Enhanced creaming of milk fat globules in milk emulsions by the application of ultrasound and detection by means of optical methods


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Abstract

The effects of application of ultrasonic waves to recombined milk emulsions (3.5% fat, 7% total solids) and raw milk on fat destabilization and creaming were examined. Coarse and fine recombined emulsions ($\text{D}[4,3] = 2.7 \mu m$ and $9.3 \mu m$) and raw milk ($\text{D}[4,3] = 4.9 \mu m$) were subject to ultrasound for 5 min at 35°C and 400 kHz or 1.6 MHz (using a single transducer) or 400kHz (where the emulsion was sandwiched between two transducers). Creaming, as confirmed by Turbiscan measurements, was more evident in the coarse recombined emulsion and raw milk compared to that of the recombined fine emulsion. Particle size analysis, supported by microscopic images, showed that both flocculation and particle coalescence occurred upon ultrasound treatment, the extent of which was dependent on the milk sample and ultrasound conditions. These results imply that the ultrasound has potential to pre-dispose fat particles in milk emulsions to creaming due to flocculation and coalescence, not only in standing wave systems, but in systems with inhomogeneous sound distributions.

Keywords

Ultrasound, separation, milk, standing waves, milk fat globule, emulsion, coalescence

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1. Introduction

Ultrasonics has been proposed as a technique to separate particles under a standing wave field. A number of publications concentrate on the removal of solid particles (mainly polystyrene and polyamide beads) in batch (Tolt and Feke, 1993; Whitworth et al., 1991) and continuous processes at laboratory scale (Johnson and Feke, 1995; Pangu and Feke, 2004; Hawkes and Coakley, 2001; Mandralis and Feke, 1993; Kapishnikov et al., 2006; Groeschl, 1998a; Groeschl, 1998b). In the food area, ultrasound has been used to split canola oil emulsions by enhancing particle flocculation and coalescence (Nii et al., 2009).

Particles in a standing pressure wave field experience the so called primary acoustic radiation force, which can be expressed analytically for a compressible sphere (Yosioka and Kawasima, 1955):

\[ F_{ac} = -\frac{4\pi}{3} R^3 k E_{ac} \Phi \sin(2kx) \]  

(1)

where \( R \) denotes the particle radius, \( k \) the wave number of the ultrasound (=2\( \pi /\lambda \), with \( \lambda \) being the wavelength), \( E_{ac} \) the average acoustic energy density, \( \Phi \) the acoustic contrast factor and \( x \) the distance from a nodal point of the standing wave. When particles with a non-zero acoustic contrast factor (ACF) are subjected to a standing ultrasonic wave the acoustic radiation force drives them either to the nodes or antinodes for particles with positive and negative ACF values respectively. The spatial distance between successive bands is therefore \( \lambda/2 \). The acoustic contrast factor is given by

\[ \Phi = \frac{5 \rho_M - 2 \rho_P}{2 \rho_M + \rho_P} \frac{\beta_M}{\beta_P} \]  

(2)

\[ \beta = \frac{\rho}{c^2} \]
where $\rho_M$, $\rho_P$ and $\beta_M$, $\beta_P$ are the density and the compressibility of the continuous medium and the dispersed particles respectively.

In a pressure field, the container or chamber walls act as pressure antinodes as they are the points where the pressure differences are built up. As can be derived from Eq. 2, fat particles in an aqueous environment show a negative contrast factor and therefore have the tendency to move towards the walls. In addition, Eq. 2 shows that even particles with zero density difference with respect to their surrounding medium can be manipulated by ultrasound, as long as their compressibilities differ. After the particles form bands of high concentration at the pressure nodes or antinodes the so-called “second acoustic force” or Bjerknes force (Apfel, 1988) drives them together, leading to clusters. The second acoustic force originates from interactions of the particles with the fluid, e.g. reflections of the ultrasound field at the particles’ surface.

