**Effect of salt and fat reduction on proteolysis, rheology and cooking properties of
Cheddar cheese**

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ABSTRACT

Full-fat (FF, 33%), reduced-fat (RF, 22%) and half-fat (HF, 16%) Cheddar-style cheeses, each with full salt (FS, 1.9%), reduced salt (RS, 1.2%) or half salt (HS, 0.9%) variants, were made on three separate occasions. Reducing salt from 1.9 to 1.2 or 0.9% in the FF, RF and HF cheeses resulted in lower intact casein, firmness, fracture stress and work to extend the molten cheese, and higher heat-induced flow. The fracture strain of the RF and HF cheeses increased while that of the FF cheese decreased on reducing salt content. The results show the response to reducing salt depended on the variable studied, extent of salt reduction and fat level. Generally, reducing fat had opposite effects to those of salt reduction. There was a significant interaction between salt and fat content fracture characteristics, heat-induced flow, and extensibility of molten cheese at ripening times ≥ 90 d.

1. Introduction

Cheddar is one of the largest cheese varieties globally, with approximately 1.6 m tonnes produced annually in the US, where it ranks second to Mozzarella (Statista, 2015). It is extensively consumed as both a table cheese and as an ingredient in various culinary dishes in food service and in formulated foods products such as soups and sauces (Guinee, 2016). Apart from flavour, quality criteria of major importance include the texture properties of the unheated cheese and the cooking behaviour of the heated cheese. Depending on the cooking application, various degrees of melt, flow, flow-resistance and extensibility may be required. Although cheese consumption rates globally have been increasing steadily during the recent years, there are concerns in relation to its contribution to the intake of dietary sodium and saturated fat, which, when consumed in excess, are frequently considered to increase the risk of type 2 diabetes, cardiovascular disease, hypertension and mortality (He & McGregor, 2007; van Aerde et al., 2013). This concern is evident in many nutritional guidelines that now recommend consuming reduced-fat, reduced-salt dairy products as a means of reducing the intake of saturated fat in the diet (Bahl, 2015; Lamarche & Couture, 2014). However, there are significant inter-study discrepancies on the impact of dairy fat on health, with some recent studies (Crichton & Alkerwi, 2014; Soedamah-Muthu, Masset, Verberne, Geleijnse, & Brunner, 2013) indicating no association, or an inverse association, between the consumption of dairy products and obesity, cardiovascular disease and mortality.

Extensive research has been undertaken on the effects of reducing salt or fat on cheese, as a means of providing insights for the development of reduced-fat or reduced-salt cheeses with quality characteristics (flavour, texture and cooking properties) as close as possible to the control cheese. Salt reduction is paralleled by increases in moisture content, water activity, rate of lactose metabolism, extent of proteolysis and a lower rate of starter cell autolysis

(Kelly, Fox, & McSweeney, 1996; McCarthy, Wilkinson, Kelly, & Guinee, 2015; McMahon et al., 2014; Murtaza et al., 2014; Rulikowska et al., 2013). These changes are paralleled by an increase in moisture and moisture-in-non-fat substances and reductions in protein content, fracture force and firmness of the unheated cheese. The flow and strength of the heated cheese are also altered to an extent dependent of level of salt reduction (Ganesan, Brown, Irish, Brohersen, & McMahon, 2014; Henneberry, Kelly, Kilcawley, Wilkinson, & Guinee, 2015; Mistry & Kasperson, 1998; Mpagana & Hardy, 1986; Murtaza et al., 2014). Reducing fat content of cheese leads to higher concentrations of protein, moisture content and pH, and a reduction in moisture-non-fat substances. Simultaneously, the calcium phosphate casein network becomes denser and more continuous and less interrupted by fat globules. As a result, the unheated cheese becomes increasingly firm, rubbery, and on heating tends to dehydrate and crust or puff without flow, owing to a reduction in the lubricating and moisture-retentive effects of fat (Fenelon & Guinee, 2000; Guinee, Auty, & Fenelon, 2000; Henneberry et al., 2015).

To date, there has been little focus on the combined effects of reducing salt and fat simultaneously, despite the consumer push for foods with reduced levels of these nutrients, the dietary intake of which in developed countries is in excess of that recommended by health agencies (Kim, Lopetcharat, Gerard, & Drake, 2012). Paulson, McMahon, and Oberg (1998) found that the mean protein hydration, translucence, and extent of flow of non-fat Mozzarella over a 24-day holding period increased as salt level was increased from 0.14% (unsalted) to 0.7% (w/w). Similarly, Henneberry et al. (2015) found that reducing fat (from ~22% down to 11%) and salt (from 1.7% down to 1.0%) resulted in higher levels of protein and moisture, lower contents of moisture-in-non-fat substances, fat-in-dry matter and salt-in-moisture. The reduced-salt, reduced-fat cheeses had lower water binding capacity and primary proteolysis, were firmer and more chewy, underwent less flow on heating and

required higher work to extend the molten cheese (Henneberry et al., 2015). Compared with the full-fat, full-salt cheese, the heated reduced-fat, reduced-salt cheese had a lower sensory acceptability as reflected by lower scores for attributes such as *moistness*, *salt taste*, *cream flavour*, and *fat flavour*; this difference was associated with differences in types and concentrations of volatile compounds (Henneberry et al., 2016). In a previous study (McCarthy et al., 2015), the effects of reducing salt and fat on the composition, lactose metabolism, water activity and microbiology of Cheddar cheese was investigated. Lactose content, pH and water activity were significantly affected by the interaction of fat and salt. During the course of the 270 day ripening period, the lactose level (% w/w) of the full-fat, full-salt cheese decreased slowly from ~ 0.45 at 1 d to 0.02 at 270 d, while the pH simultaneously decreased from ~ 5.35 to 5.15 over the same period; conversely, the lactose decreased from 0.05 to 0% in 90 d and the pH increased from 5.20 to 5.35 at 270 d.

In the current study, the effects of altering salt and fat on the proteolysis, water sorption, texture properties and cooking characteristics of the same Cheddar cheeses, as described by McCarthy et al. (2015), were investigated.

2. Materials and methods

2.1. Standardisation of milk and cheese manufacture

Cheddar cheeses with different levels of fat and salt were manufactured in triplicate trials, as described by McCarthy et al. (2015). In each trial, 9 variants of Cheddar cheese were produced: full-fat, full-salt (FFFS); full-fat, reduced-salt (FFRS); full-fat, half-salt (FFHS); reduced-fat, full-salt (RFFS); reduced-fat, reduced-salt (RFRS); reduced-fat, half-salt (RFHS);

half-fat, full-salt (HFFS); half-fat, reduced-salt (HFRS); and half-fat, half-salt (HFHS) (Table 1).

