Impact of fat reduction on flavor and flavor chemistry of Cheddar cheeses

M. A. Drake,^{*1} R. E. Miracle,^{*} and D. J. McMahon[†]

^{*}Department of Food, Bioprocessing and Nutritional Sciences, Southeast Dairy Food Research Center, North Carolina State University, Raleigh 27695

[†]Western Dairy Center, Utah State University, Logan 84322-8700

ABSTRACT

A current industry goal is to produce a 75 to 80% fat-reduced Cheddar cheese that is tasty and appealing to consumers. Despite previous studies on reduced-fat cheese, information is critically lacking in understanding the flavor and flavor chemistry of reduced-fat and nonfat Cheddar cheeses and how it differs from its full-fat counterpart. The objective of this study was to document and compare flavor development in cheeses with different fat contents so as to quantitatively characterize how flavor and flavor development in Cheddar cheese are altered with fat reduction. Cheddar cheeses with 50% reduced-fat cheese (RFC) and low-fat cheese containing 6% fat (LFC) along with 2 full-fat cheeses (FFC) were manufactured in duplicate. Cheeses were ripened at 8°C and samples were taken following 2 wk and 3, 6, and 9 mo for sensory and instrumental volatile analyses. A trained sensory panel ($n = 10$ panelists) documented flavor attributes of cheeses. Volatile compounds were extracted by solid-phase microextraction or solvent-assisted flavor evaporation followed by separation and identification using gas chromatography-mass spectrometry and gas chromatography-olfactometry. Selected compounds were quantified using external standard curves. Sensory properties of cheeses were distinct initially but more differences were documented as cheeses aged. By 9 mo, LFC and RFC displayed distinct burnt/rosy flavors that were not present in FFC. Sulfur flavor was also lower in LFC compared with other cheeses. Forty aroma-active compounds were characterized in the cheeses by headspace or solvent extraction followed by gas chromatography-olfactometry. Compounds were largely not distinct between the cheeses at each time point, but concentration differences were evident. Higher concentrations of furanones (furanol, homofuranol, sotolon), phenylethanal, 1-octen-3-one, and free fatty acids, and lower concentrations of lactones were present in LFC compared with FFC after 9 mo of ripening. These results confirm that flavor dif-

ferences documented between full-fat and reduced-fat cheeses are not due solely to differences in matrix and flavor release but also to distinct differences in ripening biochemistry, which leads to an imbalance of many flavor-contributing compounds.

Key words: cheese, fat reduction, low fat, flavor chemistry

INTRODUCTION

Flavor remains a driving force for cheese purchase and consumption (Drake et al., 2008a,b; Childs and Drake, 2009). Trends toward healthier eating have provided an increased interest in lower fat cheeses (Gerdes, 2005). However, fat reduction in Cheddar cheese results in appearance, flavor, and texture changes (Mistry, 2001; Banks, 2004), and consumer perception of low- and reduced-fat cheese has not traditionally been positive, an attitude that continues today (Childs and Drake, 2009).

Lower fat cheeses are made from lower fat milks and thus have higher protein to fat ratios than full-fat cheeses. To compensate for the increased protein concentration and firmer texture, water may be added back into the cheeses by several different make-procedure alterations, but the fundamental composition of the cheeses is still altered (Johnson and Chen, 1995). Many studies have documented the effect of up to 50% fat reduction on flavor and texture properties of Cheddar cheeses (Drake and Swanson, 1996; Drake et al., 1997; Gwartney et al., 2002; Yates and Drake, 2007). More recently, Rogers et al. (2009) evaluated the sensory texture and rheological properties of Cheddar cheeses with different fat contents manufactured using identical manufacture procedures, rennet, and starter culture. This study enabled a precise understanding of the effect of modest to extreme fat reduction on texture and mechanical properties. To our knowledge, no studies have documented the sensory properties of cheeses with greater than 50% fat reduction across ripening. Low-fat cheese is defined as having 3 g of fat or less per reference amount, which equates to more than a 75% fat reduction for Cheddar cheese (CFR 21 [101.62b]; FDA-DHHS, 2002).

Received April 18, 2010.

Accepted July 30, 2010.

¹Corresponding author: mdrake@unity.ncsu.edu

Very few studies have investigated the flavor chemistry effect of fat reduction in cheese. Milo and Reineccius (1997) evaluated aroma-active compounds from one commercial full-fat Cheddar cheese and one commercial 40% fat-reduced Cheddar cheese purchased on the retail market. Sensory analysis was not conducted. They reported distinct differences between the 2 cheeses in the concentrations of several aroma-active volatiles, but cheeses from different manufacturers can vary widely in flavor (Drake et al., 2008a, 2009) so without experimental controls or analysis of multiple samples, it was not possible to confirm that observed differences were due solely to fat content. More recently, Carunchia Whets-tine et al. (2006) evaluated the sensory properties and volatile profiles of Cheddar cheeses with and without the fat removed by a novel process. They found that flavor profiles of full-fat cheese and the same full-fat cheese with the fat removed after ripening were almost identical. Further, volatile and aroma-active compounds between the cheeses with and without the fat removed were similar. These results, in combination with those from Milo and Reineccius (1997), suggest that the flavor differences documented in fat-reduced cheeses are not solely the result of altered texture and changes in volatile compound release but are also the result of altered biochemistry and a different array or balance of volatile compounds produced between full-fat and fat-reduced cheeses during ripening. A complete understanding of the effect of fat reduction on sensory properties and volatile compound differences may enable identification of methods to enhance the flavor properties of cheeses with fat reduction. Because most consumers have indicated they are not willing to sacrifice flavor or texture in fat-reduced cheese (Childs and Drake, 2009), it is crucial to have a better understanding of the impact of fat reduction on cheese sensory properties and flavor-contributing compounds.

The purpose of this study was to determine the effect of fat reduction on the sensory properties and flavor chemistry of Cheddar cheeses and how these parameters affect cheese ripening. This study was part of a multi-university investigation to evaluate low-fat cheese. Cheese manufacture and chemical analysis were conducted at Utah State University (Logan). Cheeses were shipped on ice by overnight carrier to North Carolina State University (Raleigh) at each time point for sensory and volatile compound analysis.

MATERIALS AND METHODS

Cheddar Cheese Production

Fresh cow milk was obtained from Utah State University's Caine Dairy Research and Teaching Center

(Wellsville, UT) and transported to the Gary Haight Richardson Dairy Products Laboratory (Logan, UT). Milk was standardized to protein to fat ratios of 0.83, 1.9, and 5.0 for making full-fat, 50% reduced-fat, and low-fat cheeses, respectively, and then pasteurized at 73°C for 15 s. When making low-fat cheese, milk (682 kg) was cooled to 10°C and poured into a Tetra Scherping horizontal cheese vat (Tetra Pak Cheese and Powder Systems Inc., Winsted, MN), acidified to pH 6.25 with distilled white vinegar (Heinz North America, Pittsburgh, PA), and then warmed to the set temperature. Four cheeses (in duplicate) were made in randomized order using the procedure described by Rogers et al. (2009). This included 2 full-fat cheeses (**FFC1** and **FFC2**) that differed only in inclusion of a curd washing while making FFC2, 1 reduced-fat cheese (**RFC**), and 1 low-fat cheese (**LFC**). All of the cheeses used a single-strain *Lactococcus lactis* ssp. *lactis* starter culture (M70, Danisco USA Inc., New Century, KS). Double-strength chymosin (Maxiren) and single-strength annatto cheese color were from DSM Food Specialties, USA Inc. (Eagleview, PA). The cheeses were stored at 8°C for 9 mo, with sample blocks shipped to North Carolina State University for sensory flavor profiling and volatile compound analysis at 0.5, 3, 6, and 9 mo of age.