A review dealing with the effects of ultrasound on proteins in dairy products was recently published by Ashokkumar et al. (2010). However, the information on the use of ultrasound for separation of fat in milk is scarce. A few references dealing with the separation of milk fat globules are found in the field of biotechnology where fat particles are separated from red blood cells using standing waves (Petersson et al., 2004; Petersson et al., 2005). Miles et al. (1995) determined the threshold levels for the separation of micro-organisms from suspensions followed in a cuvette resonance chamber set up and further suggests that the application of ultrasound standing waves (1-3 MHz) can enhance not only bacteria but also cream separation. However, a systematic evaluation of the effects of ultrasound standing waves on the creaming properties of milk has not been done to date. The present contribution evaluates the formation of milk fat globule banding, flocculation and coalescence, in coarse and fine emulsions of recombined milks and in raw milk.
2. Materials and methods

Sample preparation

To study the effect of ultrasound on the creaming of milk fat globules three model systems were used. These comprised of two models made out of recombined milk emulsions (a coarse emulsion and a fine emulsion) and freshly collected raw milk.

The recombined milk emulsion was prepared by dispersion of skim milk powder (SMP, Tatura Milk Industries Limited, Victoria, Australia) in water at 50°C followed by the addition of anhydrous milk fat (AMF) (Murray Goulburn Co-operative Company Limited, Victoria Australia) to obtain 7% total solids emulsion with 3.5% fat. The AMF was previously dyed by adding 0.01% oil-red-O colorant (BDH Laboratory suppliers, Poole, England). An Ultra-turrax operated at 20,000 rpm for 3 min (ultra-turrax T25, IKA-Labortechnik, Staufen, Germany,) was utilised to form a coarse recombined milk emulsion (hereafter termed “coarse emulsion”). To reduce the particle size, the coarse emulsion was treated with a laboratory homogenizer after two passes (FOSS NIRSystems Inc., Laurel, USA, Type D head, equivalent to a treatment of approximately 140 bar). This homogenized emulsion of recombined milk emulsion was hereafter termed a “fine emulsion”. All trials including raw milk used fresh milk directly obtained from Bega Cheese (Victoria, Australia) on the day of the experiment.

Resonance chamber configuration and sample treatment

The sonication of the samples (7 mL) was carried out in a Turbiscan tube (Formulaction, Toulouse, France) which was sealed with a metal plate at the bottom, acting as a sound transmitter into the fluid. Fig. 1 and Fig. 2 illustrate the experimental set up for the one transducer plate (1) and two transducer plate (2)
configuration. Ultrasound frequencies used were 400 kHz and 1.6 MHz with the single transducer set-up and only at 400 kHz with the two transducer plate set-up. The sample was placed in a water bath with 35°C in order to minimize the temperature increase due to the energy dissipation. In Fig. 2 the tube walls acted as a sound transmitter as the set up had to be submerged in the water bath. Therefore, the sound distribution in the tube in this case is complex and not predictable, as the glass walls transmit and interfere with the external sound field of the transducers. In all experiments the ultrasound treatment time was set to 5 min. All ultrasonication runs were carried out as triplicates.

Two different ultrasound transducer systems were used with 400 kHz (Submersible Transducers, Sonosys Ultraschallsysteme GmbH, Neuenbuer, Germany) and 1.6 MHz (Nebulizer, APC International Inc., Mackayville, Pennsylvania, USA). To estimate the power input into the liquid a slightly modified set up compared to Fig. 1 served as model system. A defined mass of water (10 g ± 0.1 g) was filled into the tube, which was not submerged but in contact to air (metal cap still in the water bath). By measuring the temperature increase after a defined period of time (120 s) the power input into the liquid could be estimated. For transferring these results to the dairy system this approach assumes that the differences in the physical properties of water and milk are negligible or do not influence the power input. It is also assumed that the heat conduction into the ambient through the glass walls is negligible compared to the energy input through the dissipation of sound energy. The power input values could be determined to be 1.6 W ± 0.2 W for the 400 kHz and 0.35 W ± 0.07 W for the 1.6 MHz unit, respectively. No acoustic streaming was present at all times, which would lead to a remixing of the particles in the dairy systems due to turbulent structures.
The sound intensity in the tube was estimated by using a hydrophone (TC 4038, Reson A/S, Slangerup, Denmark). It was inserted into the set up at different positions to get an approximation of the different sound levels throughout the tube. For the described process parameters this sound pressure amplitude ranged around 350 to 500 kPa, which corresponds to an average acoustic energy density $E_{ac}$ of 10 to 25 J/m$^3$.

