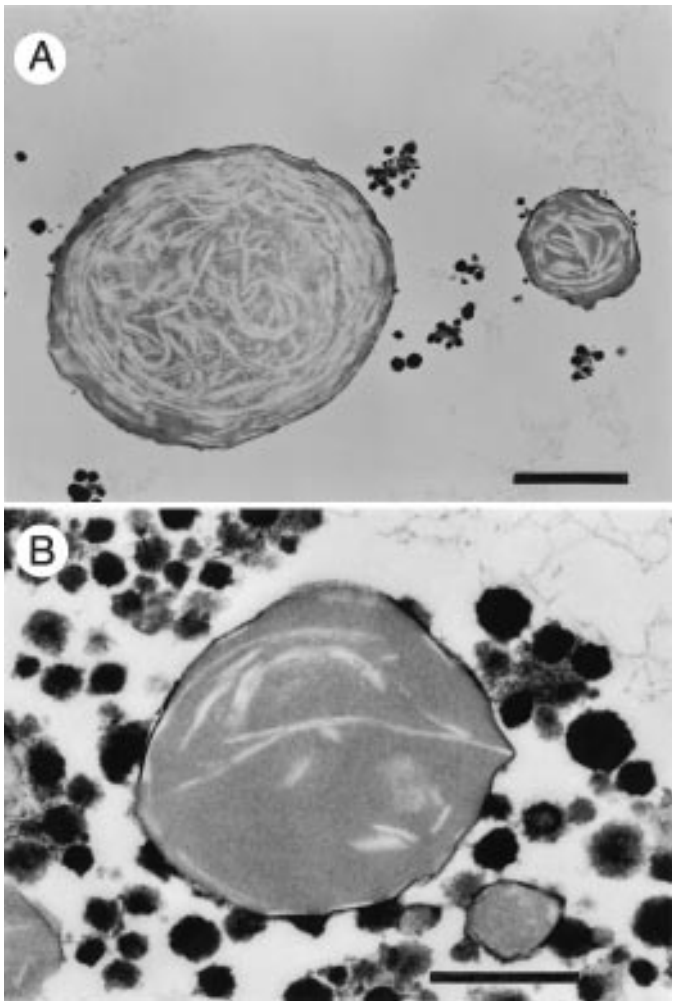


Figure 1. A. Milk fat globule showing the intricate structure of needle-like crystals present in the cross-section after fixation at 4°C and examination by transmission electron microscopy. B. Globule distorted by the presence of the internal crystalline structure. Bar = 0.5 μm (37).

Partial Coalescence

When an oil-in-water emulsion is placed in a shear field and the fat globule membrane between two colliding globules is ruptured, the fat generally flows together, causing the loss of identity of the original particle and creating a larger one. Many of the triglyceride emulsions common in the food industry, particularly dairy emulsions, are stored at temperatures at which fat crystallization occurs (9, 37). Such globules show intricate patterns of crystals within the globule (Figure 1A) and show crystals actually growing or protruding through the membrane (Figure 1B). Crystals can be found both radial and tangential to the surface, indicating that a solid shell, liquid core model is not appropriate to describe partially crystalline globules (10). If crystals are present in the oil phase, coalescence may be incomplete, leading to the formation of irregularly aggregated globules that retain some of their original identity but are intricately linked (Figure 2). This process has been referred to as partial coalescence. This form of aggregation exhibits important differences from true coalescence of liquid globules. The identity of the individual globules is still retained in the aggregates. Because of the irregular form of the aggregates, the viscosity of the emulsion may increase. The aggregation can proceed until a continuous network is formed throughout the volume, thus giving the product solid properties (yield stress) and immobilizing other particles (e.g., air cells) present. Finally, the rate of aggregation greatly depends on agitation, but liquid droplets rarely show an appreciable dependence of coalescence on agitation (8, 10, 11, 24).

Aggregation can occur via perikinetic (Brownian motion) or orthokinetic (shear-induced) mechanisms.

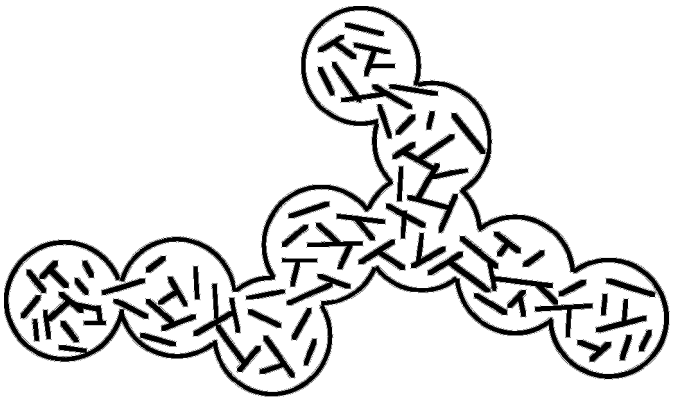


Figure 2. A schematic representation of the network of partially coalesced fat globules formed during whipping, illustrating the important role of fat crystals in the coalescence globules (visualized as the straight lines within the globule).

A very important feature of partial coalescence is the role that agitation and air incorporation have on its onset because of the large differences in rate between perikinetic and orthokinetic aggregation. van Boekel and Walstra (52, 53) demonstrated that velocity gradients in liquid emulsions containing partially crystalline fat globules increased the rate of partial coalescence by a factor of 10^6. The most probable explanation for this shear dependence is that crystals protruding from the oil-water interface (Figure 1B) pierce the thin aqueous film between closely approaching globules (10, 24). Air has also been shown to have a great effect on the formation of fat clustering in partially crystalline emulsions, both when the emulsion is in the static state (e.g., sparging) and during agitation (54). Thus, the combination of air and agitation produces extremely rapid partial coalescence, as can easily be demonstrated by whipping a bowl of heavy cream, a process that can easily be continued to the point of coalescence (e.g., flotation churning during butter making).

Another important factor to consider is the role of the membrane in the stability of the emulsion to partial coalescence. Williams and Dickinson (57) showed that the orthokinetic stability of an emulsion stabilized by β-LG increased as the concentration of protein used in the formation of the emulsion increased, because of smaller mean droplet sizes with increased protein and the amount of protein adsorbed at the interface (per square micrometer, the surface excess), which increased as the amount of protein used is increased. Britten et al. (12) showed that resistance to stirring-induced coalescence was improved by increasing the proportion of denatured whey protein isolate (**WPI**). Increased proportions of denatured WPI increased the emulsifying activity of the protein blends, increased emulsion viscosity, and increased emulsion stability. Proteins adsorb to surfaces by orienting their hydrophobic regions toward the fat interface. If protein unfolding has occurred prior to emulsion formation, more of the hydrophobic regions should be exposed, such that the extent of denaturation was correlated with the formation of intact, stronger membranes. Important differences have been shown in the behavior of various milk protein emulsion membranes to partial coalescence (36); emulsions stabilized by whey protein generally are more susceptible to partial coalescence than are emulsions stabilized by casein.