Cheeses were received at North Carolina State University at each time point by overnight shipment on cold packs. Upon receipt, cheeses were carefully examined for damage and then placed at 3°C in the dark until sensory and instrumental analyses. Cheese blocks were removed from vacuum-sealed packaging and 1 cm was trimmed from all sides of each block before sensory or instrumental analyses. Sensory properties and head-space volatiles of cheeses were evaluated within 1 wk of receipt. Additional samples were immediately frozen at -80°C for solvent extraction and volatile compound analysis (within 6 mo of receipt).

Descriptive Sensory Analysis

Sensory testing was conducted in compliance with the North Carolina State University Institutional Review Board for Human Subjects approval. Cheddar cheeses were cut into 3.5-cm cubes for descriptive sensory analysis. The cheeses were placed into lidded 58-mL soufflé cups with randomly generated 3-digit codes. The cheeses were tempered at 12°C for 1 h and were served at this temperature with room-temperature deionized water and unsalted crackers for palate cleansing. Descriptive analysis was conducted using a 0- to 15-point universal intensity scale with the Spectrum method (Meilgaard et al., 1999; Drake and Civille, 2003) and an established cheese flavor sensory language

(Drake et al., 2001, 2008a,b, 2009; Drake, 2007). A trained descriptive sensory panel ($n = 10$; 9 females, 1 male, ages 23–47 yr), with over 150 h of experience each with descriptive analysis of cheese flavor, evaluated the cheeses. Consistent with Spectrum descriptive analysis training, panelists were presented with reference solutions of sweet, sour, salty, and bitter tastes to learn to use the universal intensity scale (Meilgaard et al., 1999; Drake and Civille, 2003) followed by training with Cheddar cheese flavor references (Drake et al., 2001) and discussion and evaluation of Cheddar cheeses to clarify descriptor concepts and to consistently score product attributes. Analysis of variance of data collected from the last part of training indicated that the panelists could consistently use the attributes to differentiate the products.

Cheeses were evaluated by panelists monadically in a randomized balanced design. Each cheese was evaluated in triplicate by each panelist. Evaluations were conducted individually using Compusense Five v4.6 (Compusense, Guelph, Ontario, Canada) or paper ballots in an enclosed room, with positive air pressure, dedicated to sensory analysis and free from external aromas, noise, and distractions. Panelists were instructed to expectorate samples after evaluation.

Solid-Phase Microextraction GC-MS

Headspace volatiles of cheeses were evaluated by solid-phase microextraction (SPME) GC-MS. Finely grated samples of each cheese (5 g) were loaded in triplicate into 20-mL autosampler vials with steel screw tops containing silicone septa faced in Teflon (Microliter Analytical, Sawanee, FL). Internal standard solution (2-methyl-3-heptanone in methanol, Sigma-Aldrich, Milwaukee, WI) was added to each vial to control for analysis variability with samples of cheese running only after >4 h at storage temperature. A previously published study established that equilibrium occurred within 2 to 3 h with these vials and sample conditions to give consistent internal standard peak areas across samples (Leksrisompong et al., 2010). Samples were also evaluated in balanced randomized blocks to further minimize bias.

Samples were injected using a CombiPal autosampler (CTC Analytics, Zwingen, Switzerland) attached to an Agilent 6890N gas chromatograph with 5973 inert MS detection (Agilent Technologies Inc., Santa Clara, CA). Samples were maintained at 10°C before fiber exposure. Samples were equilibrated at 40°C for 25 min before 30-min fiber exposure of a 1-cm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) fiber at 31 mm with 4-s pulsed agitation at 250 rpm. Fibers were injected for 5 min at a depth of 50 mm. The GC

method used an initial temperature of 40°C for 5 min with a ramp rate of 8°C/min to 250°C held for 5 min. The SPME fibers were introduced into the split/splitless injector at 250°C. An Rtx-5ms column (30 m length $\times$ 0.25 mm inner diameter $\times$ 0.25 μ m film thickness; Restek, Bellefonte, PA) was used for all analyses at a constant helium flow rate of 1 mL/min. Purge time was set at 1 min. The MS transfer line was maintained at 250°C with the Quad at 150°C and Source at 250°C.

Solvent-Assisted Flavor Evaporation GC-MS

Solvent Extraction. Cheese was shredded and 75 g was weighed into each of four 250-mL Teflon bottles with Tefzel closures (Nalgene, Rochester, NY). Forty-five grams of sodium chloride was added into the bottles and into 1 bottle that contained no cheese, which was used as a blank or experimental control. Additionally, 20 μ L of internal standard (2-methyl-3-heptanone and 2-methyl pentanoic acid at 81 ppm in methanol) was added into each of the bottles. Diethyl ether (100 mL, EMD Chemicals, Gibbstown, NJ) was added to each bottle and they were agitated on a Roto Mix (Type 50800, Thermolyne, Dubuque, IA) for 30 min on the highest speed. Following this, bottles were centrifuged at $735 \times g$ for 10 min (Sorvall RC-5B centrifuge, DuPont Instruments, Newtown, CT). The separated solvent phase was collected into a glass jar. This step was repeated 2 more times with 50 mL of diethyl ether. The solvent phase was kept at -20°C and concentrated under a stream of nitrogen to 300 mL. This extraction procedure was performed in duplicate for each cheese.

Solvent-Assisted Flavor Evaporation. Volatile compounds from the cheese extracts were distilled using solvent-assisted flavor evaporation (SAFE; Ace Glassware, Vineland, NJ). The assembly used was similar to that described by Engel et al. (1999). A diffusion pump combined with a rotary vane pump was used as the vacuum system. The SAFE apparatus was connected to a primary trap and a secondary trap submerged in liquid nitrogen. The distillation procedure was carried out over 1 h under vacuum (10^5 Torr). The liquid sample was poured into the SAFE apparatus and introduced drop-wise into the vacuum until all of the liquid extract had been placed under vacuum conditions. The SAFE apparatus was kept at 40°C with a circulating water bath.

Phase Separation. Following SAFE, the distillate was concentrated under a gentle nitrogen stream to 20 mL. The concentrated distillate was washed twice with 3 mL of sodium bicarbonate (Fisher Scientific, Fairlawn, NJ) and mixed thoroughly. After each wash, the bottom layer, the water phase of the distillate, was removed and collected into a separate test tube. The

concentrated solvent was then washed with 2 mL of saturated sodium chloride solution 3 times. Each time, the solution was mixed thoroughly and the water phase removed and collected into the same test tube. The remaining layer was collected as the neutral/basic (**NB**) fraction. Acidic (**Ac**) volatiles were recovered by acidifying the water layer collected from the concentrated distillate with hydrochloric acid (18% wt/vol; Sigma Aldrich) to a pH of 2.0 to 2.5. The acidified sample was then extracted 3 times with 5 mL ethyl ether. All extracts were dried over anhydrous sodium sulfate (VWR International, West Chester, PA) before concentration to 0.5 mL under a nitrogen gas stream.

GC-MS of SAFE Extracts

Samples (1 μ L) for MS analysis were injected using a CombiPal autosampler with a 10- μ L direct injection syringe attached. An Agilent 6890N GC with 5973 inert quadrupole mass selective detector (**MSD**; Agilent Technologies Inc.), and a Varian CP-3380 GC/Saturn 2000 Ion Trap MSD (Varian Inc., Palo Alto, CA) was used to analyze solvent extracts. Separations were performed on a fused-silica capillary column (Rtx-5ms and Rtx-Wax; 30 m length $\times$ 0.25 mm inner diameter $\times$ 0.25 μ m film thickness; Restek). Helium at a constant flow rate of 1 mL/min was used. The oven temperature was programmed with an initial temperature of 40°C for 5 min, an increase of 8°C/min up to 250°C, and a final hold time of 10 min. Scan parameters for the MDS were set from 35 to 300 m/z . Each extract was injected in triplicate into a split/splitless injector at 250°C in splitless mode.