2.2. *Sampling of cheese*

The cheeses were stored at 8 °C and sampled after various times (1, 14, 30, 90, 150, 210 and 270 d). At each sampling time point, a vertical slice (~ 1.5 cm) was removed from one of the outside faces of the block and discarded, and a slice (~ 2 kg), including the freshly-exposed surface, was taken for analysis. Samples were analysed within 48 h.

2.3. *Composition analysis of cheese*

Cheese samples were grated and analysed in triplicate at 14 d for fat, NaCl, moisture and protein using standard IDF methods, as described previously (McCarthy et al., 2015).

2.4. *Proteolysis*

2.4.1. *Urea–polyacrylamide gel electrophoresis*

Cheeses were analysed in duplicate at 150 and 270 d; electrophoresis was performed on a Protean II xi vertical slab gel unit (Biorad Laboratories Ltd., Watford, Hertfordshire, UK) using a separating and stacking gel, as described by Rynne, Beresford, Kelly, and Guinee (2004). Cheese samples were prepared, electrophoresed and the resultant gels were stained (0.25%, w/v, Coomassie Blue G250 dye), de-stained (10%, v/v acetic acid) and scanned, as described by Guinee, Pudja, Miočinović, Wiley, and Mullins (2015). The areas of the

following bands were expressed as a percentage of the total band area: β -casein; α_{S1} -casein; and α_{S1} -casein (f24–199).

2.4.2. *pH 4.6 soluble nitrogen*

The levels of pH 4.6 soluble nitrogen (pH4.6SN) were measured as described by Fenelon and Guinee (2000) after 1, 14, 30, 90, 150 and 270 d.

2.5. *Dynamic water vapour sorption analysis*

The water sorption of the cheeses as a function of relative humidity was measured gravimetrically using an SPS11 automatic multisample moisture sorption analyser (Project-Messtechnik, D-Ulm, Ulm, Germany), as described by Costa et al. (2010). A 1 g, freshly grated sample from each of the 270 day-old cheese was placed on a perforated wire support (platform) located in an aluminium dish to ensure uniform air distribution during subsequent desorption. Eleven dishes, each containing a single cheese sample, were loaded onto a carousel which was then placed in the automatic multi-sample moisture sorption analyser at 15 °C. The atmosphere in the enclosed chamber of the analyser containing the cheese was initially equilibrated at 85% relative humidity (RH). Once the samples and atmosphere had equilibrated, the RH was reduced stepwise from 85% down to 5% at intervals of 10%; the time at each %RH (12 h) allowed stabilisation of sample weight loss. The weight loss as a function of RH values was recorded dynamically by the internal instrument balance at 5 s intervals. The results are expressed as water loss per 100 g cheese and water-to-protein ratio (WPR) as a function of RH. The WPR is a measure of the retention of water by the cheese matrix, and more specifically the water entrapped by the calcium phosphate *para*-casein matrix, when the cheese is exposed to drying. Consequently, the WPR was used an index of

the water-holding capacity of the cheese, which is important characteristic affecting the functionality of heated cheese (Guinee, 2015).

2.6. Rheology

Six cheese cubes (25 mm each side) were cut from each of the 9 treatment cheeses, wrapped in cling film (to avoid moisture loss) stored at 8 °C overnight, and compressed to 70% of original height at room temperature at a rate of 1 mm s⁻¹ on a TAHDi texture analyser (model TA-HDI, Stable Micro Systems, Godalming, UK), equipped with a 5 mm compression plate and a 100 kg load cell (Guinee et al., 2015). The following rheological parameters were calculated from the resultant force/time curves: firmness ($\sigma_{\max}$), the force at 70% compression; fracture stress (σ_f), the force at fracture as determined from the inflection point of the force/time curve; fracture strain, (ϵ_f), the displacement at fracture as a % of original sample height.

2.7. Functionality of heated cheese

2.7.1. Flow

The flowability was assessed using the modified Schreiber method. A disc of cheese, 4.75 cm in diameter and 4.5 mm in height, was placed on a circular glass dish and heated for 4 min at 280 °C in a convection oven (Binder FD 35, Binder GmbH, Tuttlingen, Germany). The cheese was allowed to cool to room temperature; the flow was defined as the % increase in mean diameter of the cheese disc during heating.

2.7.2. Work to extend the molten cheese

The work to uniaxially extend the hot molten cheese (95 °C) by a distance of 380 mm at a velocity of 10 mm s⁻¹ was measured in triplicate using a TAHDi texture analyser, as described by Guinee et al. (2015).

2.8. Statistical analysis

The effect of salt or fat on cheese composition at 14 d was determined by applying analysis of variance (ANOVA) using the general linear model (GLM) procedure of SAS 9.3 (SAS Institute, 2011), as described by McCarthy et al. (2015). Tukey's multiple-comparison test was used for paired comparison of treatment means and the level of significance was determined at $P < 0.05$. Linear regression analysis was used to analyse for potential correlations between response variables (e.g., level of pH 4.6 soluble N and fracture stress) and the significance of correlations was determined by applying Student's t-test to r . A split-plot design was used to determine how cheese characteristics measured throughout ripening were affected by salt, ripening time and their interaction in the full-fat, reduced-fat and half-fat cheeses, and by the effects of fat, ripening time and their interaction in the full-salt, reduced-salt and half-salt cheeses, as described by McCarthy et al. (2015). The main plot factor was salt level (in cheeses of different fat content) or fat level (in cheeses of different salt content) and the sub-plot factor was time. Similarly, a split-plot design was also used to determine potential interactive effects of salt and fat on all variables at 14, 30, 90, 150, 210 and 270 d.

3. Results and discussion

3.1. Gross composition

The compositions of the 9 treatment cheeses, which have been previously described by McCarthy et al. (2015), are summarised in Table 1. Reducing salt content from 1.9% to 0.9% increased the levels of moisture significantly in the FF, RF and HF cheeses, while reducing fat content from 33% to 16% resulted in higher levels of moisture and protein, and lower levels of salt-in-moisture (S/M) in the FS, RS and HS cheeses.