Surfactants (emulsifiers such as monoglycerides, diglycerides, or polysorbate 80) also play a critical role in promotion of partial coalescence in partially crystalline emulsions. Surfactants lower the interfacial tension between the fat and the water phases more than do proteins. In an emulsion created in the presence of both proteins and surfactants, it has been demonstrated that the surfactants become preferentially adsorbed to the surface of the fat (26, 30), displacing most, but not all, of the protein present (19, 22, 23, 31). A study of model systems by Fang and Dalgleish (31) demonstrated that Tween 60 not only competes with protein for the interface but also causes conformational changes in the protein molecules already adsorbed (23). This competition or displacement has also been demonstrated in complex, processed dairy emulsions such as ice cream mix (6, 35, 37); Figure 3 shows many casein micelles adsorbed to the periphery of the fat globule (in cross-section) in the absence of, in this case, polysorbate 80 (Figure 3A), with little if any casein micelle adsorption in the presence of polysorbate 80 (Figure 3B). As proteins are displaced, the membrane becomes more susceptible to subsequent destabilization because the protein molecules, particularly the caseins, are considerably larger than the emulsifier molecules. Thus, a membrane made up entirely of emulsifier is very thin (Figure 3B), having lower surface excess, although the emulsion is thermodynamically favored because of the lower interfacial tension and lower net free energy of the system. However, Dickinson et al. (27) pointed out that subsequent instability to shear is not induced by the protein displacement per se, but by some change in the adsorbed layer properties caused by the replacement of a pure protein monolayer by a mixed protein surfactant monolayer.

Structure Formation

Whipped cream. Whipped cream relies heavily on partial coalescence for the development of structure as it is converted from a viscous liquid into a visco-

elastic solid during the process of whipping. Figure 4 illustrates the build-up of the semicontinuous network of fat surrounding and stabilizing the air bubbles. In a study of the whipping of heavy cream, Schmidt and van Hooydonk (48) stated that the proteinaceous membrane that envelops the air bubble is penetrated by fat globules as the whipping process proceeds, and this fat penetration offers foam stability to the whipped product. Brooker et al. (15) offered a more detailed explanation of the whipping and foam stabilization process in heavy cream. During the initial stages of whipping, air bubbles were stabilized primarily by β-CN and whey proteins with little involvement of fat. Adsorption of fat to air bubbles occurred when the fat globule membrane coalesced with the air-water interface. Only rarely did fat spread at this interface. The final cream was stabilized by a crosslinking of fat globules surrounding each air cell to adjacent air cells , thus building an infrastructure in the foam (39). In skim milk foams, the initial air-water interface is also formed by the serum proteins and soluble β-CN with little involvement of micellar casein. Micelles became attached as a discontinuous layer but were not deformed or spread (13). Thus, the important role of the protein, both in the serum phase and at the membrane, cannot be overlooked in the development of whipped cream structure (45). Bruhn and Bruhn (16) observed that UHT cream took about 40% longer to whip than did raw or pasteurized cream. The results of Britten et al. (12) related to enhanced stability of emulsions with denatured WPI lead to a postulation that the UHT-treated cream resulted in greater amounts of protein adsorption or increased membrane integrity, ultimately increasing the stability to partial coalescence.

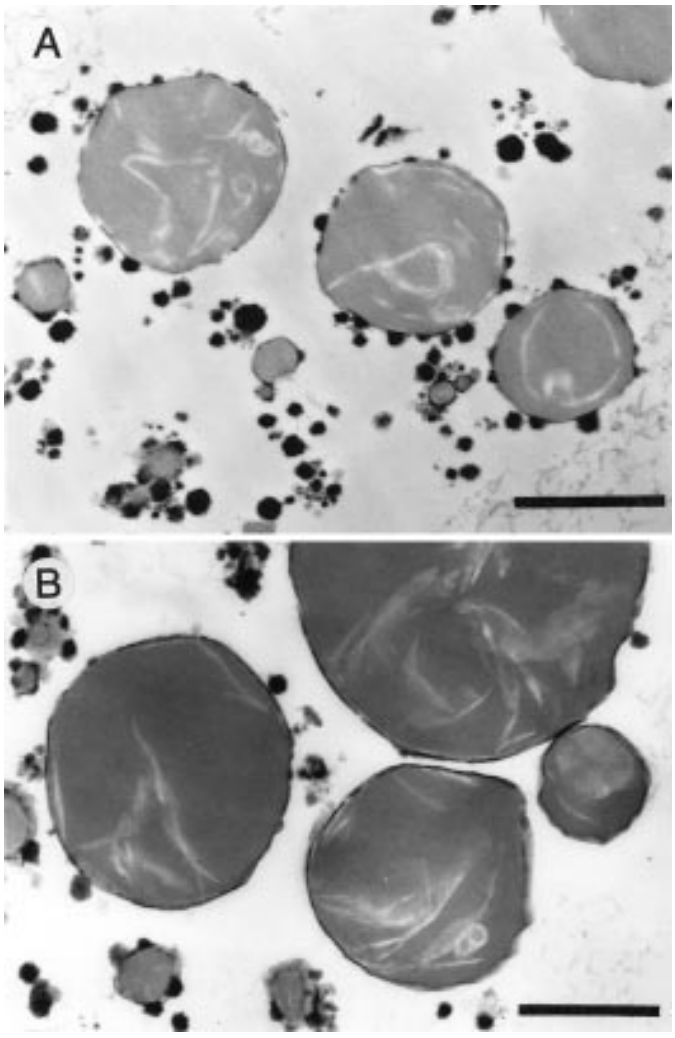
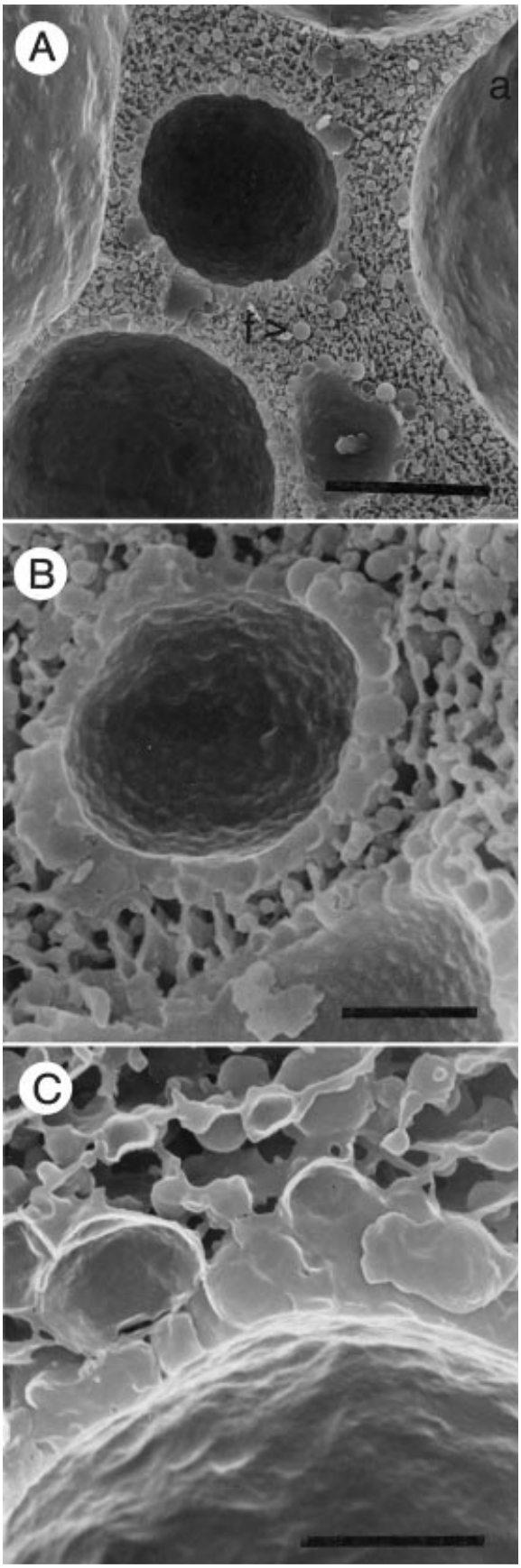