**Turbiscan measurements**

In order to get an estimation of the creaming in the sample a Turbiscan MA 2000 (Formulaction, Toulouse, France) was employed, which scans the whole sample in the tube. The Turbiscan measures backscattered and transmitted light as a function of the axial tube coordinate and time. Due to the increase of backscattered light at the layers with a higher number of dispersed particles, it is possible to measure high cream concentration regions.

Scans were performed over a 10 minute period right after removing the samples from the ultrasonic set up. For each model system a non-sonicated control was treated exactly in the same way as the sonicated samples. They were filled into the Turbiscan tube, put into the water bath and after 5 min they were placed into the Turbiscan and measured for further 10 min.

**Creaming and recovery rates**

To compare the different creaming extents the ratio of the area of the peak corresponding to the separated cream phase was calculated with respect to the total backscattering measured in the sample (Eq. 3). Fig. 3 illustrates the computation of the “creaming extent” (CE). The cream phase was defined as the curve area, starting where the backscattering value is higher than 1.5 % in comparison to the baseline.
value representing the bulk liquid. The 1.5% value represents the measurement error of backscattering determined for the Turbiscan equipment. For comparison between different measurements (e.g. initial particle concentration) the area under the cream phase curve was related to the area under the whole curve. Analytically this can be expressed as

\[
\text{creaming extent} = \frac{\int_0^L BS(z)_{\text{cream phase}} \, dz}{\int_0^L BS(z) \, dz}
\]  

(3)

where \( z \) represents the axial position in the tube (origin at the bottom), \( L \) the free surface and \( BS(z) \) the backscattering at position \( z \).

This approach assumes that the “backscattering potential” and hence number of particles, which equals concentration, is shifted when a cream phase is formed. To assure that this procedure yields valid results, the so called “recovery rate” (RR) was computed with the following equation

\[
\text{recovery rate} = \frac{\int_0^L BS(z)_{\text{sample}} \, dz}{\int_0^L BS(z)_{\text{control}} \, dz}
\]  

(4)

where \( BS(z)_{\text{sample}} \) stands for the backscattering of the sample and \( BS(z)_{\text{control}} \) for the corresponding non-ultrasonic treated control at the same time. If this value is close to unity this means that the overall backscattering of the sample and the control match. For instance, assuming no change in particle sizes, a recovery rate of one can be attributed to the fact that all particles are moved to another position in the tube but do not flocculate or coalesce. It also guarantees that no significant non-linear effects are
introduced due to high particle concentrations and the backscattering is directly proportional to the square root of the concentration.

Particle sizing and microscopy

All particle size measurements were conducted with a Galai CIS-1 (Galai Production LTD, Haemek, Israel), which provides particle size ranges allowing the detection of changes in size. All measurements were repeated twice per sample treatment. Samples were adjusted to a detectable dilution range with distilled water. To differentiate between flocculation (which is a reversible phenomenon in which the integrity of the interfacial layer of the initial fat droplet is maintained) and coalescence (where there disruption of the interfacial layer and the formation of a larger oil droplet) the particle size increase for the same set of described experiments was conducted a second time. After sonication the cream phase was remixed by shaking the Turbiscan tube gently to break up particle clusters and determine if particle coalescence occurred. After the Turbiscan measurements microscopy images (400x lens, Olympus BH-2 light microscope, soft imaging system Color View IIIu, Japan) and particle size distributions of the top cream layer (1 ml extracted from the surface with a pipette) were recorded to observe potential changes in the globule structure and concentration.