3.2. *Proteolysis*

3.2.1. *Urea-polyacrylamide gel electrophoresis*

The levels of intact α_{S1} - and β -caseins and α_{S1} -casein (f24–199) expressed as a % of total protein (total band area), are shown in Table 2. Similar to previous studies (Fenelon & Guinee, 2000; Voigt et al., 2012), the level of intact α_{S1} -casein was notably lower than that of β -casein, especially at 270 d when little, or no, non-degraded α_{S1} -casein remained. α_{S1} -Casein was mainly hydrolysed to fractions previously identified as α_{S1} -casein (f24–199) and α_{S1} -casein (f102–199) (McSweeney, Pochet, Fox, & Healy, 1994; Mooney, Fox, Healy, & Leaver, 1998), and to a lesser extent to peptides of higher electrophoretic mobility. The principal breakdown products of β -casein were β -casein (f106–209) (γ_2), and β -casein (f189–209) (β_1).

The levels of intact α_{S1} -casein in the 150 day-old FF, RF and HF cheeses decreased slightly, but significantly, as the salt content was reduced (Table 2). The pattern and level of α_{S1} -casein degradation products was similar for the FF and RF cheeses at 150 d; in the HF cheese the level of α_{S1} -casein (f24–199) in the FS variant was lower than in the corresponding RS and HS variants. In contrast, salt content had no effect on the level of β -casein at 150 d. A similar trend was observed at 270 d, with reduction in salt content

coinciding with lower and higher levels of α_{S1} -casein and α_{S1} -casein (f24–199), respectively, in the RF and HF cheeses but not in the FF cheeses, where residual α_{S1} -casein (~ 6% of total casein) was already very low (Table 2). In contrast to 150 d, the level of β -casein decreased slightly, but significantly, with salt reduction in the FF and RF cheeses but not in the HF cheeses. The modest effect of salt on levels of intact β -casein is at variance with the results of Kelly et al. (1996) who showed a notable increase in β -casein degradation on reducing S/M in a range (5.4 to 2.7%) comparable with that in the current study. Similarly, our results differ from those of Thomas and Pearce (1981) who found that the extent of β -casein degradation increased linearly from ~ 52% at 4.0% S/M to ~ 100% at 8.0% S/M in 1 mo old full-fat Cheddar cheese. However, the current trend concurs with that of many other studies showing little variation in the extent of β -casein degradation with S/M in the range 0.5 to 5.5% in Cheddar ripened for up to 9 mo (Mistry & Kaperson, 1998; Phelan, Guiney, & Fox, 1973) or in Mozzarella cheese with S/M in the range 1.0–3.5% (Arboatti et al., 2014; Henneberry et al., 2015). Inter-study discrepancies on the effect of salt on β -casein degradation may relate to many factors including the type/specificity of coagulant (ratio of chymosin and pepsin, cheese pH), the degree of aggregation of casein as affected by various parameters (e.g., pH, moisture content, concentration of calcium, protein and fat content) which affect susceptibility of the substrate to hydrolysis (Mulvihill & Fox, 1978).

Reducing fat content generally resulted in higher levels of non-degraded α_{S1} - and β -caseins in the FS, RS and HS cheeses at 150 d (Table 2). This trend, also observed by Fenelon and Guinee (2000) for Cheddar after ripening times ≥ 120 d at 8 °C, reflects the lower tendency of casein to undergo degradation in reduced-fat cheese, probably because of the greater volume fraction and higher degree of aggregation of the calcium phosphate *para*-casein that may render it less accessible to proteinases such as chymosin and plasmin. Phelan et al. (1973) reported that dilution of protein content of Cheddar cheese from 25 to 12.5% by

addition of water significantly increased hydrolysis of both α_{S1} - and β -caseins on incubation at 2 °C for 5 d. A similar trend was observed at 270 d, except that the concentration of α_{S1} -casein in all cheeses (apart from RFFS) was quite low and generally unaffected by fat level.

3.2.2. pH 4.6 soluble nitrogen

The level of pH4.6SN in the FF, RF and HF cheeses increased significantly with ripening time (Table 3; Fig. 1a,b,c). The increase in pH4.6SN, which for the FFFS cheeses was typical in magnitude to that previously reported for Cheddar under similar ripening conditions (Fenelon & Guinee, 2000; McMahon et al., 2014), is attributed to the hydrolysis of the *para*-casein principally by residual chymosin. The mean level of pH4.6SN over ripening was not affected by salt content, except in the HF cheese where the mean level in the HFRS and HFHS was significantly higher than that in the HFFS cheese (Fig 1c). The inhibitory effect of salt on proteolysis concurs with the results of Mistry and Kasperson (1998) that also showed a reduction in pH 4.6SN from ~ 24 to 20% total N in 170 day-old reduced-fat (15%, w/w) Cheddar cheese on increasing S/M from 2.7 to 4.5%. However, the absence of an effect of salt content on pH4.6SN in the FF cheeses contrasts with trends from previous studies (Kelly et al., 1996; Murtaza et al., 2014; Rulikowska et al., 2013), showing increases in pH4.6SN of ~ 2 to 5% TN at 150 d on reducing S/M content in the range 2.5 to 4.9% (w/w). The discrepancy may relate to inter-study differences in parameters such as type and level of coagulant (e.g., chymosin versus calf rennet), pH at drainage and moisture content, which ranged from 35.3–37.9% for the cheeses in the current study compared with ~ 37.0–40.6% in the latter studies. The moisture content of the FF cheeses with varying salt content were retained at $\leq 39\%$ to comply with Cheddar cheese specifications (FDA, 2012).

The levels of pH4.6SN in the FS, RS and HS cheeses were significantly affected by fat content (Table 4; Fig. 1d,e,f) with the mean levels in the RF and HF cheese over the 270-

day ripening period being significantly lower than that in the corresponding FF cheese at each salt level. The adverse effect of fat reduction on pH 4.6SN, which concurs with the increase in concentration of residual α_{S1} -casein and accumulated α_{S1} -casein (f24–199) as fat was reduced, has been attributed to the lower moisture-in-non-fat substances (MNFS) content (Creamer, 1971), a lower chymosin-to-casein ratio (Fenelon & Guinee, 2000), and a higher degree of casein aggregation (Phelan et al., 1973). Similar trends have been reported previously for other cheeses including full-salt Cheddar (Fenelon & Guinee, 2000), Kefalograviera (Michaelidou, Katsiari, Voutsinas, Kondyli, & Alichanidis, 2003) and Mozzarella (Henneberry et al., 2015; Rudan, Barbano, Yun, & Kindstedt, 1999). There was no interactive effect of salt and fat on pH 4.6SN.