Figure 3. Transmission electron micrograph of an ice cream mix emulsion in the absence (A) and presence (B) of 0.08% polysorbate 80. Bar = 1 μm (37).

Ice cream. Ice cream is a complex food colloid [which is defined as a system of discrete particles of size from 1 nm to 1 μm in a continuous phase; (29)] that also relies on partial coalescence in structure development. Its structure consists of air bubbles, fat globules, ice crystals, and an unfrozen serum phase. Ice crystals and air bubbles are usually in the range of 20 to 50 μm and 50 to 100 μm, respectively (18). The air bubbles are usually lined with fat globules, and the fat globules are coated with a protein-emulsifier layer (18). The serum phase consists of the sugars and high molecular mass polysaccharides in a freeze-concentrated solution. Various steps in the manufacturing process, including pasteurization, homogenization, aging, freezing, and hardening, contribute to the development of this structure.

To describe completely the role of partial coalescence in structure formation, it is necessary to begin with the formation of the emulsion at homogenization and the role of the ingredients present at homogenization. After preheating or pasteurization, the mix is at a temperature sufficient to have melted all the fat present, and the fat passes through one or two homogenizing valves. Immediately following homogenization, the newly formed fat globule is practically devoid of membranous material and readily adsorbs amphiphilic molecules from solution (25, 56). The immediate environment supplies the surfactant molecules, which include caseins, undenatured whey proteins, phospholipids, lipoprotein molecules, components of the original milk fat globule membrane, and any added chemical surfactants (7, 46). The mem-



brane formed during homogenization continues to develop during the aging step, and rearrangement occurs until the lowest possible energy state is reached (6, 7). If surfactants are present during homogenization, the membrane will be practically devoid of protein (Figure 3), rendering it much more susceptible to partial coalescence in succeeding steps (6, 35, 37).

The next stage of structure development occurs during the concomitant whipping and freezing steps. Air is incorporated through a lengthy whipping process (batch freezers) or is drawn into the mix by vacuum or injected under pressure in continuous freezers (6). This process causes the emulsion to undergo partial coalescence or fat destabilization, during which clumps and clusters of the fat globules form an internal fat structure or network in the frozen product in a manner analogous to the whipping of heavy cream (7, 15, 24). Crosslinking of fat globules from one air cell to the next, thus forming an infrastructure, as may be the case in whipped cream, is less likely in ice cream because of the reduction in dispersed phase volume from the heavy cream system to the ice cream mix system; however, the air bubbles, fat globules, and aqueous phase are being freeze-concentrated at the same time. It is at this stage that the emulsifiers have the greatest impact (Figure 5). The membrane created by the addition of surfactant is not sufficient to prevent the fat globules from coalescing during collision, thus setting up the internal fat matrix. The fat globule clusters formed during the process of partial coalescence are responsible for surrounding and stabilizing the air cells and creating a semicontinuous network or matrix of fat throughout the product. This structure results in the beneficial properties of dryness upon extrusion during the manufacturing stages (aids in packaging and novelty molding, for example), a smooth texture in the frozen dessert, and resistance to meltdown or good shape retention properties (necessary for soft serve operations) (6, 7, 42).

Changes in the fat emulsion have recently been studied by Gelin et al. (33), who demonstrated through light-scattering measurements of fat globule size distribution and aggregation that the freezing step is responsible for considerable fat aggregation

Figure 4. The structure of whipped cream as determined by scanning electron microscopy. A. Overview showing the relative size and prevalence of air bubbles (a) and fat globules (f); bar = 30 μm. B. Internal structure of the air bubble, showing the layer of partially coalesced fat that has stabilized the bubble; bar = 5 μm. C. Details of the partially coalesced fat layer, showing the interaction of the individual fat globules. Bar = 3 μm.