Statistics

Changes in particle size were evaluated by using the General Linear Model in the Minitab Statistical package to a 95% level of significance (Minitab ® Release 14.11, 2003, Coventry, UK). The Tukey method was applied at 95% confidence level for pairwise comparisons.
3. Results and Discussion

3.1 Particle size of initial emulsions

Fig. 4 shows the number distribution of all samples, where a wider distribution can be found in the case of raw milk. The calculated volume mean diameters $D_{4,3}$ for the samples were 4.9 µm for raw milk, 2.7 µm for the fine emulsion and 9.3 µm for the coarse emulsion.

3.2 Effect of ultrasonication

3.2.1 Creaming behavior

The creaming behavior expressed as the creaming extent from Turbiscan readings as well as particle size results are presented after sonication runs. The extent of creaming was dependent on the milk sample used, the frequency applied and the transducer geometry. Differences in creaming were obtained with the use of a single transducer at the two frequencies (400kHz or 1.6 MHz) and also at fixed frequency (400 KHz) when different transducer set-ups were used (single or two transducer geometry).

3.2.1.1. Single transducer configuration at various frequencies

By applying one transducer and a reflector (Fig. 1) and adjusting the distance between them a planar standing wave could be achieved. Under these conditions the force on a particle is maximized. This effect is shown as an example in Fig. 5 for the coarse emulsion of recombined milk. It can be seen that the ultrasound leads to the formation of bands with higher fat concentration. After switching off the ultrasound field floccules start rising immediately and re-disperse at the same time. If the sonicated sample is stirred all floccules completely re-disperse back into the solution. This re-
dispersing suggests that the fat globules clustered in bands made up of discrete single droplets. Miles et al. (1995) have identified the threshold amplitudes to form bands in suspensions of latex microspheres at particle size ranges between 1 and 5 µm at 1 MHz and higher frequencies. The minimum average sound pressure determined for our systems was 350 kPa, which exceeds the threshold values reported for banding of all particles sizes tested at 1 MHz.

The enhanced creaming extent caused by ultrasonics in the coarse emulsion, in comparison to the untreated control, could be observed with the naked eye. The top layer exhibited a more intense red color which is due to the higher concentration of fat particles. In these experiments with the Turbiscan tubes, the Turbiscan readings (Fig. 6) reveal that hardly any natural creaming could be observed for the coarse emulsion of recombined milk without ultrasound after 10 min. The results for the single transducer for the two frequencies are summarized in Table 1 and Table 2. Comparing the results for the least stable coarse emulsion at 400 kHz and 1.6 MHz it becomes obvious that the higher frequency leads to a two-fold increase in creaming extent. The increase with higher frequency was also observed with the raw milk. In this case a weak level of creaming could be measured at 400 kHz after 10 min, in contrast to 1.6 MHz. The more prominent separation observed in the coarse emulsion could be due to the presence of larger particles in the 9 to 15 µm range, which were not present in milk.

The fine emulsion showed no creaming, regardless of the frequency and settling time during the Turbiscan trials. The smaller particle sizes of the fine emulsion compared to the coarse emulsion and the raw milk contributed to the resistance for the fine emulsion to creaming. Table 1 and Table 2 reveal that all the observed separations occurred during the sonication for the coarse emulsion at 400 KHz and 1.6 MHz and
for the raw milk at 1.6 MHz. Thus, these experiments clearly reveal that ultrasound can be used to accumulate and separate milk fat in its native environment.

3.1.2. Particle size changes

During particle flocculation the probability of coalescence rises due to the increased local concentration. Both processes, pure flocculation and coalescence, differ from the point of view of their physics. Both phenomena result in an increase in particle size.

In the case of flocculation where two or more fat droplets aggregate while each maintaining their interfacial layer, there is an apparent hydrodynamic increase. In flocculation, the clustered fat globules may be re-dispersed. In the case of coalescence, there is disruption of the original interfacial layer of droplets, leading to an irreversible increase in particle size of the oil droplet. Both flocculation and coalescence result in enhanced creaming. This has been shown in previous studies which mention these mechanisms operating for the ultrasonic enhanced separation of algae and vegetable oil from the continuous medium (Bosma et al., 2003; Nii et al., 2009).