Gas Chromatography-Olfactometry

Gas chromatography-olfactometry (**GC-O**) analysis was performed using HP 5890 series II gas chromatographs (Hewlett-Packard Co., Palo Alto, CA) equipped with a flame-ionization detector (**FID**), a sniffing port, and a split/splitless injector. Neutral/basic and Ac fractions were analyzed from each solvent extraction. Two microliters of sample was injected using a split/splitless injector in split mode at 250°C onto a polar capillary column (Rtx-Wax; 30 m length $\times$ 0.25 mm inner diameter $\times$ 0.25 μ m film thickness; Restek) and a nonpolar capillary column (Rtx-5ms; 30 m length $\times$ 0.25 mm inner diameter $\times$ 0.25 μ m film thickness; Restek). The volatiles extracted by SPME were also injected and sniffed on both polar and nonpolar columns using 2-cm DVB/CAR/PDMS fibers and a narrow-bore SPME injection liner. Cheese sample for SPME GC-O were prepped by the same method as that of samples

for SPME GC-MS but without the addition of internal standard.

Column effluent was split 1:1 between the FID and the sniffing port using deactivated fused-silica capillaries (1 m length $\times$ 0.25 mm inner diameter). The GC oven temperature was programmed from 40°C to 200°C at a rate of 10°C/min with an initial hold for 3 min and final hold of 20 min. The FID was maintained at a temperature of 300°C, and the sniffing port was maintained at 105°C. The sniffing port was supplied with humidified air at 30 mL/min. The post-peak intensity of aroma-active compounds was evaluated (Van Ruth, 2001). Each extract, or duplicate fibers from each cheese replicate, was sniffed in duplicate by 2 experienced sniffers, each with >50 h of experience on GC-O of dairy products, on both polar and nonpolar columns.

Aroma Extract Dilution Analysis

Aroma extract dilution analysis (**AEDA**) was performed on solvent extracts under the same conditions as those for post-peak intensity GC-O. The NB fractions were injected onto the nonpolar capillary column and the Ac fractions were injected onto the polar capillary column. Each sample was diluted stepwise at a ratio of 1:3 (vol/vol) with diethyl ether. Samples were evaluated by 2 experienced sniffers until no odors were detected. The greatest dilution in which a compound was sniffed was reported as the flavor dilution (**log₃ FD**) factor (Grosch, 1993).

Volatile Compound Identification

Volatile compounds from SAFE and SPME extractions were identified using the NIST 2005 library of spectra and comparison of spectra of authentic standards injected under identical conditions. Relative abundance of compounds was calculated using the calculated recovery of the internal standard concentration to determine relative concentrations of each compound. Retention indices were calculated (van den Dool and Kratz, 1963) using an alkane series (Sigma Aldrich). For verification of aroma-active compound identity, retention index and aroma properties were also compared with authentic standards injected under identical conditions.

Quantification of Odorants

Eighteen compounds (acetic acid, butyric acid, hexanoic acid, octanoic acid, furaneol, homofuraneol, sotolone, δ -decalactone, γ -decalactone, δ -dodecalactone,

1-octen-3-one, 2,3-butanedione, methional, dimethyl trisulfide, 2-acetyl-thiazoline, skatole, phenyl acetic acid, and phenyl ethanol) were selected for quantification because of their different polarities and because current AEDA results as well as previous studies showed differences in these compounds with differences in fat content (Milo and Reineccius, 1997). Concentrations of selected compounds were calculated using a 5-point standard curve (minimum $R^2 > 0.92$). The curve was constructed by the direct addition of known amounts of standards to odor-free water before solvent extraction—SAFE. The NB fraction compound concentrations were determined on a Rtx-5ms column using GC-MS and the Ac fraction compound concentrations on a Rtx-Wax column using GC-MS. All standards were obtained from Aldrich Chemical Company (St. Louis, MO).

Statistical Analysis

Analysis of variance was conducted to determine if differences existed in sensory properties or volatile compound relative abundances using XL-STAT (version 2009, 1995–2009, Addinsoft, Paris, France). Principal component analysis was also applied to the correlation matrix of sensory and volatile component data individually to visualize how products were differentiated across sensory attributes or volatile components. Partial least squares regression (PLS) was applied to volatile and sensory data to further identify possible relationships between volatile aroma-active compounds and specific flavors (XL-STAT). Concentrations for the 14 non-free fatty acid compounds were set as the explanatory variables against the sensory mean flavor attributes as dependent variables (taste attributes were not used in the model). The sum of the coefficients of determination for the dependent variables (R^2Y cumulative) yielded the percent variability in sensory attributes explained by compound concentrations.

RESULTS AND DISCUSSION

Sensory Analysis

Proximate analysis results for the cheeses confirmed that the targeted fat reductions were achieved for the reduced-fat and low-fat cheeses and that the 2 full-fat cheeses were similar (Table 1). As expected, moisture and protein contents were higher in the reduced-fat cheeses compared with the full-fat cheeses and these differences contributed to distinct texture and rheological properties (Rogers et al., 2009) and flavor properties (current study). Few sensory differences were documented between FFC1 (no wash) and FFC2 (washed curd), confirming that the curd washing procedure used

to manufacture the RFC and LFC was not the driving force for observed differences in flavor between these cheeses and the FFC1. Initially (after 2 wk of ripening), flavor profiles of the cheeses were similar (Table 2). Milkfat flavor decreased as fat content decreased—the only attribute that was different between the reduced-fat cheeses and the full-fat cheeses. No differences were documented between the 2 full-fat cheeses that differed by a curd washing step (which was also applied to the reduced- and low-fat cheeses). By 3 mo of ripening, diacetyl flavor decreased in all cheeses and was not detected by 6 mo, consistent with previous studies (Carunchia Whetstine et al., 2007). Other flavor changes were documented from the 2-wk time point that differentiated the full-fat cheeses from the cheeses with fat reduction. These changes were more pronounced in LFC compared with RFC and became more evident after 6 and 9 mo of ripening. At 3 mo, sulfur flavor was higher in FFC1, whereas bitter taste was evident in FFC2 and higher in the 2 fat-reduced cheeses compared with FFC2. A low but detectable intensity of rosy/burnt flavor was documented in the LFC. After 6 mo of ripening, this off-flavor (Carunchia Whetstine et al., 2005) increased in the LFC and was evident in the RFC, whereas bitter taste increased in all 4 cheeses. After 9 mo of ripening, sulfur and brothy flavors were higher in both FFC1 and FFC2 compared with the LFC; rosy/burnt flavor was highest in the LFC compared with the RFC and not detected in either full-fat cheese.

Differences in milkfat flavor would be expected between full-fat cheeses and cheeses with a fat reduction. Lactones are the flavorants in milkfat and they impart delicate, sweet, coconut-like flavors (Drake et al., 2001; Schlutt et al., 2007). Lactones are derived from triglycerides and increase in relative abundance with heat treatment of fluid milk or cream. Because milkfat flavor is documented in whole milk and cream and young cheese, and Carunchia Whetstine et al. (2006) demonstrated that flavor-active volatiles were not dissolved in the fat phase of the cheese, it is likely that lactones present in the cheesemilk contribute to milkfat flavor in cheese. As such, cheesemilk with decreased fat content will have lower lactone concentrations (and reactants that can form lactones), which results in lower milkfat flavor in the resulting cheese.