3.3. Dynamic water vapour sorption analysis

The water desorption isotherms for the FF, RF and HF cheeses with different salt levels at 270 d are shown in Fig. 2. Moisture loss during desorption increased as the content of both salt and fat were reduced, a trend consistent with the increase in cheese moisture on reducing salt and fat (Table 1).

Overall, there was an interactive effect of salt and fat on the WPR, an index of water entrapment by the cheese matrix. The WPR of the FF cheese after reducing the RH to 5% decreased as the salt content was reduced from (w/w) 1.9% (FS) to 1.2% (RS) or 0.9% (HS) (Table 5). In contrast, salt content did not significantly affect the WPR in the HF cheese, whereas the WPR of the RS variant of the RF cheese was significantly higher than that of the FS or HS variant. The higher WPR of the FFFS and RFRS cheeses is consistent with their high concentrations of free amino acids compared with the FFRS and FFHS, and the RFFS and RFHS cheeses (McCarthy et al., 2015); higher concentrations of FAA would be expected

to lead to higher water binding (via hydrogen bonding of water molecules to amino and carboxyl groups) and a reduction in water vapour pressure at a given relative humidity.

The WPR of the HS cheeses increased as the fat content was reduced, suggesting an enhanced degree of water immobilisation within the cheese matrix (Table 5). Contributory factors to the increase in WPR may include the reduction in MNFS (and hence, WPR) and the increase in protein content as fat level was reduced. During the manufacture of hard and semi-hard cheeses, all the bulk phase serum, and part of the serum entrapped within the casein micelle, which amounts to $\sim 3 \text{ mg g}^{-1}$ casein, are removed as whey (Guinee, 2015). Whey removal and moisture reduction become progressively more difficult as the WPR increases, owing to the increases in volume fraction of the casein network and its capillary effect on entrapped moisture (Damodaran, 1997). However, for a given protein content, increasing fat content reduces water vapour pressure at a given relative humidity, owing to the obstruction and tortuosity created by the fat globules, around which the diffusing water molecules must proceed on migrating through the cheese matrix to the external environment (relative humidity) at the surface. In contrast to the HS cheeses, the WPR of the FS cheese decreased as the fat content was reduced (Table 5). These results suggest that the influence of fat on the water retention properties of the *para*-casein network depends on salt content (Everett, Guinee, & Johnson, 2014; Pastorino, Hansen, & McMahon, 2003; Paulson et al., 1998); hence, analysis of the data indicated a significant effect of the interaction between salt content and fat on the WPR (Table 6).

3.4. Large strain deformation behaviour

3.4.1. Fracture stress (σ_f) and firmness (σ_{max})

The σ_f and σ_{max} were significantly influenced by salt, ripening time and the interaction of salt and ripening time (Table 3; Figs. 3 and 4). The σ_f and σ_{max} of all cheeses increased slightly between 1 and 30 d. The initial increases in the latter parameters during early maturation (1–30 d) have been previously observed in reduced-fat Cheddar cheese (Rynne et al., 2004) and experimental hard model cheeses varying in pH (5.2–6.2) and moisture content (41–43%) (Watkinson et al., 2001). The increases may reflect an increase in the hydration and swelling of the calcium phosphate *para*-casein particles associated with post-manufacture cooling of the cheese (Dave, McMahon, Broadbent, & Oberg, 2001) and the concomitant solubilisation of calcium phosphate and reduction in casein-bound calcium. These changes would contribute to a higher degree of fusion of the calcium phosphate *para*-casein particles constituting the structural network of the cheese. However, with further maturation, σ_f and σ_{max} decreased in all cheeses (Figs. 3 and 4). The magnitude of the decrease over the 270-day ripening period is consistent with that from studies on full-fat, reduced-fat and half-fat Cheddar (Fenelon & Guinee, 2000; Guinee et al., 2000; Rynne et al., 2004) and reflects the hydrolysis of the casein (Fig. 1) and the attendant weakening of the *para*-casein matrix. Hence, linear regression indicated significant inverse correlations between pH4.6SN and σ_f ($r = -0.7$ to -0.8 , $df = 19$) and σ_{max} ($r = -0.74$ to -0.77 , $df = 19$) after 270 d for each of the FF, RF and HF cheeses.

Reducing salt content from 1.9 to 1.2 or 0.9% resulted in a significant decrease in the mean σ_f and σ_{max} of the FF, RF and HF cheeses over the 270-day ripening period (Table 3), with the decrease being most pronounced at ripening times ≥ 120 d (Fig. 3a,b,c and Fig 4a,b,c). This trend concurs with that of previous studies on full-fat Cheddar (Ganesan et al., 2014; Murtaza et al., 2014; Rulikowska et al., 2013) and may be least partly attributed to the increase in moisture content as salt level is reduced (Watkinson et al., 2001). However, salt content per se also exerts a concentration-dependent effect on *para*-casein hydration and the

volume fraction of the casein network, and is, thereby, likely to influence cheese rheology (Pastorino et al., 2003; Paulson et al., 1998). The effect of salt on casein hydration and swelling in cheese is corroborated by the results of a model study involving the holding of cylinders of unsalted Cheddar curd (~ 7 g) in NaCl solutions (brines with a volume of ~ 200 mL and preserved with NaN₃) of varying concentrations (0–25%, w/w); casein hydration (as measured by brine-soluble protein after 1, 2 or 3 d) increased progressively with NaCl content of the brine to 6%, and thereafter rapidly decreased as the NaCl content was further increased to ≥ 7% (w/w) (Everett et al., 2014). Hence, incremental reduction of salt content of the FF cheese was found to give a progressive reduction in the WPR at 85% RH, with values ranging from 0.90 g g⁻¹ for the FFFS to 0.58 g g⁻¹ for the FFHS cheese (Fig. 2; Table 5). Similarly, reducing S/M content from 3.0 down to 0.25% in Muenster cheese was found to reduce the degree of casein swelling and hardness, despite the increase in the moisture content of the cheese (Pastorino et al., 2003).