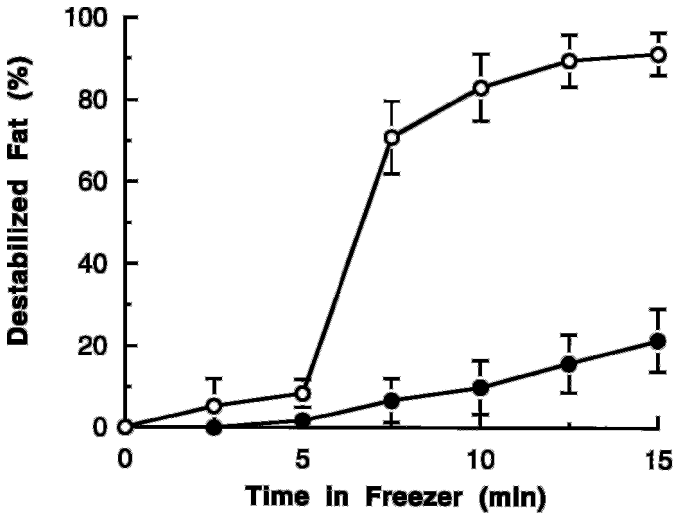


Figure 5. The effect of polysorbate 80 addition in ice cream mix (○), compared with no emulsifier (●), on the percentage of fat destabilized [determined by turbidity of a 1:500 (wt/wt) dilution of mix at 5°C] during the whipping time in the barrel of a batch freezer. Ice crystallization began after about 5 min (37).

but that this aggregation is reversible through dissociation with SDS. It was obvious from their study that the homogenization step caused a large amount of serum protein to adsorb to the fat globule [a result of the nearly 10-fold increase in surface area (55)] and that casein was preferentially adsorbed over the whey protein. The aging, freezing, hardening, and thawing steps each accounted for subsequent protein desorption, mostly of the caseins. The emulsifier used in these mixes contained saturated mono- and diglycerides but no polysorbate 80, which, based on the results of Goff and Jordan (35), may have led to greater amounts of protein desorption during the aging period if it had been present. Kokubo et al. (40) have also demonstrated, in a study of the relationship between draw temperature and overrun of ice cream and resulting de-emulsified fat, that increased fat de-emulsification as a result of decreased draw temperature or increased overrun caused changes in the fat particle size distribution. Particles ≤ 1.2 μm decreased in frequency, and particles 3 to 4 μm and 8 to 15 μm increased in frequency as fat de-emulsification increased, a result of fat globule clustering. The sequential process of partial coalescence during ice cream freezing has also been examined (35). The incorporation of air alone or the shearing action alone, independent of freezing, are not sufficient to cause the same degree of fat destabilization as when ice crystallization occurs concomitantly. The freezing process causes an increase in concentration of the mix components, such as proteins and mineral salts, in the unfrozen water phase. It is thought that the ice crystals contribute to the shearing action on the fat globules because of their physical shape and that the concentration of components also leads to enhanced destabilization. However, to create the desired fat destabilization, whipping and freezing must occur simultaneously (34).

CURRENT RESEARCH APPLICATIONS

We have recently studied the effect of the protein membrane composition on emulsion stability, and partial coalescence and foam stability after whipping of 20% milk fat emulsions in the absence of chemical surfactants. Results reported here are brief, but are intended to demonstrate how structural knowledge of whippable emulsions can be applied to the development of particular applications of interest. Emulsions were produced consisting of 20% fat (from sweet butter, 80% fat, Gay Lea Foods, Guelph, ON) and 0.085, 0.17, 0.25, 0.50, 0.75, 1.0, 1.5, or 2.0% protein from WPI (88% protein; Protose Separations, Teeswater, ON, Canada). The emulsions were heated to 70 or 90°C for 30 min, continuously stirred with a hand mixer, and then homogenized at 20.7 and 6.9 MPa in the first and second stages (Superhomo A125A; Cherry Burrell, Chicago, IL). Four replicates of each emulsion were produced. Emulsion stability was determined by measuring the fat depletion at the bot-

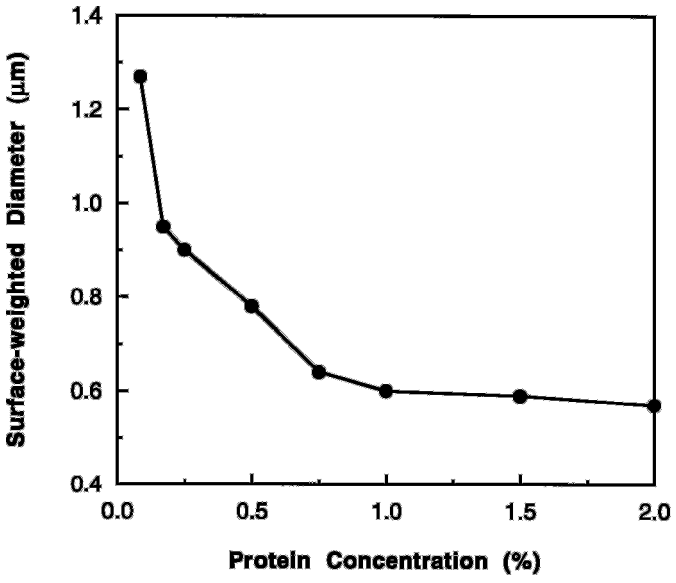


Figure 6. Mean surface-weighted diameter (d_{32}) of fat globules in emulsion after homogenization as a function of protein concentration.

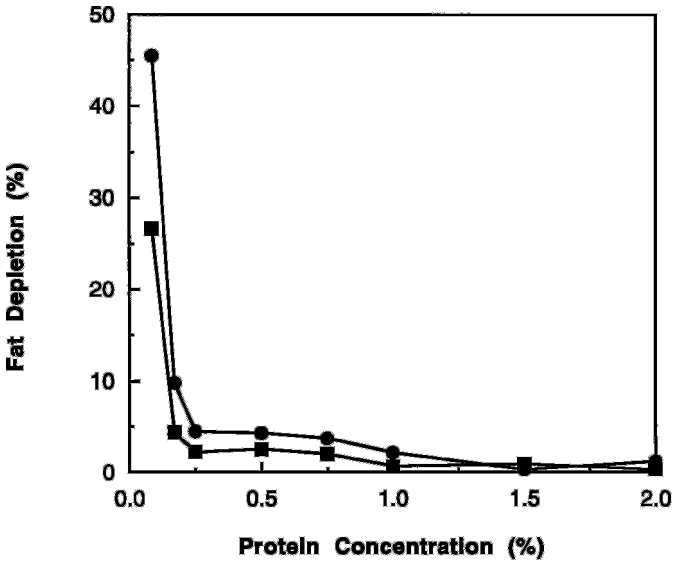


Figure 7. Fat depletion from the base of a 100-ml cylinder after quiescent storage at 4°C for 24 h (■) or 48 h (●).

tom of a 100-ml graduated cylinder in 48 h at 4°C by Babcock fat analysis (3). Emulsions were whipped with an electric mixer at high speed, and aliquots were removed each minute for overrun measurement, fat destabilization by spectroturbidity (35), and particle size analysis (Mastersizer X; Malvern Instruments, Southboro, MA). Foam stability was assessed by removing aliquots after 2 min of whipping and measuring collapse and drainage after 24, 48, and 72 h. Data were analyzed by analysis of variance using the general linear models option of SAS (47).