Fig. 7 shows that no significant particle size (P>0.05) increase was detected for the coarse emulsion in the 400 KHz single transducer set up. The same was found for raw milk and the fine emulsion for both single transducer geometries at 400 kHz and 1.6 MHz. However, the coarse emulsion showed that the number of particle sizes in the 2-3 µm range increased when using the 1.6 MHz unit.

These observations imply that the primary and secondary acoustic forces drive the particles together so they form floccules or clusters, which redisperse once ultrasonic radiation is turned off. This was verified by remixing the fat phase and finding no increased particle size. Extending the sonication time from 5 min to 30 min (data not
shown) did not result in further coalescence in all samples for the single transducers at 400 kHz and 1.6 MHz.

3.2. Two-transducer configuration at 400 KHz

3.2.1. Creaming behavior

Major differences were found when comparing the coarse emulsion after sonication in the one and two-transducer set ups, which were clearly observable with the naked eye. Firstly, there were large clusters forming at the tube walls in the two-transducer resonance chamber (Fig. 8). The clusters formed in the two transducer geometry were visually larger in size than those obtained in the one transducer geometry forming a band. After switching off the ultrasound the clusters destabilized, rising to the top of the tube, and redispersed; but not as quickly as in the case of the single transducer. The destabilized fat clusters obtained upon sonication in the two transducer geometry could still be measured minutes later with the Turbiscan (which was not the case in the single transducer geometry). Where sonication was applied with two transducers, the fat particles rose to the top forming a more distinct cream layer, which means that more particles flocculated or coalesced, and as a consequence more fat was accumulated. This effect can be noticed in Fig. 9 for the coarse emulsion and in Fig. 10 for the raw milk. Both the coarse emulsion and raw milk samples showed higher creaming extents in contrast to the fine emulsion where no creaming was observed (see Table 3).

In addition, the treatment with the two transducer configuration results in very high concentrations of milk fat in the top (i.e., creamed) layer of raw milk after sonication (Fig. 11d and Fig. 12d). These images illustrate that sonication with 1.6 MHz (Fig. 11b and Fig. 12b) drives bigger particles to the top right after ultrasonication, which
could also be confirmed with particle size analysis (data not shown). It is worth noting
that the raw milk was not influenced by the 400 kHz sonication in the single as it was
in the two transducer set up. The microscopy images in Fig. 11 and Fig. 12 show
excellent agreement with the creaming extents in tables 1 to 3.

Although the sound distribution in the tube is not predictable with the two transducer
geometry, the sound intensity seems to be higher and the particles are driven together
with a bigger force, leading to these characteristic floccules which tend to cluster at
the tube walls. The fact that these floccules rose slower than in the single transducer
geometry (Fig. 9 and Fig. 10) implies that the fat particles clustered more strongly to
the walls due to the higher intensity of the sound field. These higher forces may lead
to changes in the particle size, and possibly interfacial membranes, which is addressed
in the next section.

The recovery rate can be used to demonstrate the ability of the clustered fat droplets to
re-disperse after treatment in the two transducer set up at 400 kHz. To account for the
peaks appearing in the Turbiscan readings as a result of the large floccules distributed
along the tube walls in the two transducer set up (Fig. 9 and Fig. 10), the recovery rate
(Eq. 4) is calculated by using the integral of the curve obtained after 10 min in the
denominator. Instead of using the reading for the control sample, the 10 min reading
is used as a baseline for comparison between recovery rates. The single peak 10 min
reading mainly occurs when all floccules have risen to the top of the tube and
therefore allows the evaluation of the extent of re-dispersion of large floccules in
relative to this point in time.

Thus, all recovery rates measured through time in the tube show values higher than
one as a result of the additional peaks encountered by the Turbiscan optic sensor.

While the formed clusters disassembled into floccules or particulates rising towards
the top cream layer the recovery rates decrease with time (Fig. 13), which indicated that some globules forming the clusters partially re-dispersed.

3.2.2. Particle size changes

A comparison of particle sizes of the unsonicated milk (control) with milk sonicated in the two transducer set up shows no significant increase in particle sizes in raw milk and in the fine emulsion. For the coarse emulsion, however, a significant increase can be observed for particles in the size range greater than 6 µm (P>0.05), which is demonstrated by Fig. 7. This means that the ultrasonic forces in the coarse emulsion were enough as to promote fat destabilization probably by means of particle coalescence in addition to flocculation.