Previous studies have documented a lack of flavor development in reduced-fat cheeses or the presence of atypical flavors (off-flavor; Drake and Swanson, 1996). Both effects were observed in the current study. By 9 mo, full-fat cheeses displayed higher intensities of sulfur and brothy flavors compared with the low-fat cheese. Additionally, a rosy/burnt flavor was consistently documented in the low-fat cheese and increased in intensity with age. This flavor was also documented at

Table 1. Proximate analysis results for Cheddar cheeses with varying fat contents (adapted from Rogers et al., 2009)

Cheese ¹	Fat content (%)	Moisture content (%)	Moisture to protein ratio	Protein content (%)	pH
FFC1	31.8	37.7	1.5:1	24.6	5.2
FFC2	32.0	37.5	1.5:1	24.7	5.2
RFC	15.9	48.0	1.6:1	29.6	5.2
LFC	5.0	53.8	1.5:1	34.2	5.2

¹FFC1 = full-fat control; FFC2 = full-fat control, washed; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese.

lower intensity in 50% reduced-fat cheeses. Rosy flavor is an off-flavor encountered occasionally in aged full-fat Cheddar cheese and has been sourced to an imbalance in phenylethanal and phenyl acetic acid. Burnt flavor has not previously been documented in Cheddar cheese, and the lack of detailed descriptive analysis on reduced- and low-fat Cheddar cheeses makes it difficult to compare these results to previous studies. The sensory panel used in the current study was highly trained and experienced (Drake et al., 2008a,b, 2009). The panel described the burnt flavor as reminiscent of burned (blackened) sugar and this was used as a panel reference. Panelists also agreed that rosy and burnt flavors were 2 distinct flavors but were unable to consistently differentiate them in this study, possibly because of their low and subtle intensities and the panel's lack of experience with the

burnt flavor attribute. For the purpose of this study, the rosy and burnt attributes were combined. It is possible that the meaty off-aroma that Milo and Reineccius (1997) described in 40% reduced-fat Cheddar cheese was the same as the rosy/burnt flavor described in the current study.

All of the cheeses displayed some intensity of bitter taste by 9 mo, likely because of the single-strain starter culture used in the study. *Lactococcus lactis* M70 had been used commercially for production of reduced-fat cheeses and was utilized in this study to facilitate research on the relationships between cheese microbiology, volatile production, and sensory attributes. Bitter taste was higher in intensity in the RFC and LFC compared with FFC1 and FFC2. This may be because of increased proteolysis in these cheeses due to their higher moisture

Table 2. Sensory flavor attribute means of cheeses through 9 mo of ripening

Age and cheese type ¹	Sensory attribute ²											
	Cooked/ milky	Whey	Diacetyl	Milkfat	Sulfur	Brothy	Rosy/ burnt	Sour	Bitter	Salty	Sweet	Umami
2 wk												
FFC1	3.4 ^a	3.6 ^b	1.5 ^a	3.1 ^a	ND ³	ND	ND	3.3 ^{ab}	ND	3.8 ^a	1.7	0.7
FFC2	3.3 ^a	3.6 ^b	1.7 ^a	3.1 ^a	ND	ND	ND	3.3 ^{ab}	ND	3.9 ^a	1.7	0.7
RFC	3.5 ^a	3.9 ^a	1.5 ^a	1.9 ^b	ND	ND	ND	3.6 ^a	ND	3.8 ^a	1.4	1.0
LFC	3.5 ^a	3.7 ^{ab}	1.5 ^a	0.8 ^c	ND	ND	ND	3.6 ^a	ND	3.9 ^a	1.4	0.9
3 mo												
FFC1	2.9 ^b	2.8 ^b	0.8 ^b	3.0 ^a	1.2 ^d	1.1 ^c	ND	3.5 ^a	ND	3.5 ^{ab}	1.7	1.3
FFC2	2.9 ^b	2.7 ^b	0.6 ^b	3.0 ^a	1.0 ^{de}	1.9 ^{bc}	ND	3.3 ^{ab}	0.5 ^d	3.6 ^{ab}	1.7	1.1
RFC	2.9 ^b	2.6 ^{bc}	0.7 ^b	2.0 ^b	0.8 ^e	1.0 ^c	ND	3.3 ^{ab}	1.0 ^c	3.6 ^{ab}	1.6	1.1
LFC	2.9 ^b	2.5 ^{bc}	0.6 ^b	1.1 ^c	0.6 ^e	0.8 ^c	0.5 ^b	3.3 ^{ab}	1.1 ^c	3.5 ^{ab}	1.5	0.9
6 mo												
FFC1	2.8 ^b	1.8 ^d	ND	2.9 ^a	2.0 ^b	2.2 ^b	ND	3.1 ^b	1.0 ^c	3.6 ^{ab}	2.0	1.8
FFC2	3.0 ^b	1.9 ^d	ND	2.9 ^a	2.0 ^b	2.2 ^b	ND	3.1 ^b	1.0 ^c	3.5 ^{ab}	1.9	1.7
RFC	3.0 ^b	2.0 ^{cd}	ND	2.2 ^b	1.9 ^b	2.2 ^b	0.7 ^b	3.2 ^b	1.4 ^{bc}	3.5 ^{ab}	1.8	1.6
LFC	2.9 ^b	2.2 ^c	ND	0.9 ^c	1.6 ^c	1.9 ^{bc}	1.7 ^a	3.0 ^b	1.8 ^b	3.3 ^b	1.7	1.3
9 mo												
FFC1	2.2 ^c	1.7 ^{de}	ND	2.8 ^a	2.4 ^a	2.7 ^a	ND	3.1 ^b	1.2 ^c	3.3 ^b	2.0	1.8
FFC2	2.5 ^{bc}	1.6 ^e	ND	2.7 ^a	2.0 ^b	2.4 ^{ab}	ND	3.2 ^b	1.1 ^c	3.3 ^b	1.9	1.8
RFC	2.7 ^b	1.9 ^{de}	ND	1.9 ^b	2.2 ^{ab}	2.2 ^b	1.0 ^b	3.0 ^b	1.7 ^b	3.3 ^b	1.8	1.7
LFC	2.9 ^b	2.9 ^b	ND	0.8 ^c	1.2 ^d	1.9 ^{bc}	2.2 ^a	3.2 ^b	2.3 ^a	3.3 ^b	1.3	1.2

^{a-e}Means in a column followed by a different letter are different ($P < 0.05$).

¹FFC1 = full-fat control; FFC2 = full-fat control, washed; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese.

²Attributes were scored using a 0- to 15-point universal intensity scale (Meilgaard et al., 1999) using an established cheese flavor language (Drake et al., 2001; Drake, 2007). Most cheese flavor attributes fall between 0 and 5 on this scale (Drake et al., 2008a,b, 2009).

³ND = not detected.

contents or their decreased fat concentrations. Fat can mask sensory perception of bitter hydrophobic peptides (Olson and Johnson, 1990), making them less noticeable in a full-fat cheese than in a low-fat cheese.

Instrumental Analysis

Consistent with sensory results, instrumental volatile analysis confirmed small but distinct initial differences in volatile compounds among the cheeses that diverged as the cheeses ripened. Forty aroma-active compounds were consistently identified in the solvent extracts or headspace of the cheeses (Tables 3 and 4). Compounds detected in FFC1 and FFC2 were similar, so results are shown only for FFC1. These compounds have been previously reported in Cheddar cheeses (Milo and Reineccius, 1997; Carunchia Whetstine et al., 2005, 2006).