As protein concentration was increased from 0.085 to 0.75%, the mean surface-weighted fat globule diameter (d_{32}) decreased and reached a minimum at protein concentrations greater than 0.75% (Figure 6), which was similar to the results of Fang and Dalgleish (31, 32) and Williams and Dickinson (57). Emulsions with greater than 0.25% protein were found to be stable to creaming under quiescent conditions (Figure 7). However, during whipping and agitation, differences in the behavior of the emulsions were considerable. The whipping ability (as determined by overrun) is shown in Figure 8. Maximum overrun was reached within 1 min in all cases and decreased as agitation continued. The whipping stage beyond maximum overrun formation has been shown in whipped cream to correspond to a decrease in air bubble size and to a stabilization of the remaining air bubbles by fat as partial coalescence proceeds (15, 45, 48). Protein dependence on this process was also demonstrated. At a protein concentration of 0.5%, overrun at 1 min was the highest of all the emulsions. Below 0.5% protein, initial overrun was low and decreased rapidly during the whipping process, likely because of little, if any, protein in the serum phase acting as the initial air bubble membrane. This result suggests, in keeping with the results of Brooker et al. (15) and Needs and Huitson (44), that serum protein may actually initiate stabilization of air bubbles by the partially coalescing fat. Foam development was fairly stable over the range between 0.5 and 1.5% protein (Figure 8).

Less than 10% fat destabilization in the emulsions occurred at protein concentrations of greater than 1% (Figure 9), suggesting that small droplet size and complete protein surface coverage led to globules that were too stable to undergo extensive partial coalescence. However, at protein concentrations between 0.25 and 1%, substantial destabilization was noted during the whipping process. This fat destabilization manifested itself in production of stable foam. Above 0.5% protein, substantial collapse was noted in the foams after 24, 48, and 72 h (Figure 10). However, at 0.25% protein, the foams were more stable to collapse. Between 0.25 and 0.5% protein, the foams also showed less drainage over 72 h than those produced with greater than 0.5% protein (Figure 11). When the size distribution of fat globules in these emulsions was examined, it was evident that a small number of larger globules and clusters had formed after whipping that were responsible for the resulting foam

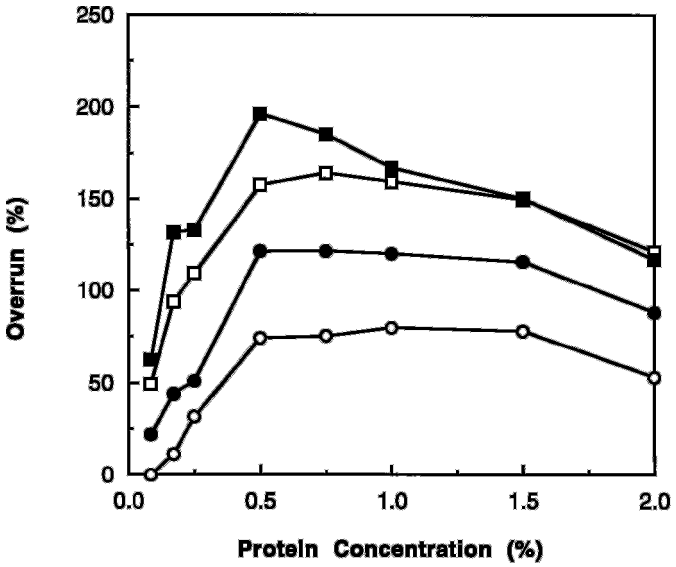


Figure 8. Percentage of overrun developed in emulsions as a function of protein concentration and whipping times of 1 min (■), 3 min (□), 5 min (●), and 7 min (○).

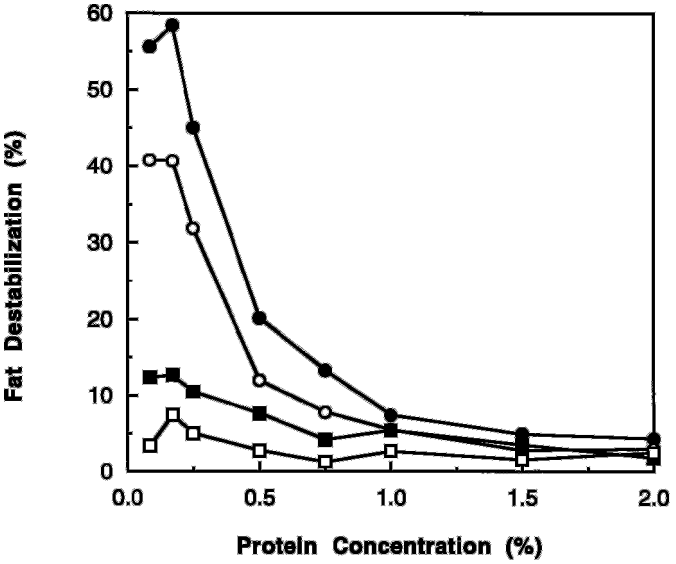


Figure 9. Fat destabilization in emulsions as a function of protein concentration and whipping times of 30 s (□), 90 s (■), 180 s (○), and 240 s (●).

stiffness. This is demonstrated in Figure 12 as the broad peak of fat globule sizes greater than 4 μm, which was not evident in the emulsions before whipping. It was thus concluded that a small range of protein concentrations existed, between 0.25 and 0.5% in this particular case, at which the initial size of the fat globule was small, the emulsion was stable to creaming in the quiescent state, the emulsion formed significant fat destabilization during whipping and agitation, and the resulting foam was stable to collapse and drainage. This result is very significant, given that the fat content in these emulsions was only 20%.