On the other hand, even though flocculation was achieved, the raw milk matrix has shown to require greater forces to achieve particle coalescence. This may be due to differences in the interfacial properties of the different fat globules and the presence of larger sized droplets in the 9 to 15 µm range in the coarse emulsion, which were not present in milk. In addition, in fresh raw milk, the fat droplet is surrounded by the natural milk fat globule membrane (MFGM), which is rich in phospholipids, whereas in recombined emulsions, proteins form the interfacial layer.

Only a few literature references deal with the phenomenon of coalescence in standing ultrasound fields, as solid particles are often used as dispersed phase, which usually do not exhibit coalescence. In particular some work has shown instantaneous coalescence of particles in vegetable oil emulsions in standing ultrasonic wave fields (Pangu and Feke, 2007; Pangu and Feke, 2009).
4. Conclusion

This contribution shows for the first time that the application of ultrasound at frequencies lower than 1 MHz leads to enhanced creaming in a coarse recombined milk emulsion formulated with skim milk powder and milk fat and in raw milk. This was supported by microscopy imaging as well as Turbiscan readings, which showed higher particle concentration in the top cream layer as a result of ultrasound. Particle flocculation and clustering was detected in both the coarse emulsion and raw milk, where in the coarse emulsion particle coalescence was observed in the two transducer system at 400 kHz. However, no coalescence was observed in milk in the two transducer set up. These findings suggest that a non standing wave system with two transducers can enhance particle coalescence.

Separation of milk fat in dairy streams can benefit from the increased coalescence phenomena by pre-treating milk with high frequency ultrasound. Further research is required to determine the kinetics of flocculation, coalescence and creaming of milk fat globules in high frequency ultrasonic systems. Parameters from kinetic models will enable the design of ultrasonic based unit operations applicable to the dairy industry.

Acknowledgements

The authors gratefully acknowledge the support by the Erlangen Graduate School in Advanced Optical Technologies (SAOT) by the German National Science Foundation (DFG) in the framework of the excellence initiative. The authors would also like to acknowledge Dr. Kai Knoerzer and Ms. Elodie Cotte for their contribution in this project.
References


Fig. 1. Experimental set up for the one transducer geometry (400 kHz and 1.6 MHz)

Fig. 2. Experimental set up for the two transducer geometry. In this set up sound is also transferred into the fluid through the tube walls (only 400 kHz)
Fig. 3. Example for the computation of the creaming extent. This figure shows the backscattering of the coarse emulsion control (no ultrasonic treatment) in comparison with the sonicated sample (measurement 1 min after switching of ultrasound). The total area under the graphs is equal for all times.
Fig. 4. Cumulative number distribution for the raw milk, coarse emulsion and fine emulsion. The coarse emulsion shows more similarities regarding the particle sizes and can therefore be used as a milk model, with the advantage of using dye to visualize the particle concentration.
Fig. 5. a) Dyed coarse emulsion under sonication (400 kHz) in an open vessel (no reflector). The distinct bands can clearly be observed. b) After switching of the ultrasound field the formed floccules start to rise immediately. The formation of the streaks leads to the conclusion that the floccules comprise of single particles.
Fig. 6. Example of the Turbiscan reading for the control samples. Here the results for the coarse emulsion are used, as it represents the most unstable of all three dispersions. In neither of the samples any natural creaming could be observed. Only the range between 8 mm and 63 mm where the backscattering shows the constant value of 53 % can be considered to be inside the tube. The region below 8 mm marks the metal base and the strong decay of backscattering above 63 mm the beginning of the free surface of the sample. This holds true for all following Turbiscan readings.
Fig. 7. Particle size distribution after the sonication of the coarse emulsion at 400 kHz (one and two transducer geometry) and 1.6 MHz at 35°C and gentle remixing of the cream and the “skimmed” phase. Different letters represent significant differences per treatment (P<0.05)
Fig. 8. Coarse emulsion after sonication in the sandwich two transducer geometry. Large particle clusters were formed at the tube wall showing a greater lag time for re-dispersion than bands observed in a single transducer set up.
Fig. 9. Turbiscan reading after the sonication of the coarse emulsion in the one and two transducer geometry. For the two transducers the formed clusters persist longer than for the single transducer.
Fig. 10. Turbiscan reading after the sonication of raw milk in the one and two transducer geometry. Like in the coarse emulsion the particle clusters persist longer than for the single transducer.
Fig. 11. Microscopy image of the top layer 10 min after sonication for the different frequencies for the coarse emulsion. The particle concentration correlates very well with the computed creaming extents in the tables 1 to 3.
Fig. 12. Microscopy image of the top layer 10 min after sonication for the different frequencies for the raw milk. The particle concentration correlates very well with the computed creaming extents in the tables 1 to 3.
Fig. 13. Example for the recovery rate as a function of time for raw milk in the two transducer geometry. The recovery rate is greater than one, showing the higher integral backscattering compared to the steady state 10 min after sonication. The decrease can be assigned to reversible re-dispersion of particles out of the floccules.
### Table 1