As expected, some highly volatile compounds were detected by SPME GC-O that were not detected by SAFE GC-O; similarly, some higher molecular weight aroma-active volatiles were detected by SAFE GC-O that were not detected by SPME GC-O (Tables 3 and 4). These differences were expected given the nature of the 2 extraction procedures used (McGorin, 2007) and were the reason that we employed both time-consuming approaches to obtain a complete picture of the aroma-active volatiles in the cheeses. No compounds were detected in low-fat cheeses that were not present in full-fat cheeses or vice versa, consistent with the hypothesis that sensory flavor differences are caused by differences in compound concentration as well as matrix differences (differences in compound release).

The GC-O results provide a powerful method to determine which compounds potentially play a role in flavor and, when combined with sensory results, enable a link between volatile compound and sensory results. Key high-impact odorants changed between cheeses after 2 wk of ripening compared with 9 mo of ripening and similar to sensory results, the key odorants changed between full-fat and low-fat cheeses at these different ripening times. Odorant FD values and intensities for RFC were in between those of FFC and LFC, as might be expected. High-impact odorants ($FD_3 > 5$) in FFC after 2 wk of ripening included acetic and butyric acids, the furanones furaneol, norfuraneol, and homofuraneol, 2, 3-butanedione (diacetyl), 2/3-methyl butanal, acetoin, and 2 lactones. At 2 wk of age, key odorants in low-fat cheeses were similar to those in full-fat cheeses except that acetoin, norfuraneol, and the 2 lactones were not high-impact odorants. In contrast, after 9 mo of ripening, many key odorants changed within each cheese type and more differences existed between FFC and LFC. Acetic and butyric acids, 2/3-methyl butanal, butyl acetate, norfuraneol, and homofuraneol were

potent odorants ($FD_3 > 5$) in FFC ripened for 9 mo, whereas 2,3-butanedione, acetic, butyric, 2/3-methyl butanal, thiofuran, 2- and 3-methyl butyric acids, methional, dimethyl trisulfide, 1-octen-3-one, 2 methoxy-3, 6-dimethyl pyrazine, the furanones (norfuraneol, furaneol, sotolon, and homofuraneol), 2-acetyl thiazoline, and phenylethanal were potent odorants in LFC. These results are consistent with the sensory results, which indicated small differences in flavor among the cheeses initially and divergences as the cheeses aged. Furaneol, homofuraneol, and methional were reported as high-impact odorants in 40% reduced-fat cheeses by Milo and Reineccius (1997).

Our AEDA results provide a suggestion of the most potent aroma (flavor)-contributing compounds in a given extracted sample (FFC, RFC, LFC) (Audouin et al., 2001) although we recognize that flavor dilution values do not represent actual concentrations of compounds, only their aroma activity in the extracts. $\log_3$ FD factors for the same compound differing by 2 or more $\log_3$ FD are considered suggestive of concentration differences. Based on high-impact odorants from AEDA and previous studies (Milo and Reineccius, 1997), 18 odorants were selected for quantification by external standard curves (Table 5) and gave results consistent with GC-O.

Concentrations of high-impact odorants changed within and between cheese treatments with ripening. Most notably, furanone concentrations (furaneol, homofuraneol, and sotolon) increased more within the LFC between 2 wk and 9 mo than for the FFC. Of these 3 compounds, the largest increase in concentration was for homofuraneol. Milo and Reineccius (1997) suggested that this compound was responsible for off-flavors in reduced-fat cheeses and that differences in nonstarter lactic acid bacteria populations were responsible for the observed increases. Furanones can be formed as Maillard reaction products from the reaction of pentoses and hexoses with amino acids, most notably glycine and glutamate (Hayashida et al., 1999; Ohata et al., 2007). The reaction is facilitated by heating, but studies have also demonstrated that certain strains of yeast facilitate formation ((Hayashida et al., 1999; Ohata et al., 2007). This phenomenon has not been directly demonstrated, but it has been hypothesized that certain strains of lactobacilli could also increase concentrations of these compounds (Rychlik et al., 1997; Milo and Reineccius, 1997).

Increases in phenylethanal and 1-octen-3-one were also higher for LFC compared with both FFC. These compounds have rosy and metallic/mushroom aromas, and phenylethanal can cause rosy/floral off-flavors in aged full-fat cheeses (Carunchia Whetstine et al., 2005). Phenylethanal was not previously reported in low-fat

Table 3. Solvent-assisted flavor evaporation (SAFE) gas chromatograph-olfactometry (GC-O) results with aroma extract dilution analysis (AEDA) flavor dilution (FD) factors for cheeses after 2 wk or 9 mo of ripening

No.	Compound	Aroma ¹	Fraction ²	RI ³		log ₃ FD factor ⁴						Identification method ⁵
				Rtx-5ms	Rtx-Wax	FFC1 2 wk	RFC 2 wk	LFC 2 wk	FFC1 9 mo	RFC 9 mo	LFC 9 mo	
1	Ethyl acetate	Fruity	NB	<600	907	<1	<1	<1	<1	1	1	MS, RI, Odor
2	2,3-Butanedione (diacetyl)	Butter	NB	<600	950	5	5	6	1	5	7	MS, RI, Odor
3	Acetic acid	Vinegar	Ac	605	1400	9	6	8	8	8	10	MS, RI, Odor
4	Acetoin	Butter	NB	659	1270	5	4	3	4	5	6	MS, RI, Odor
5	2/3 Methyl butanal	Malty	NB	662	798	6	5	5	5	5	6	MS, RI, Odor
6	Thiofuran	Rubber garlic	NB	677	1035	4	5	4	2	7	8	RI, Odor
7	Ethyl butanoate	Fruity	NB	750	1028	<1	<1	<1	<1	1	2	MS, RI, Odor
8	Propyl butanoate	Fruity	NB	803	1228	1	<1	5	<1	<1	2	RI, Odor
9	Butyric acid	Cheesy	Ac	820	1550	8	7	7	6	8	7	MS, RI, Odor
10	Butyl acetate	Solvent	NB	821	1075	3	<1	4	5	<1	2	RI, Odor
11	Hexenal	Fruity fatty	NB	851	1220	2	<1	<1	<1	<1	2	RI, Odor
12	2-Methyl butyric acid	Cheesy	Ac	870	1610	4	4	4	3	8	7	MS, RI, Odor
13	Heptanal	Green, waxy	NB	882	1174	2	<1	3	2	<1	2	RI, Odor
14	3-Methyl butyric acid	Cheesy	Ac	885	1625	4	4	4	3	8	7	MS, RI, Odor
15	2-Acetyl-1-pyrroline	Popcorn	NB	900	1295	<1	<1	<1	ND ⁶	ND	<1	MS, RI, Odor
16	Methional	Potato earthy	NB	903	1458	1	7	6	3	7	5	MS, RI, Odor
17	Dimethyl trisulfide	Garlic	NB	974	1332	3	4	3	1	7	6	MS, RI, Odor
18	1-Octen-3-one	Mushroom	NB	976	1357	3	4	6	1	7	9	MS, RI, Odor
19	Hexanoic acid	Sweaty	Ac	1024	1809	3	1	3	2	2	3	MS, RI, Odor
20	Norfuraneol	Curry burnt sugar	Ac	1044	2113	7	5	4	5	7	12	RI, Odor
21	Phenylethanal	Rosy	NB	1048	1625	4	4	2	<1	7	5	MS, RI, Odor
22	2-Methoxy-3,6-dimethylpyrazine	Earthy	NB	1058	1413	1	3	5	3	4	5	RI, Odor
23	Furaneol	Burnt sugar	Ac	1064	2043	5	5	4	1	8	10	MS, RI, Odor
24	2-Acetyl thiazoline	Popcorn	NB	1104	1767	4	5	5	4	6	6	MS, RI, Odor
25	Sotolone	Burnt sugar curry	Ac	1107	2205	<1	6	8	<1	9	12	MS, RI, Odor
26	Homofuraneol	Burnt smoky	Ac	1159	2067	7	7	7	5	7	9	MS, RI, Odor
27	γ -Octalactone	Fatty fruity	NB	1220	1910	2	<1	<1	3	<1	<1	MS, RI, Odor
28	Phenyl acetic acid	Floral	Ac	1260	2565	<1	<1	<1	2	4	3	MS, RI, Odor
29	Octanoic acid	Burnt waxy	Ac	1279	2040	<1	<1	<1	<1	<1	1	MS, RI, Odor
30	Skatole	Fecal	NB	1354	2484	<1	<1	2	<1	<1	2	MS, RI, Odor
31	γ -Nonalactone	Coconut	NB	1366	2033	5	2	4	1	<1	1	RI, Odor
32	γ -Decalactone	Fruity wax	NB	1472	2140	5	1	2	<1	<1	<1	RI, Odor
33	δ -Decalactone	Fatty coconut	NB	1530	2216	4	2	3	4	1	2	MS, RI, Odor
34	δ -Dodecalactone	Fatty butter milk-fat	NB	1730	2426	1	<1	<1	<1	<1	<1	MS, RI, Odor