The research indicates the potential for the development of lower fat whipping creams for the retail market. Preliminary work has been conducted to test the concept of altering the fat globule membrane composition to affect whipped cream formation and stability. A further set of emulsions has been prepared containing 18% (wt/wt) fat from sweet butter (80% fat; Gay Lea Foods, Guelph, ON), 0.175 to 0.55% WPI (92% protein; Protose Separations, Teeswater, ON), 4.0 to 6.0% SNF (skim milk powder, 97% solids; Gay Lea Foods, Guelph, ON), 5.0 to 8.0% sugar (Redpath Sugars, Toronto, ON), and 0.45 to 0.60% stabilizer (Aeratex, a proprietary blend of mono- and diglycerides, disodium phosphate, sodium citrate, guar gum, carrageenan, locust bean gum, and soybean lecithin; Food Specialties, Mississauga, ON, Canada). The emulsions were prepared in two stages by heating the butter, WPI, and a portion of the water to 70°C for 30 min, homogenizing at 20.7 MPa, 6.9 MPa on the second stage, cooling to 4°C, and blending with the skim milk powder, sugar, stabilizer, and remainder of the water, which had previously been heated to 70°C for 30 min and cooled to 4°C. Emulsion stability was tested by examination of creaming after 24 h in a 100-ml graduated cylinder. Overrun and foam stability were examined by whipping the emulsions with an electric mixer at high speed for 2 min.

Several combinations of WPI, sugar, and stabilizer produced emulsions that were stable to creaming before whipping and stable foams after whipping. None, however, matched the control (35% fat real cream) for foam stiffness or mouthfeel. Although this project was only a very preliminary examination of product development applications, it suggests that appreciation of a two-step process of selective homogenization and membrane formation, followed by posthomogenization blending of further proteinaceous ingredients undesired at the fat globule surface, produced a stable emulsion capable of being whipped into a stable foam.

This concept of creating either membranes that are partially depleted of protein or membranes developed through selective homogenization of the fat with proteins of choice, followed by further addition of protein to the aqueous phase, depends on very slow or no protein displacements or rearrangements to the membrane protein with those in the aqueous phase after

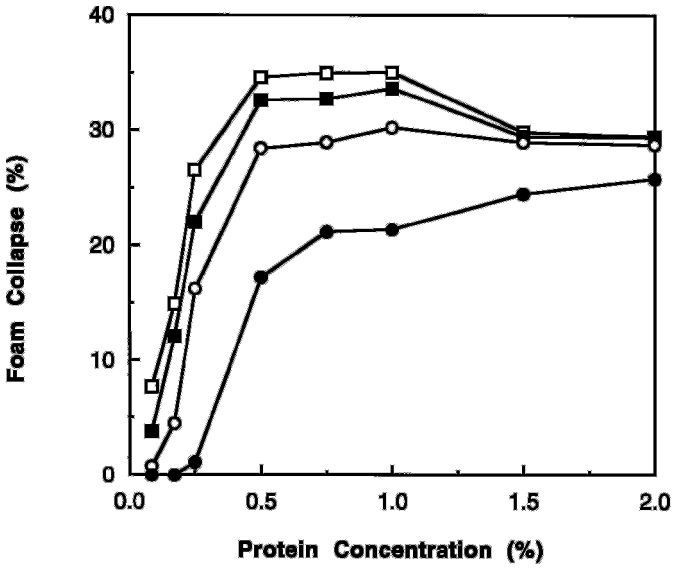


Figure 10. Foam collapse (percentage decrease in foam height) of emulsions after 1 min of whipping as a function of protein concentration and storage at 4°C for 4 h (●), 24 h (○), 48 h (■), and 72 h (□).

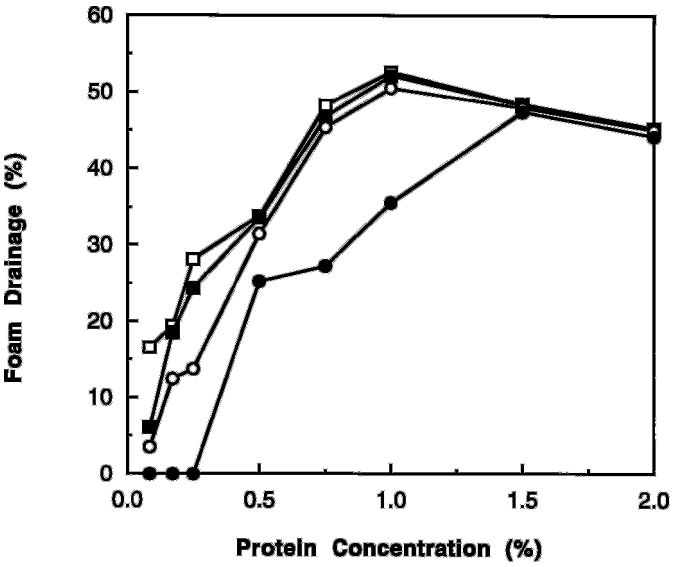


Figure 11. Liquid drainage (percentage of original volume) from foams after 1 min of whipping as a function of protein concentration and storage at 4°C for 4 h (●), 24 h (○), 48 h (■), and 72 h (■).

homogenization. This displacement is a function of the reversibility of protein adsorption, a subject that has received some study in the past, but mostly in model systems of pure proteins, with or without added surfactants (19, 21, 22, 26, 28). Dickinson et al. (28) showed from exchange experiments that β-CN rapidly displaced α_{s1}-CN from an emulsion droplet surface, but the reverse was true to a much lesser extent. Dickinson and Gelin (26) reported that α_s-CN addition to a β-LG stabilized emulsion did not lead to displacement of the globular protein from the interface. These researchers also concluded that the adsorption of β-LG to the interface was strongly dependent upon the species present during emulsion formation; if β-LG was the emulsifying species, then its adsorption was highly irreversible, suggesting that the selective homogenization concept advanced herein may produce the desired results, but further research is necessary in this area.

CONCLUSIONS

Emulsion stability is an important consideration in food product development and shelf-life determination. As has been discussed, several types of instability can cause a reduction or loss of the dispersed state. Membrane adsorption is critical in producing stable emulsions because of interfacial tension and surface load (particle density) considerations. Many studies have been reported on the adsorption of proteins and other surfactants to the surface of fat globules in emulsions and the relationship between such membrane formation and resulting emulsion stability. However, emulsion instability in the form of partial coalescence results in structure formation in foamed dairy emulsions, such as ice cream and whipped cream. Published research is also sufficient to enable understanding of the process of partial coalescence, although the need for basic study in this area still remains. The challenge for product development, however, is to utilize this knowledge from emulsion stability in basic systems to create new and innovative structures and products and to incorporate new and different ingredients into the process.