The σ_f and σ_{max} of the FS, RS and HS cheeses were significantly affected by fat content and the interaction of fat and ripening time, with the mean values over the 270-day ripening period decreasing in the following order: HF > RF > FF (Table 4; Fig. 3d,e,f and Fig. 4d,e,f). The inverse relationship between fat content and σ_f or σ_{max} is consistent with previous studies (Fenelon & Guinee, 2000; Rudan et al., 1999) and mirrors the inverse relationship between contents of fat and protein (*para*-casein), the principal structural components controlling the extent of deformation on application of stress (Guinee, 2015). Hence, linear regression indicated significant positive relationships between protein content (which increased as fat content was reduced) and σ_f ($r = 0.7$ to 0.8 , $df = 19$) and σ_{max} ($r = 0.8$ to 0.9 , $df = 19$) for the FS, RS and HS cheeses.

There was a significant interaction between salt and fat on σ_f or σ_{max} at times ≥ 90 d (Table 6), with the decrease in both parameters on reducing salt content becoming more

pronounced as the fat content was also reduced (Fig. 3a,b,c). This trend is consistent with the higher magnitude of the moisture increase, concomitant with salt reduction, as the fat content of the cheese was reduced (Table 1).

3.4.2. Fracture strain

The fracture strain (ϵ_f) of the FF, RF and HF cheeses was significantly influenced by salt, ripening time and the interaction of salt and ripening time (Table 3; Fig. 5). The ϵ_f increased significantly in most cheeses during the first 150 to 210 d and thereafter decreased on further ripening. Similarly, Watkinson et al. (2001) found that ϵ_f of model semi-hard cheeses increased continuously over an 87 d ripening at 4 °C to an extent dependent on pH in the range 5.2–5.8. This trend contrasts with that reported by Visser (1991), who found that the ϵ_f of Gouda cheese decreased continuously with time over a 9 mo ripening period. However, unlike the cheeses in the current study and that of Watkinson et al. (2001), where the moisture remained constant during ripening, the moisture content of the Gouda cheese decreased from ~ 43% at 2 weeks to ~ 37% at 9 mo (Visser, 1991).

The mean ϵ_f over the 270-day ripening period was significantly affected by salt content in the FF, RF and HF cheeses, but with the trend differing according to fat content. While the ϵ_f of the FFFS was higher than that of FFRS or FFHS (Fig. 5a), the ϵ_f of the RFFS and HFFS was lower than that of the corresponding RFRS and RFHS cheeses (Fig. 5b), and HFRS and HFHS cheeses (Fig. 5c). The increase in ϵ_f with S/M in RF and HF cheeses is consistent with an increase in casein hydration (Everett et al., 2014) and attendant swelling of the *para*-casein network (Paulson et al., 1998), factors that would lead to a more continuous *para*-casein network that in turn would be capable of greater displacement before fracture (Guinee, 2015). Similarly, the reduction in the ϵ_f of FF cheese as salt content was reduced is consistent with the reduction in pH (McCarthy et al., 2015). The difference between the FF

and the RF or HF cheeses in the response of fracture strain to salt content probably relates to differences in pH and the interactive effect of salt and pH on ϵ_f . Visser (1991) showed the ϵ_f of model Gouda cheeses increased significantly with S/M in the range 0.1 to 3.3%, remained relatively constant in the range 3.3 to 5.3% and decreased sharply as % S/M was increased further to 6%. Separately, Visser (1991) found that the ϵ_f of Gouda cheese increased significantly with pH in the range 5.0 to 5.42, and that the pH at which ϵ_f was maximum occurred at pH 5.25–5.35, becoming higher as ripening time increased from 1 week to 3 mo. Similarly, Watkinson et al. (2001) found that the pH of the model Cheddar-type cheese increased with pH in the range 5.2–5.8. Hence, while the negative effect of salt reduction on ϵ_f is exacerbated by the concomitant reduction in pH in the FF cheese (from 5.31 in the FFFS cheese to 5.12 in the FFHS cheese), it is off-set by the relatively high pH of the RF and HF cheeses (~ 5.26–5.35 in the FS, RS and HS variants) (Table 1).

The ϵ_f was affected by fat and the interaction of fat and ripening time in the RS and HS cheeses, but was unaffected by fat in the FS cheeses (Table 4, Fig. 5d,e,f). The mean ϵ_f over the 270 d ripening period in the RS and HS cheeses was lower in the FF variant than in the corresponding RF or HF variants, which were similar. In contrast, fat content had no effect on the ϵ_f of the FS cheeses. The difference in the response of ϵ_f to fat in the FS cheeses compared with the RS or HS cheeses may be related to the effect of pH, with an increase in pH in the region 5.0–5.4 resulting in higher ϵ_f (Visser, 1991; Watkinson et al., 2001). For the cheeses in the current study, the mean pH of the FFRS cheese over the 270-day ripening period was significantly lower than that of the corresponding RFRS and HFRS (pH 5.14 versus 5.26 and 5.31, Table 1) and that of FFHS cheese was lower than that of the RFHS and HFHS (pH 5.12 versus 5.26 and 5.31, Table 1); however, the mean pH of the FS cheese (~ 5.33) was unaffected by fat content (Table 1; McCarthy et al., 2015). The current results (higher ϵ_f in RFRS and HFRS compared with FFRS, and in RFHS and HFHS compared with

FFHS) also concur with the general observation of cheese becoming more brittle as the pH is reduced in the region 5.4–5.0, owing to a reduction in the degree of hydration of the *para*-casein matrix (Creamer, 1985) and its ability to flow when displaced.

There was a significant interaction between salt and fat on ϵ_f at times ≥ 90 d (Table 6, Fig. 5), with the increase in ϵ_f on reducing fat content becoming more pronounced as the salt content is reduced (Fig. 5d,e,f).

3.5. *Physical characteristics of the heated cheese*

3.5.1. *Flow*

The flow of the cheese, as measured using the Schreiber method, was significantly affected by salt level, ripening time, and the interaction of salt and ripening time in the FF, RF and HF cheeses (Table 3; Fig. 6). The mean flow of all cheeses increased significantly during maturation, with the extent of flow being most marked during the first 30 d. This trend is similar to that reported previously for various cheese types including Cheddar and Cheddar-style cheeses (Guinee et al., 2000; Olson, Van Hekken, Tunick, Soryal, & Zengc, 2007) and Mozzarella (Henneberry et al., 2015; McMahon, Paulson, & Oberg, 2005). The age-related increase in flow has been attributed to increases in casein hydrolysis and hydration (Guinee et al., 2000; Paulson et al., 1998). Hence, regression analysis of the data for pH4.6SN over ripening time indicated a logarithmic relationship correlation between pH4.6SN and extent of flow for the FF ($R^2 = 0.71$; df, 19), RF ($R^2 = 0.86$; df, 19) and HF ($R^2 = 0.81$; df, 19) cheeses.