¹Odor description at the GC-sniffing port.²NB = neutral/basic; Ac = acidic.³Retention indices (RI) were calculated from GC-O data.⁴Flavor dilution as determined at the GC-sniffing port. FFC1 = full-fat control; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese.⁵Compounds were identified by comparison with authentic standards on the following criteria: RI and odor property at the GC-sniffing port as well as RI and spectra on the GC-MS.⁶ND = not detected.

Table 4. Aroma active compounds detected in cheeses after 9 mo of ripening by solid-phase microextraction (SPME) gas chromatography-olfactometry (GC-O)

No.	Compound	Aroma ¹	RI ² (Rtx-5ms)	Post-peak intensity ³			Identification method ⁴
				FFC1	RFC	LFC	
1	Methanethiol	Rotten	<600	2.5	1.5	1	Odor, RI, MS
2	Dimethyl sulfide	Sulfurous	<600	ND ⁵	ND	1	Odor, RI
3	2,3-Butanedione	Buttery	600	3.5	2	2.5	Odor, RI, MS
4	Acetic acid	Acetic	645	ND	ND	2	Odor, RI, MS
5	2/3-Methyl butanal	Malty	650	ND	2	ND	Odor, RI, MS
6	Ethyl butyrate	Fruity	750	2	2.5	2.5	Odor, RI, MS
7	Unknown	Waxy	816	ND	1.5	ND	
8	Butyric acid	Cheesy	850	2.5	3	2	Odor, RI, MS
9	Hexenal	Fruity	852	ND	1.5	ND	Odor, RI, MS
10	Unknown	Brothy	890	2	ND	ND	
11	2-Acetyl-1-pyrroline	Malty popcorn	900	ND	ND	1	Odor, RI, MS
12	Methional	Potato	925	3.5	3	2	Odor, RI, MS
13	Dimethyl trisulfide	Garlic	980	1	ND	ND	Odor, RI, MS
14	1-Octen-3-one	Mushroom	990	1	1	ND	Odor, RI, MS
15	(Z)-1,5-Octadien-3-one	Green floral	1000	1.5	2	2	Odor, RI
16	Unknown	Musty brothy	1060	ND	ND	1.5	
17	Hexanoic acid	Sweaty	1085	ND	2	ND	Odor, RI, MS
18	1-Nonen-3-one	Earthy	1090	2.5	3	2.5	Odor, RI
19	Nonanal	Sweet fatty	1105	2	2	ND	Odor, RI, MS
20	2-Acetyl-2-thiazoline	Popcorn	1110	3.5	3	2.5	Odor, RI, MS
21	Unknown	Musty solvent	1155	2	1	ND	
22	(E,Z)-2,6-Nonadienal	Cucumbers	1165	ND	2	2	Odor, RI
23	Homofuraneol	Cotton candy/burnt	1170	ND	ND	1.5	Odor, RI, MS
24	Unknown	Sweet	1226	2	ND	1.5	
25	Unknown	Tortilla	1250	1	2	ND	
26	Decanoic acid	Cheesy	1363	ND	ND	1	Odor, RI, MS
27	Unknown	Sweet coconut	1445	2	ND	ND	
28	δ -Decalactone	Dusty sweet	1550	1	ND	ND	Odor, RI, MS
29	δ -Dodecalactone	Sweet fatty	1610	1.5	ND	ND	Odor, RI, MS

¹Odor description at the GC-sniffing port.²Retention indices (RI) were calculated from GC-O data.³Post-peak intensities as determined at the GC-sniffing port. Cheeses: FFC1 = full-fat control; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese.⁴Compounds were identified by comparison with authentic standards on the following criteria: RI and odor property at the GC-sniffing port as well as RI and spectra on the GC-MS.⁵ND = not detected.

cheese, but is one likely source of the rosy off-flavor consistently noted in LFC (Figure 1). 1-Octen-3-one was previously reported and AEDA indicated higher concentrations in reduced-fat cheeses, although it was not quantified (Milo and Reineccius, 1997). Furanone compounds and 1-octen-3-one are likely sources of the burnt off-flavor noted in the LFC (Figure 1). Interestingly, decreased sulfur flavor in LFC compared with FFC after 9 mo was noted by sensory panelists. Our analysis using SPME GC-O also suggested that LFC had lower concentrations of methanethiol, a compound purported to be a crucial precursor of aged cheese/sulfur flavor-contributing compounds (Seefeldt and Weimer, 2000). Acetic acid concentrations were higher in aged LFC compared with aged FFC, consistent with previous work (Milo and Reineccius, 1997) and also because the LFC received a milk preacidification treatment using vinegar.

Unlike in previous studies, methional was not different between FFC and RFC or LFC after 9 mo. This difference and the lack of phenylethanal noted in the previous study may be due to differences in the starter culture system or cheese make-procedure. Crucial and unique to this study was that all of the cheeses were manufactured in a controlled experimental design rather than commercially purchased with no knowledge of age, make-procedure, or starter culture differences, meaning that differences in sensory and volatile compounds can be directly compared, unlike in previous studies. The curd washing step applied to the reduced-fat cheeses (RFC and LFC) had a minor effect on flavor development, as evidenced by the differences between FFC1 (no wash) and FFC2 (washed curd). However, the fact that these differences were minor indicates that the washing step was not the source of the large differences observed in the flavor of the LFC compared with the FFC1 after

Table 5. Concentrations (mg/kg or µg/kg) of selected aroma-active compounds as determined by solvent-assisted flavor evaporation (SAFE) extraction¹