The practical applications discussed demonstrate an integrated approach to product development in the area of emulsion partial coalescence. Control of membrane composition seems to be vital to partial coalescence and foam stability of protein-stabilized emulsions in the absence of chemical surfactant additives (e.g., polysorbate 80), and such control might be possible through selective homogenization of the fat in the presence of the desired membrane constituents. Once the membrane is formed, it appears to be more stable to competitive displacement by proteins. Such a process necessitates rethinking the traditional manufacturing techniques of blending all ingredients together, followed by pasteurization and homogeniza-

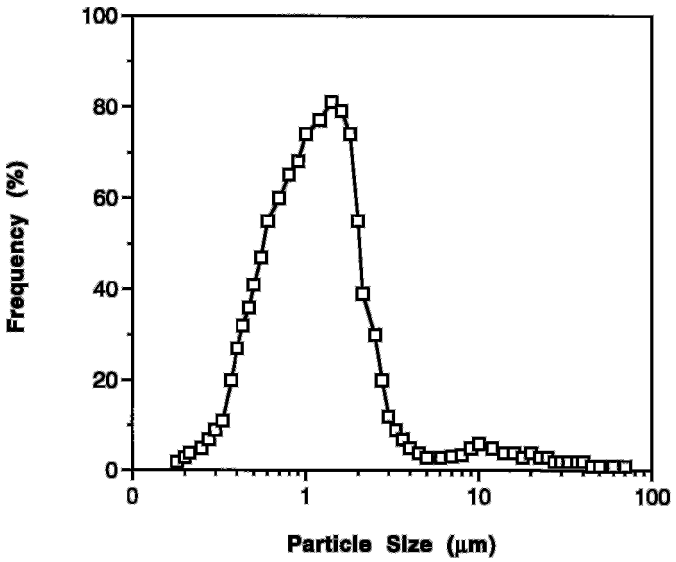


Figure 12. Typical size distribution of fat globules in a whipped emulsion that showed appreciable levels of fat destabilization during whipping. In this case, the protein content in the emulsion was 0.5%, and the sample was taken after 2 min of whipping.

tion. However, if a process such as selective homogenization could be demonstrated to give functional benefits, then the extra manufacturing steps may prove to be advantageous to new product development.

ACKNOWLEDGMENTS

Appreciation is expressed to the Ontario Ministry of Agriculture, Food and Rural Affairs for financial support; Sandy Smith, Shanti Anant, and Andres Flores for technical assistance; and Douglas Dalgleish for helpful discussions.

REFERENCES

1 Agboola, S. O., and D. G. Dalgleish. 1995. Calcium-induced destabilization of oil-in-water emulsions stabilized by caseinate or by β-lactoglobulin. J. Food Sci. 60:389.
2 Anderson, M., B. E. Brooker, and E. C. Needs. 1987. The role of proteins in the stabilization/destabilization of dairy foams. Page 100 *in* Food Emulsions and Foams. E. Dickinson, ed. R. Soc. Chem., London, England.
3 Atherton, H. V., and J. A. Newlander. 1977. Page 71 *in* Chemistry and Testing of Dairy Products. 4th ed. AVI Publ. Co., Westport, CT.
4 Aynié, S., M. Le Meste, B. Colas, and D. Lorient. 1992. Interactions between lipids and milk proteins in emulsion. J. Food Sci. 57:883.
5 Barfod, N. M., and N. Krog. 1987. Destabilization and fat crystallization of whippable emulsions (toppings) studied by pulsed NMR. J. AOAC 64:112.
6 Barfod, N. M., N. Krog, G. Larsen, and W. Buchheim. 1991. Effect of emulsifiers on protein-fat interaction in ice cream mix during aging I. Quantitative analyses. Fat Sci. Technol. 93:24.
7 Berger, K. G. 1990. Ice cream. Page 367 *in* Food Emulsions. 2nd ed. K. Larsson and S. Friberg, ed. Marcel Dekker, Inc., New York, NY.
8 Boode, K. 1992. Partial coalescence in oil-in-water emulsions. Ph.D. Diss., Wageningen Agric. Univ., Wageningen, The Netherlands.
9 Boode, K., C. Bisperink, and P. Walstra. 1991. Destabilization of O/W emulsions comtaining fat crystals by temperature cycling. Colloids Surf. 61:55.
10 Boode, K. and P. Walstra. 1993. Partial coalescence in oil-in-water emulsions. 1. Nature of the aggregation. Colloids Surf. A: Physicochem. Eng. Aspects 81:121.
11 Boode, K., P. Walstra, and A.E.A. deGroot-Mostert. 1993. Partial coalescence in oil-in-water emulsions. 2. Influence of the properties of the fat. Colloids Surf. A: Physicochem. Eng. Aspects 81:139.
12 Britten, M., H. J. Giroux, Y. Jean, and N. Rodrigue. 1994. Composite blends from heat denatured and undenatured whey protein: emulsifying properties. Int. Dairy J. 4:25.
13 Brooker, B. E. 1985. Observations on the air serum interface of milk foams. Food Microstruct. 4:289.
14 Brooker, B. E. 1990. The adsorption of crystalline fat to the air-water interface of whipped cream. Food Struct. 9:223.
15 Brooker, B. E., M. Anderson, and A. T. Andrews. 1986. The development of structure in whipped cream. Food Microstruct. 5:277.
16 Bruhn, C. M., and J. C. Bruhn. 1988. Observations on the whipping characteristics of cream. J. Dairy Sci. 71:857.
17 Buchheim, W., N. M. Barfod, and N. Krog. 1985. Relation between microstructure, destabilization phenomena and rheological properties of whippable emulsions. Food Microstruct. 4: 221.
18 Caldwell, K. B., H. D Goff, and D. W. Stanley. 1992. A low-temperature scanning electron microscopy study of ice cream. I. Techniques and general microstructure. Food Struct. 11:1.
19 Chen, J., and E. Dickinson. 1993. Time-dependent competitive adsorption of milk proteins and surfactants in oil in water emulsions. J. Sci. Food Agric. 62:283.
20 Chen, J., E. Dickinson, and G. Iveson. 1993. Interfacial interactions, competitive adsorption and emulsion stability. Food Struct. 12:135.
21 Courthaudon, J.-L., and E. Dickinson. 1991. Competitive adsorption of lecithin and β-casein in oil in water emulsions. J. Agric. Food Chem. 39:1365.
22 Courthaudon, J.-L., E. Dickinson, and D. G. Dalgleish. 1991. Competitive adsorption of β-casein and nonionic surfactants in oil in water emulsions. J. Colloid Interface Sci. 145:390.
23 Dalgleish, D. G., M. Srinivasan, and H. Singh. 1995. Surface properties of oil-in-water emulsion droplets containing casein and Tween 60. J. Agric. Food Chem. 43:2351.
24 Darling, D. F. 1982. Recent advances in the destabilization of dairy emulsions. J. Dairy Res. 49:695.
25 Darling, D. F., and D. W. Butcher. 1978. Milkfat globule membrane in homogenized cream. J. Dairy Res. 45:197.
26 Dickinson, E., and J.-L. Gelin. 1992. Influence of emulsifier on competitive adsorption of α_s-casein and β-lactoglobulin in oil-in-water emulsions. Colloids Surf. 63:329.
27 Dickinson, E., R. K. Owusu, and A. Williams. 1993. Orthokinetic destabilization of a protein-stabilized emulsion by a water-soluble surfactant, J. Chem. Soc. Faraday Trans. 89:865.
28 Dickinson, E., S. E. Rolfe, and D. G. Dalgleish. 1988. Competitive adsorption of α_{s1}-casein and β-casein in oil-in-water emulsions. Food Hydrocolloids 2:397.
29 Dickinson, E., and G. Stainsby. 1982. Colloids in Food. Appl. Sci. Publ., New York, NY.
30 Euston, S. E., H. Singh, P. A. Munro, and D. G. Dalgleish. 1995. Competitive adsorption between sodium caseinate and oil-soluble and water-soluble surfactants in oil-in-water emulsions. J. Food Sci. 60:1151.
31 Fang, Y., and D. G. Dalgleish. 1993. Casein adsorption on the surfaces of oil-in-water emulsions modified by lecithin. Colloids Surf. B: Biointerfaces 1:357.
32 Fang, Y., and D. G. Dalgleish. 1993. Dimensions of the adsorbed layers in oil-in-water emulsions stabilized by caseins. J. Colloid Interface Sci. 156:329.
33 Gelin, J.-L., L. Poyen, J.-L. Courthadon, M. Le Meste, and D. Lorient. 1994. Structural changes in oil-in-water emulsions during the manufacture of ice cream. Food Hydrocolloids 8:299.
34 Goff, H. D., B. Freslon, M. E. Sahagian, T. D. Hauber, A. P. Stone, and D. W. Stanley. 1995. Structure development in ice cream-dynamic rheological measurements. J. Texture Stud. 26: 517.
35 Goff, H. D., and W. K. Jordan. 1989. Action of emulsifiers in promoting fat destabilization during the manufacture of ice cream. J. Dairy Sci. 72:18.
36 Goff, H. D., J. E. Kinsella, and W. K. Jordan. 1989. Influence of various milk protein isolates on ice cream emulsion stability. J. Dairy Sci. 72:385.
37 Goff, H. D., M. Liboff, W. K. Jordan, and J. E. Kinsella. 1987. The effects of polysorbate 80 on the fat emulsion in ice cream mix: evidence from transmission electron microscopy studies. Food Microstruct. 6:193.
38 Govin, R., and J. G. Leeder. 1971. Action of emulsifiers in ice cream utilizing the HLB concept. J. Food Sci. 36:718.
39 Kalab, M. 1985. Microstructure of dairy foods. 2. Milk products based on fat. J. Dairy Sci. 68:3234.
40 Kokubo, S., K. Sakurai, M. Hattori, and M. Tomita. 1994. Effect of drawing temperature at a freezer and overrun on deemulsified fat of ice cream. J. Jpn. Soc. Food Sci. Technol. 41:347. (Cited in Dairy Sci. Abstr. 57:3397.)
41 Krog, N., N. M. Barfod, and W. Buchheim. 1987. Protein-fat-surfactant interactions in whippable emulsions. Page 144 *in* Food Emulsions and Foams. E. Dickinson, ed. R. Soc. Chem., London, England.