Salt significantly affected the mean flow over ripening, with the mean flow of the RS and HS variants of the FF, RF and HF cheeses being significantly higher than the corresponding FS variants (Fig. 6a,b,c). There was a significant interactive effect between

salt level and ripening time in the FF, RF and HF cheeses, with the difference between FS and the RS or HS variants for each fat level increasing during the initial 30 d of ripening. The increase in flow on reducing salt level from 1.9% to 1.2% or 0.9% (w/w) concurs with the results previous studies on Mozzarella in which salt was varied in range ~ 0.7–1.9% (Ganesan et al., 2014; Henneberry et al., 2015), and is most likely associated with the concomitant increases in moisture content.

Fat had an effect opposite to that of salt on flow, which decreased on reducing fat from 33% to 22% in the FS, RS and HS cheeses (Table 4; Fig. 6d,e,f), and from 22% to 16% in the FS cheese. The lower flow in the RF and HF cheeses is consistent with the increases in the volume fraction of the calcium phosphate *para*-casein network and intact casein content, and reductions in moisture-to-protein ratio and fat level; consequently less free moisture and free fat are available during heating to lubricate the relative displacement of contiguous planes of the melting cheese mass (Guinee et al., 2000; Pastorino et al., 2002; Rudan & Barbano, 1998). As the concentration of protein increases, the calcium phosphate *para*-casein (network) becomes more fused and continuous, making displacement of adjoining planes, and hence, flow, more difficult especially as the level of free fat decreases simultaneously (Guinee et al., 2000). While free fat and free moisture contribute to flow of heated cheese, the role of free-fat as being preponderant has been demonstrated by comparison of the functionality of Cheddar cheese (33% fat) made from control or homogenised milk (Guinee et al., 2000). In the control cheese, heating was paralleled by the extensive coalescence of fat globules and the melted cheese was glossy, moist, succulent, flowable and fluid; in contrast, the fat globules in the cheese made from the homogenised milk at respective first and second stage pressures of 25 and 5 MPa remained intact and discrete during heating and the heated cheese was ‘dry’, matt and non-fluid. The results of Wadhwani, McManus, and McMahon (2011) suggest that adequate free fat at the surface the melting cheese (~ 10 mg g⁻¹ cheese),

as a result of migration of free oil from pools of non-globular fat extant within the cheese matrix or created as a result of heat-induced coalescence fat globules, is necessary to prevent dehydration and drying-out during cooking; apart from crusting and burning, dehydration leads to concentration of protein and exacerbates flow restriction.

While there was a significant interactive effect between salt and fat on the flow at all sampling times, the effect of fat level was much greater than that of salt (Fig. 6).

3.5.2. *Extensibility*

Molten Mozzarella typically forms into strings when extended uniaxially; at a microstructural level, the strings correspond to layers of unidirectional-oriented proteins (fibres) that overlap to varying degrees. Cheese stringiness is especially desirable in pizza, in which Cheddar cheeses is frequently used an adjunct to Mozzarella to impart flavour and browning (Barrett, 2013). The work to extend (EW) of the 270 day-old cheeses was an index of energy or work required to pull the molten cheese mass into strings. The EW values for the full-fat cheeses (211 to 319 mJ) are similar in magnitude to those reported for Kashkaval-type cheeses (Guinee et al., 2015).

The EW decreased significantly as the salt content was reduced in FF, RF and HF cheeses and increased as the fat content was reduced in FS, RS and HS cheeses (Table 5), indicating that molten cheese becomes increasingly tougher and more difficult to string or extend as the fat content was reduced, and easier as salt content is reduced. Hence, there was a significant effect of the interaction between salt and fat on EW, with the percentage increase in EW with fat reduction becoming higher as salt content was increased from 0.9 to 1.9% (w/w). These trends concur with those reported by Henneberry et al. (2015) for Mozzarella-style cheeses varying in fat (11 or 23%) and salt content (0.9 or 1.7%, w/w).

Similar to flow, the effects of salt and fat on EW are likely to be associated with the respective increases in protein and moisture content as the levels of salt and fat are reduced.

4. Conclusion

The effects of reducing salt level (% w/w) from 1.9 (full-salt) to 1.2 (reduced-salt) or 0.9 (half-salt) on the water-to-protein ratio, proteolysis, fracture behaviour (fracture stress, firmness and fracture strain) and cooking characteristics of Cheddar-style cheeses with fat levels (% w/w) of 33 (full-fat), 22 (reduced-fat) or 16 (half-fat), were investigated. The results show the response to salt reduction depended on the extent of salt reduction and the variable studied. Hence, while the fracture stress, firmness and work to extend or string (the molten cheese) decreased in the FF, RF and HF cheeses, the heat-induced flow and the fracture strain of the RF and HF cheeses increased and that of the FF decreased on reducing salt content. These effects occurred mostly on reducing salt from 1.9% to 1.2%, with further reduction of salt to 0.9% having no effect. Generally, reducing fat content was associated with effects opposite to those found on reducing salt: increases in the fracture stress, firmness, fracture strain and work to extend melted cheese, and a reduction in flow on heating. However, the response to altering fat level in cheeses of different salt content depended on both variable and salt level. There were significant interactive effects of fat and salt content on the fracture properties, flow and EW at 90, 150, 210 and 270 d. The effects of salt and fat on the fracture and cooking characteristics were associated with their effects on moisture content, pH, casein hydration and casein hydrolysis. The current study formed part of a project entitled Cheese Board 2015 (<http://www.cheeseboard2015.com>), with the task of developing a knowledge platform that would assist the commercial development of reduced-salt, reduced-fat, dry-salted cheeses. The effects of reducing salt and fat on the composition

and changes in lactose metabolism, water activity and microbiology of Cheddar cheese, made from the same milk under standardised conditions, during ripening has already been reported (McCarthy et al., 2015). The effects of salt and fat reduction on free fatty acid and free amino acid profiles, volatile compounds and sensory analysis of the unheated and heated cheeses will form the topic of a later communication. The current findings together with latter studies should assist the development of production strategies for Cheddar-style cheeses with varying degrees of salt and fat reduction.

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Table 1.