Compound	Cheese ²									LSD ³
	FFC1 2 wk	FFC1 6 mo	FFC1 9 mo	RFC 2 wk	RFC 6 mo	RFC 9 mo	LFC 2 wk	LFC 6 mo	LFC 9 mo	
	mg/kg									
Acetic acid	874.3	5,657	933.5	595.0	3,669	1,457	1,067	9,018	4,924	1,987
Butyric acid	1,385	2,295	3,201	445.2	2,344	756.7	402.8	1,955	4,071	906.2
Hexanoic acid	1,946	3,006	2,654	112.3	2,127	1,639	756.7	1,936	1,600	307.4
Octanoic acid	182.3	515.0	670.9	121.9	ND ⁴	ND	ND	ND	ND	121.9
	µg/kg									
Furaneol	7.79	9.08	11.3	7.59	30.8	19.8	8.69	18.0	18.2	3.47
Homofuraneol	69.11	83.59	50.92	210.9	525.2	290.1	54.97	135.9	304.8	24.00
Sotolone	10.89	8.83	6.10	11.41	38.79	28.36	17.93	87.75	52.79	25.69
δ-Decalactone	65.3	61.6	34.3	ND	123.5	70.8	18.1	71.9	47.1	9.28
γ-Octalactone	4.07	1.87	8.39	3.05	9.00	3.10	1.92	9.38	0.49	3.53
δ-Dodecalactone	6.27	6.53	3.33	5.26	7.03	ND	ND	7.02	ND	1.01
1-Octen-3-one	63.69	17.25	ND	164.25	72.04	26.80	200.33	12.90	380.07	17.25
Diacetyl	593.8	715.5	741.8	750.7	683.3	471.2	754.1	755.2	230.3	150.2
Methional	211.8	18.52	201.8	756.1	50.2	12.5	697.6	3.53	151.2	49.62
Dimethyl trisulfide	4.08	4.02	6.77	10.9	15.0	1.45	7.48	3.35	6.58	1.10
2-Acetyl-thiazoline	5.4	61.3	52.0	34.5	668.8	284.1	110.5	862.3	ND	2.26
Skatole	ND	0.55	ND	ND	1.80	2.10	0.10	0.08	ND	0.10
Phenyl acetic acid	ND	32.0	19.0	24.0	30.0	49.0	15.0	16.0	22.0	8.00
Phenylethanal	27.01	330.7	380.4	320.5	640.2	821.5	189.3	121.0	594.4	40.15

¹Response factors of selected compounds were calculated by direct addition of known amounts of standards to odor-free water before solvent extraction-SAFE. Response factors for compounds were determined using a 5-point standard curve (minimum $R^2 > 0.92$).

²FFC1 = full-fat control; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese.

³Compound concentrations different by greater than the LSD value are significantly different at $P < 0.05$.

⁴ND = not detected.

9 mo of ripening. The large concentration differences in key odorants between FFC and LFC after 9 mo of ripening, absent initially at 2 wk, clearly indicate differences in the biochemistry of these cheeses. Differences in moisture content may influence enzymatic reactions or actual microflora (starter and nonstarter populations), which will influence production of volatile compounds and should be directly addressed and compared in future studies.

The changes in the actual matrix of a full-fat cheese and low-fat cheeses may also influence flavor (Delahunty et al., 1996). Concentration differences were found in key odorants of FFC and LFC, but the actual matrix of LFC compared with that of FFC was quite different. Full-fat Cheddar cheese is 37% moisture and 32% fat. In contrast, LFC is more than 50% moisture and 5% fat, so FFC represents a more nonpolar matrix, whereas LFC represents a more polar matrix. This difference may influence detection thresholds of key odorants. The protein content of LFC is higher than that of FFC and this might influence flavor because proteins may bind volatile aroma-active components (Leksrisonpong et al., 2010). The difference in polarity of the matrix (FFC vs. LFC) seems more likely to influence the role that many compounds play in flavor of LFC because

the decrease in fat and increase in water is more than the increase in protein of LFC compared with FFC. Leksrisonpong et al. (2010) studied casein binding of 3 dairy aromatics (furaneol, δ-decalactone, and diacetyl) in 0, 10, and 20% fat emulsions at different pH values. They reported minimal but distinct binding effects of casein on the 3 compounds. Similarly, fat content played a minimal role in threshold of furaneol, but affected the orthonasal threshold of diacetyl and δ-decalactone.

The extent that matrix polarity influences the role that key odorants identified in this study play on flavor of LFC versus FFC is a topic of current ongoing research. Our results from this study indicate that the balance of flavor-active compounds, not just changes in volatile compound release, contribute to differences in flavor and flavor development of cheeses with reduced fat. Not surprisingly, these changes are magnified as the fat content is reduced, particularly beyond 50% fat reduction.

CONCLUSIONS

By making full-fat, 50% reduced-fat, and low-fat cheeses at one location and using the same starter culture, we observed several differences in sensory and

Figure 1. Partial least squares regression (PLS) plot for volatile compound concentration (not including free fatty acids) prediction of sensory flavor attributes (not basic tastes) of cheeses. Triangles (blue) = dependent sensory variables; circles (red) = independent explanatory variables; squares (green) = observations. FFC1 = full-fat control; RFC = 50% reduced-fat cheese; LFC = 83% reduced-fat cheese. Color version available in the online PDF.

chemical flavor attributes. We propose that the factors contributing to differences in flavor and flavor development in such cheeses include the balance of flavor-active compounds as well as differences in volatile com-

pound release, whereas the inclusion of curd washing in the lower fat cheeses (used to control cheese pH and moisture) was not a contributing factor. The full-fat cheeses had greater milkfat flavor that was attributed

to the fat content of the cheese, and they also displayed higher intensities of sulfur and brothy flavors. Analysis by SPME GC-O suggested that reduced concentrations of methanethiol were present in low-fat cheese; methanethiol is a crucial precursor of flavor-contributing compounds in aged cheese.

After cheese aging, large concentration differences between full-fat and low-fat cheeses were observed for key odorants, indicating differences in the biochemistry of these cheeses. However, the same compounds were detected in all cheeses, which is consistent with the hypothesis that sensory flavor differences in cheese are due to differences in compound concentration as well as matrix differences that influence compound release. A low intensity of rosy and burnt flavors was present in the low-fat cheeses by 3 mo, and these flavors increased during 6 mo of aging and then also became evident in the reduced-fat cheese. A greater increase in phenylethanal was detected in low-fat cheese than in full-fat cheese during aging, and this is one of the likely sources of the rosy off-flavor. A burnt flavor reminiscent of the flavor of burned (blackened) sugar was apparent in the low-fat cheeses. The concentration of furanones increased in low-fat cheese more than in full-fat cheese, with the largest increase occurring for homofuraneol. The furanone compounds and 1-octen-3-one are the likely sources of the burnt off-flavor that is consistently present in low-fat cheeses.

All of the cheeses had some bitterness, and bitter taste was greatest in the low-fat cheese. No measurement of bitter compounds was performed and this difference in sensory attributes may represent a cheese matrix effect. The presence of fat can alter sensory perception of bitter hydrophobic peptides and reduce their rate of release from the cheese mass during chewing, thus making them less noticeable in a full-fat cheese than in a low-fat cheese. Similarly, a full-fat cheese containing 33% milkfat represents a more nonpolar matrix compared with low-fat cheese that contains only 6% milkfat and would thus present a more polar matrix. This difference in polarity may influence detection thresholds of key odorants and influence the role many compounds play in the perceived flavor of low fat cheese

ACKNOWLEDGMENTS

Paper No. FSR-10-22 of the Journal Series of the Department of Food, Bioprocessing and Nutrition Science, North Carolina State University (Raleigh). Support from the North Carolina Agricultural Research Service, Dairy Management Inc. (Rosemont, IL), Southeast Dairy Foods Research Center (Raleigh, NC), and Western Dairy Center (Logan, UT) are gratefully acknowledged. We thank Stephen Larsen (Western Dairy

Center, Logan, UT) who was the cheesemaker for this project. The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones not mentioned.