42 Lin, P. M., and J. G. Leeder. 1974. Mechanism of emulsifier action in an ice cream system. J. Food Sci. 39:108.
43 Melsen, J. P., and P. Walstra. 1989. Stability of recombined milk fat globules. Neth. Milk Dairy J. 43:63.
44 Needs, H. C., and A. Huitson. 1991. The contribution of milk serum proteins to the development of whipped cream structure. Food Struct. 10:353.
45 Noda, M., and Y. Shiinoki. 1986. Microstructure and rheological behaviour of whipping cream. J. Texture Stud. 17:189.
46 Oortwijn, H., and P. Walstra. 1979. The membranes of recombined fat globules. 2. Composition. Neth. Milk Dairy J. 33:134.
47 SAS® User's Guide: Statistics. Version 6 Edition. 1988. SAS Inst., Cary, NC.
48 Schmidt, D. G., and A.C.M. van Hooydonk. 1980. A scanning electron microscopal investigation of the whipping of cream. Scanning Electron Microsc. III:653.
49 Stanley, D. W., H. D. Goff, and A. S. Smith. 1996. Texture-structure relationships in foamed dairy emulsions. Food Res. Int. 29:1.
50 Tomas, A., J.-L. Courthadon, D. Paquet, and D. Lorient. 1994. Effect of surfactant on some physico-chemical properties of dairy oil-in-water emulsions. Food Hydrocolloids 8:543.
51 Tomas, A., D. Paquet, J.-L. Courthadon, and D. Lorient. 1994. Effect of fat and protein contents on droplet size and surface protein coverage in dairy emulsions. J. Dairy Sci. 77:143.
52 van Boekel, M.A.J.S., and P. Walstra. 1981. Effect of couette flow on stability of oil-in-water emulsions. Colloids Surf. 3:99.
53 van Boekel, M.A.J.S., and P. Walstra. 1981. Stability of oil-in-water emulsions with crystals in the disperse phase. Colloids Surf. 3:109.
54 Walstra, P. 1987. Overview of emulsion and foam stability. Page 242 *in* Food Emulsions and Foams. E. Dickinson, ed. R. Soc. Chem., London, England.
55 Walstra, P., and R. Jenness. 1984. Dairy Chemistry and Physics. John Wiley & Sons, New York, NY.
56 Walstra, P., and H. Oortwijn. 1982. The membranes of recombined fat globules. 3. Mode of formation. Neth. Milk Dairy J. 36: 103.
57 Williams, A., and E. Dickinson. 1995. Shear-induced instability of oil-in-water emulsions. Page 252 *in* Food Macromolecules and Colloids. E. Dickinson and D. Lorient, ed. R. Soc. Chem., London, England.