Effect of salt and fat reduction on the gross composition and pH of Cheddar-style cheeses. ^a

Cheese code	Fat (%, w/w)	Moisture (%, w/w)	Protein (%, w/w)	NaCl (%, w/w)	S/M (%, w/w)	pH
Full-fat, full-salt (FFFS)	33.8 ^{aA}	35.3 ^{bC}	25.9 ^{aB}	1.9 ^{aA}	5.5 ^{aA}	5.31 ^{aA}
Full-fat, reduced-salt (FFRS)	33.0 ^{abA}	37.4 ^{abC}	25.9 ^{aB}	1.3 ^{bA}	3.4 ^{bA}	5.14 ^{bC}
Full-fat, half-salt (FFHS)	32.5 ^{bA}	37.9 ^{aB}	24.9 ^{aB}	0.9 ^{cA}	2.3 ^{cA}	5.12 ^{bC}
Reduced-fat, full-salt (RFFS)	23.2 ^{aB}	38.9 ^{cB}	33.3 ^{aA}	1.9 ^{aA}	4.7 ^{aB}	5.32 ^{aA}
Reduced-fat, reduced-salt (RFRS)	22.8 ^{abB}	40.3 ^{bB}	31.4 ^{aA}	1.3 ^{bA}	3.3 ^{bAB}	5.26 ^{aB}
Reduced-fat, half-salt (RFHS)	22.7 ^{bAB}	40.9 ^{aA}	32.2 ^{aA}	0.9 ^{cA}	2.3 ^{cA}	5.26 ^{aB}
Half-fat, full-salt (HFFS)	16.5 ^{aC}	41.3 ^{bA}	34.2 ^{aA}	1.9 ^{aA}	4.7 ^{aB}	5.35 ^{aA}
Half-fat, reduced-salt (HFRS)	16.3 ^{aC}	43.2 ^{aA}	33.9 ^{aA}	1.2 ^{bA}	2.8 ^{bC}	5.31 ^{aA}
Half-fat, half-salt (HFHS)	16.2 ^{aB}	43.6 ^{aA}	33.6 ^{aA}	0.9 ^{cA}	1.9 ^{cA}	5.31 ^{aA}

^a The composition was measured at 14 d; the presented pH is the mean of the pH values measured at 1, 14, 30, 90, 120, 180, 210 and 270 d. Data are the mean values of three replicate trials; values within a column relating to full-fat cheese, reduced-fat cheese or half-fat cheese and not sharing a common lower-case superscript letter differ significantly ($P < 0.05$) for the statistical effect of salt; values within a column relating to full-salt, reduced-salt or half-salt cheeses and not sharing a common upper-case superscript letter differ significantly ($P < 0.05$) for the effect of fat.

12 **Table 2**
 13
 14 Percentages of different caseins in 150 and 270 day-old Cheddar-style cheeses. ^a
 15

Casein	Cheese code								
	Full-fat, full-salt (FFFS)	Full-fat, reduced-salt (FFRS)	Full-fat, half-salt (FFHS)	Reduced-fat, full-salt (RFFS)	Reduced-fat, reduced-salt (RFRS)	Reduced-fat, half-salt (RFHS)	Half-fat, full-salt (HFFS)	Half-fat, reduced-salt (HFRS)	Half-fat, half-salt (HFHS)
150 day-old cheese									
Intact β -casein	30.7 ^{aA}	30.3 ^{aA}	29.9 ^{aA}	30.1 ^{aA}	28.0 ^{aA}	28.8 ^{aA}	27.5 ^{aA}	26.4 ^{aB}	26.7 ^{aB}
Intact α_{S1} -casein	8.8 ^{aC}	7.7 ^{bC}	7.4 ^{bC}	14.7 ^{aA}	8.8 ^{bB}	8.3 ^{bB}	11.4 ^{aB}	9.2 ^{bA}	9.3 ^{bA}
α_{S1} -casein (f24–199)	21.6 ^{aA}	21.9 ^{aB}	21.4 ^{aB}	19.4 ^{aB}	20.5 ^{aB}	20.3 ^{aB}	21.2 ^{bA}	25.7 ^{aA}	24.6 ^{aA}
270 day-old cheese									
Intact β -casein	30.1 ^{aA}	29.8 ^{abA}	26.4 ^{bA}	29.3 ^{aA}	27.8 ^{abA}	25.9 ^{bA}	27.2 ^{aB}	25.4 ^{aB}	26.4 ^{aA}
Intact α_{S1} -casein	6.4 ^{aB}	6.1 ^{aA}	6.3 ^{aA}	14.1 ^{aA}	6.2 ^{bA}	6.1 ^{bA}	7.1 ^{aB}	5.9 ^{bA}	5.6 ^{bA}
α_{S1} -casein (f24–199)	20.4 ^{aB}	20.5 ^{aB}	17.4 ^{aC}	20.8 ^{bB}	21.9 ^{abB}	24.2 ^{aB}	23.6 ^{bA}	26.8 ^{aA}	27.1 ^{aA}

16
 17 ^a Values within a row relating to full-fat cheese, reduced-fat cheese or half-fat cheese and not sharing a common lower-case superscript letter differ
 18 significantly ($P < 0.05$) for the statistical effect of salt; values within a row relating to full-salt, reduced-salt or half-salt cheeses and not sharing a
 19 common upper-case superscript (A, B, C) differ significantly ($P < 0.05$) for the effect of fat.
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Table 3

Statistical significances (*P*-values) for changes in pH 4.6 soluble nitrogen (pH4.6SN), firmness, fracture stress, fracture strain and flow in full-fat, reduced-fat and half-fat Cheddar-style cheeses with different salt levels. ^a

Factor	pH4.6SN	Fracture stress	Firmness	Fracture strain	Flow
Full-fat cheese					
<i>Main plot</i>					
Salt content (SC)	-	***	***	*	***
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (SC × RT)	-	***	*	**	***
Reduced-fat cheese					
<i>Main plot</i>					
Salt content (SC)	-	***	*	**	***
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (SC × RT)	-	***	*	*	**
Half-fat cheese					
<i>Main plot</i>					
Salt content (SC)	*	***	*	**	**
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (SC × RT)	-	***	*	*	*

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27 ^a Differences in contents of salt and fat are given Table 1. There were 2 degrees of freedom (df) for salt content, 6 for ripening time (except in the case
28 of pH4.SN where there were 5) and 12 for interaction of salt and ripening time (except in the case of pH4.6SN where there were 10). The significance
29 for changes in the studied parameters are presented as follows: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.00$.