REFERENCES

- Audouin, V., F. Bonnet, Z. M. Vickers, and G. A. Reineccius. 2001. Limitations in the use of odor activity values to determine important odorants in foods. Pages 156–171 in *Gas Chromatography-Olfactometry: The State of the Art*. J. V. Leland, P. Schieberle, A. Buettner, and T. E. Acree, ed. ACS Symposium Series No. 782. American Chemical Society, Washington, DC.
- Banks, J. M. 2004. The technology of low-fat cheese manufacture. *Int. J. Dairy Technol.* 57:199–207.
- Carunchia Whetstone, M. E., K. R. Cadwallader, and M. A. Drake. 2005. Characterization of rose/lyral flavors in Cheddar cheese. *J. Agric. Food Chem.* 53:3126–3132.
- Carunchia Whetstone, M. E., M. A. Drake, B. K. Nelson, and D. Barbano. 2006. Flavor profiles of full fat, reduced fat and cheese fat made from aged Cheddar with the fat removed using a novel process. *J. Dairy Sci.* 89:505–517.
- Carunchia Whetstone, M. E., P. J. Luck, M. A. Drake, E. A. Foegeding, P. D. Gerard, and D. M. Barbano. 2007. Characterization of flavor and texture development within 291 kg blocks of milled and stirred curd Cheddar cheese. *J. Dairy Sci.* 90:3091–3109.
- Childs, J. L., and M. A. Drake. 2009. Consumer perception of fat reduction in cheeses. *J. Sens. Stud.* 24:902–921.
- Delahunty, C. M., J. R. Piggot, J. M. Conner, and A. Patterson. 1996. Comparative volatile release from traditional and reduced fat Cheddar cheeses upon mastication in the mouth. *Ital. J. Food Sci.* 2:89–98.
- Drake, M. A. 2007. Defining cheese flavor. Pages 370–395 in *Improving the Flavor of Cheese*. B. Weimer, ed. CRC Press, New York, NY.
- Drake, M. A., T. D. Boylston, K. D. Spence, and B. G. Swanson. 1997. Improvement of sensory quality of reduced fat Cheddar cheese with a *Lactobacillus* adjunct. *Food Res. Int.* 30:35–40.
- Drake, M. A., and G. V. Civille. 2003. Flavor lexicons. *Compr. Rev. Food Sci.* 2:33–40.
- Drake, M. A., S. C. McIngvale, K. R. Cadwallader, and G. V. Civille. 2001. Development of a descriptive sensory language for Cheddar cheese. *J. Food Sci.* 66:1422–1427.
- Drake, M. A., and B. G. Swanson. 1996. Fat mimetics in low fat cheeses. *J. Food Sci.* 61:1267–1270.
- Drake, M. A., M. D. Yates, and P. D. Gerard. 2008a. Determination of regional differences in flavor for U.S. Cheddar cheeses aged for 6 months or longer. *J. Food Sci.* 73:S199–S208.
- Drake, S. L., P. D. Gerard, and M. A. Drake. 2008b. Consumer preferences for mild cheddar cheese flavors. *J. Food Sci.* 73:S449–S455.
- Drake, S. L., S. L. Lee, S. Clark, K. Lopetcharat, and M. A. Drake. 2009. Mapping regional differences in consumer liking for sharp Cheddar cheeses. *J. Food Sci.* 74:S276–S285.
- Engel, W., W. Bahr, and P. Schieberle. 1999. Solvent assisted flavor evaporation—A new and versatile technique for the careful and direct isolation of aroma compounds from complex food matrices. *Eur. Food Res. Technol.* 209:237–241.
- FDA-DHHS. 2002. 21CFR101.62b: Nutrient content claims for fat, fatty acid, and cholesterol content of foods. Food and Drug Administration—Department of Health and Human Services, Washington, DC. http://edocket.access.gpo.gov/cfr_2002/aprqr/21cfr101.62.htm
- Gerdes, S. 2005. Dairy detective: New life for lower-fat cheese. *Dairy Foods* 48:(November).
- Grosch, W. 1993. Detection of potent odorants in foods by aroma extract dilution analysis. *Trends Food Sci. Technol.* 4:68–73.
- Gwartney, E. A., E. A. Foegeding, and D. K. Larick. 2002. The texture of commercial full-fat and reduced-fat cheese. *J. Food Sci.* 67:812–816.

- Hayashida, Y., H. Kuriyama, K. Nishimura, and J. C. Slaughter. 1999. Production of 4-hydroxyfuranones in simple media by fermentation. *Biotechnol. Lett.* 21:505–509.
- Johnson, M. E., and C. M. Chen. 1995. Technology of manufacturing reduced-fat cheddar cheese. Pages 331–337 in *Chemistry of Structure-Function Relationships in Cheese*. E. L. Malin and M. H. Tunick, ed. Plenum Press, New York.
- Leksrisompong, P., D. M. Barbano, E. A. Foegeding, P. D. Gerard, and M. A. Drake. 2010. The roles of fat and pH on the detection thresholds and partition coefficients of three compounds: Diacetyl, δ -decalactone, and furaneol. *J. Sens. Stud.* 25:347–370.
- McGorin, R. J. 2007. Flavor analysis of dairy products. Pages 23–49 in *Flavor of Dairy Products*. K. R. Cadwallader, M. A. Drake, and R. J. McGorin, ed. ACS Symposium Series No. 971. American Chemical Society, Washington, DC.
- Meilgaard, M., G. V. Civille, and B. T. Carr. 1999. *Sensory Evaluation Techniques*. 3rd ed. CRC Press Inc., Boca Raton, FL.
- Milo, C., and G. A. Reineccius. 1997. Identification and quantification of potent odorants in regular fat and low fat mild Cheddar cheese. *J. Agric. Food Chem.* 45:3590–3594.
- Mistry, V. 2001. Low fat cheese technology. *Int. Dairy J.* 11:413–422.
- Ohata, M., K. Kohama, Y. Morimitsu, K. Kubota, and E. Sugawara. 2007. The formation mechanism by yeast of 4-hydroxy-2(or 5)-ethyl-5(or 2)-methyl-3(2H)-furanone in miso. *Biosci. Biotechnol. Biochem.* 71:407–413.
- Olson, N. F., and M. E. Johnson. 1990. Light products: Characteristics and economics. *Food Technol.* 44:93–96.
- Rogers, N. R., M. A. Drake, C. R. Daubert, D. J. McMahon, T. K. Bletsch, and E. A. Foegeding. 2009. The effect of aging on low-fat, reduced-fat, and full-fat Cheddar cheese texture. *J. Dairy Sci.* 92:4756–4772.
- Rychlik, M., R. Warmke, and W. Grosch. 1997. Ripening of Emmental cheese wrapped in foil with and without addition of *Lactobacillus casei* ssp. *casei*. 3. Analysis of character impact flavor compounds. *Lebensm. Wiss. Technol.* 30:471–478.
- Schlutt, B., N. Moran, P. Schieberle, and T. Hofmann. 2007. Sensory-directed identification of creaminess enhancing volatiles and semi-volatiles in full fat cream. *J. Agric. Food Chem.* 55:9634–9645.
- Seefeldt, K. E., and B. C. Weimer. 2000. Diversity of sulfur compound production in lactic acid bacteria. *J. Dairy Sci.* 83:2740–2746.
- van den Dool, H., and P. D. Kratz. 1963. A generalization of retention index system including linear temperature programmed gas-liquid partition chromatography. *J. Chromatogr.* 11:463–467.
- Van Ruth, S. 2001. Methods for gas chromatography-olfactometry: A review. *Biomol. Eng.* 17:121–128.
- Yates, M. D., and M. A. Drake. 2007. Texture properties of Gouda cheese. *J. Sens. Stud.* 22:493–506.