Creaming extents (CE) and recovery rates (RR) for the experiments with the single transducer geometry at a frequency of 400 kHz for the coarse emulsion (coarse), fine emulsion (fine) and raw milk:

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>CE</th>
<th>RR</th>
<th>CE</th>
<th>RR</th>
<th>CE</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coarse</td>
<td>coarse</td>
<td>fine</td>
<td>fine</td>
<td>raw milk</td>
<td>raw milk</td>
</tr>
<tr>
<td>0*</td>
<td>0.086</td>
<td>99%</td>
<td>0</td>
<td>100%</td>
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<td>100%</td>
</tr>
<tr>
<td>1</td>
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<td>99%</td>
<td>0</td>
<td>100%</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
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<td>0</td>
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<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>0.104</td>
<td>99%</td>
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<td>100%</td>
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<td>10</td>
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<td>0</td>
<td>100%</td>
<td>0.0185</td>
<td>100%</td>
</tr>
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</table>

*1 min after sonication

### Table 2

Creaming extents (CE) and recovery rates (RR) for the experiments with the single transducer geometry at 1.6 MHz for the coarse emulsion (coarse), fine emulsion (fine) and raw milk:

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<tbody>
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<td>coarse</td>
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<td>fine</td>
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<td>raw milk</td>
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<td>99%</td>
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<td>0</td>
<td>100%</td>
<td>0.119</td>
<td>99%</td>
</tr>
<tr>
<td>5</td>
<td>0.237</td>
<td>98%</td>
<td>0</td>
<td>100%</td>
<td>0.119</td>
<td>99%</td>
</tr>
<tr>
<td>7</td>
<td>0.239</td>
<td>98%</td>
<td>0</td>
<td>100%</td>
<td>0.119</td>
<td>99%</td>
</tr>
<tr>
<td>10</td>
<td>0.238</td>
<td>99%</td>
<td>0</td>
<td>100%</td>
<td>0.119</td>
<td>99%</td>
</tr>
</tbody>
</table>

*1 min after sonication

### Table 3

Comparison between the creaming extents (CE) and recovery rates (RR) for the experiments with the one and two transducer geometry at 400 kHz for the coarse emulsion (coarse), fine emulsion (fine) and raw milk (10 min after sonication, as only then all particle clusters had risen to the top):

<table>
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<th></th>
<th>CE</th>
<th>RR</th>
<th>CE</th>
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<td>fine</td>
<td>fine</td>
<td>raw milk</td>
<td>raw milk</td>
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<tr>
<td>one transducer</td>
<td>0.104</td>
<td>99%</td>
<td>0</td>
<td>100%</td>
<td>0.0185</td>
<td>100%</td>
</tr>
<tr>
<td>two transducer</td>
<td>0.551</td>
<td>91%</td>
<td>0</td>
<td>100%</td>
<td>0.643</td>
<td>85%</td>
</tr>
</tbody>
</table>