30 **Table 4**

31 Statistical significances (*P*-values) for changes in pH 4.6 soluble nitrogen (pH4.6SN), firmness, fracture stress, fracture strain and flow in full-salt,
 32 reduced-salt and half-salt Cheddar-style cheeses with different fat levels. ^a

Factor	pH4.6SN	Fracture stress	Firmness	Fracture strain	Flow
Full-salt cheese					
<i>Main plot</i>					
Fat content (FC)	***	***	***	-	**
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (FC × RT)	-	**	*	-	*
Reduced-salt cheese					
<i>Main plot</i>					
Fat content (FC)	**	**	**	*	***
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (FC × RT)	*	*	**	**	*
Half-salt cheese					
<i>Main plot</i>					
Fat content (FC)	**	***	***	**	***
<i>Sub-plot</i>					
Ripening time (RT)	***	***	***	***	***
Interaction (FC × RT)	-	**	***	**	**

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 34 ^a Differences in contents of salt and fat are given Table 1. There were 2 degrees of freedom (df) for salt content, 6 for ripening time (except in the case
 35 of pH4.SN where there were 5) and 12 for interaction of salt and ripening time (except in the case of pH4.6SN where there were 10). The significance
 36 for changes in the studied parameters are presented as follows: *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.00.

Table 5

Effect of salt and fat reduction on the proteolysis, rheology and heat-induced parameters of 270 day-old Cheddar-style cheeses.^a

Parameters	Cheese code								
	Full-fat, full salt (FFFS)	Full-fat, reduced-salt (FFRS)	Full-fat, half-salt (FFHS)	Reduced-fat, full-salt (RFFS)	Reduced-fat, reduced-salt (RFRS)	Reduced-fat, half-salt (RFHS)	Half-fat, full-salt (HFFS)	Half-fat, reduced-salt (HFRS)	Half-fat, half-salt (HFHS)
pH4.6SN (%TN)	20.9 ^{aA}	21.7 ^{aA}	22.5 ^{aA}	17.8 ^{aAB}	19.4 ^{aA}	17.8 ^{aA}	14.1 ^{aB}	17.1 ^{aA}	20.0 ^{aA}
Fracture stress (kPa)	374.5 ^{aC}	286.8 ^{bC}	241.4 ^{bC}	698.8 ^{aB}	534.3 ^{bB}	481.2 ^{bB}	943.2 ^{aA}	712.9 ^{bA}	652.4 ^{cA}
Firmness (N)	311.3 ^{aC}	273.1 ^{bB}	234.1 ^{cC}	527.3 ^{aB}	415.9 ^{bA}	346.1 ^{cB}	664.8 ^{aA}	493.9 ^{bA}	455.3 ^{bA}
Fracture strain	0.49 ^{aB}	0.41 ^{bB}	0.40 ^{bB}	0.50 ^{bAB}	0.57 ^{aA}	0.58 ^{aA}	0.58 ^{aA}	0.61 ^{aA}	0.61 ^{aA}
Flow (%)	51.6 ^{bA}	60.9 ^{aA}	61.9 ^{aA}	30.7 ^{bB}	34.1 ^{abB}	39.43 ^{aB}	23.51 ^{bB}	29.78 ^{aB}	32.72 ^{aB}
WPR	0.16 ^{aA}	0.13 ^{bB}	0.08 ^{cB}	0.11 ^{bB}	0.15 ^{aA}	0.10 ^{bA}	0.11 ^{aB}	0.11 ^{aC}	0.11 ^{aA}
EW (mJ)	319 ^{aB}	228 ^{bB}	211 ^{bC}	443 ^{aB}	355 ^{bB}	308 ^{bB}	806 ^{aA}	511 ^{bA}	458 ^{bA}

^a Abbreviations are: pH4.6SN, pH4.6 soluble nitrogen; WPR, water-to-protein ratio at 5% relative humidity; EW, work required to extend cheese to 380 mm; Max force, maximum force required to extend the molten cheese. Data are the mean values of three replicate trials. Values within a row relating to full-fat cheese, reduced-fat cheese or half-fat cheese and not sharing a common lower-case superscript letter differ significantly ($P < 0.05$) for the statistical effect of salt. Values within a row relating to full-salt, reduced-salt or half-salt cheeses and not sharing a common upper-case superscript letter differ significantly ($P < 0.05$) for the effect of fat.

Table 6

Interactive effects of salt and fat reduction on proteolysis, rheology and heat-induced parameters during ripening of Cheddar-style cheeses^{a, b, c, d}

Parameters	Interaction (salt × fat content)					
	Day 14	Day 30	Day 90	Day 150	Day 210	Day 270
pH4.6SN (%TN)	-	-	-	-	-	-
Fracture stress (kPa)	-	-	**	**	**	**
Firmness (N)	-	*	**	**	**	***
Fracture strain	-	-	*	*	**	**
Flow (%)	-	*	**	**	**	**
WPR						**
EW (mJ)						**

^a Abbreviations are: pH4.6SN, pH4.6 soluble nitrogen; WPR, water-to-protein ratio at 5% relative humidity; EW, work required to extend cheese to 380 mm (EW was measured after 270 d of ripening only). Data are the mean values of three replicate trials. The significance of the interactive effects of salt and fat are presented as follows: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.00$.

Figure legends

Fig. 1. Changes in levels of pH 4.6 soluble-nitrogen (pH4.6SN) in Cheddar-style cheeses with different salt and fat levels during ripening. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■) and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Fig. 2. Moisture desorption isotherms for 270 day-old Cheddar-style cheeses with different salt and fat levels. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■) and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Fig. 3. Changes in fracture stress (δ_f) in Cheddar-style cheeses with different salt and fat levels during ripening. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■) and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Fig. 4. Changes in firmness ($\delta_{\max}$) in Cheddar-style cheeses with different salt and fat levels during ripening. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■)

and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Fig. 5. Changes in fracture strain (ϵ_f) in Cheddar-style cheeses with different salt and fat levels during ripening. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■) and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Fig. 6. Changes in flow on heating Cheddar-style cheeses with different salt and fat levels during ripening. The cheeses, described in Table 1, include: full-salt (●), reduced-salt (■) and half-salt (▲) variants of full-fat (a), reduced-fat (b) and half-fat (c) cheeses, and full-fat (○), reduced-fat (□) and half-fat (△) variants of full-salt (d), reduced-salt (e) and half-salt (f) cheeses. Presented values are the means of three replicate trials; error bars represent standard deviations of the mean.

Figures

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.