Influence of Additives and Mixing Time on Crumb Grain Characteristics of Wheat Bread

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ABSTRACT

The effect of additives and processing parameters on wheat bread were investigated objectively using image analysis (IA). Five different bread types were produced by varying the ingredients (standard, standard with fat, standard with emulsifiers) and changing the mixing times (90, 150, and 240 sec). A digital IA system for wheat bread was developed from generic commercial software. The system yielded reproducible results for a variety of bread crumb grain image features. Bread slices were scanned and evaluated using the IA system. Image characteristics were determined for each bread type. All data was statistically evaluated to detect significant differences between bread types. It was shown quantitatively that inclusion of fat or emulsifiers or extension of mixing time had a significant effect on crumb grain features such as mean cell area, total cell area, and number of cells/cm^2. The five bread types could be distinguished solely by crumb grain characteristics.

The three-dimensional structure of a food is characterized by the organization of its molecular, microscopic and macroscopic components. Interactions and steric hindrances of macromolecules govern structure at the molecular level. Larger components such as proteins or starch granules and their interactions play a major role in food structure at the microscopic level. Finally, the size and shape of its isolated components determine the macroscopic structure of a food. The overall texture of the food depends on the three-dimensional network formed from the individual components.

The three-dimensional structure and appearance of a bakery product influences its textural and sensorial properties (mouthfeel). Therefore, knowledge of the structural organization of bakery products is essential to explain (or to improve the understanding of) the enormous influence of the appearance of, for example, a bread crumb on the consumers perception of product quality.

Several researchers in North America and in Europe have studied the three-dimensional structure of cereals and their products using image analysis (IA). To date, the major fields of application of IA in the cereal area have included discrimination between wheat and nonwheat components in grain (Zayas et al 1989), differentiation between bread brands (Zayas 1993), direct quantification of technologically relevant bread crumb grain features (Sapirstein et al 1994, Rogers et al 1995), discrimination between mill fractions of hard and soft wheat (Zayas and Steele 1996), and quantification of surface lipid concentrations of milled rice kernels as an indication of the degree of milling (Liu et al 1998). European research activities have included development of a crumb grain score table (Dallmann 1958), extraction of bread crumb features from video images (Bertrand et al 1992), description of the crumb grain structure of bakery goods (Noll and Kuhn 1997), characterization of the layering of puff pastry (Noll and Kuhn 1997), and distribution of phenolic materials in durum wheat grain (Saadi et al 1998).

Originally, bread crumb grain analysis was conducted visually with product scoring based on experience. This method evolved to comparing bread slices with a table of photographs (Dallmann 1958). As technology advanced, video cameras (Zayas et al 1989, Sapirstein et al 1994), scanners (Bertrand et al 1992, Rogers et al 1995, Noll and Kuhn 1997), and various types of microscopes (Harrigan 1997, Harrigan and Bussmann 1998) became useful tools for image acquisition. Image evaluation software was initially developed in-house (Zayas et al 1989, Sapirstein et al 1994, Noll and Kuhn 1997) and therefore was not readily accessible. It is being gradually supplemented with sophisticated commercial, but often expensive, generic IA software packages.

A system widely used involves presenting slices of products to a panel. The members then attempt to evaluate a variety of quality parameters. Problems associated with the current grain scoring system include a lack of documentation and the subjective nature of the scoring. Variations between taste panel members can be extreme, as can those from an individual scoring samples over a period of days or months.

In this study the influence of additives and processing parameters on wheat bread were investigated using a simple, inexpensive, robust and versatile digital IA system capable of objective and quantitative measurement of bread crumb grain characteristics. Several characteristics were selected in the discrimination of standard bread and bread produced using fat, emulsifiers and extended mixing times. Characteristic features data obtained with the new method were analyzed using a one-way analysis of variance (ANOVA) to differentiate the bread types.

MATERIALS AND METHODS

Ingredients

Commercial bakers wheat flour containing 12.2% protein and 20 ppm of ascorbic acid was used (Odlum Group, Dublin, Ireland). Dried yeast obtained from Mauri Foods (Camellia, NSW, 2142, Australia), and table salt and potable drinking water were incorporated in the formula.

Five formulas were used for the trials: standard; standard with fat; standard with emulsifiers; 150 sec of mix time; 240 sec of mix time. The formulas were calculated on a 1,000 parts flour basis. Standard contained 1,000 parts flour, 600 parts water, 20 parts salt, and 15 parts yeast. Standard with fat also contained 50 parts commercial margarine (80% fat). Standard with emulsifiers contained 5 parts diacetyl tartaric acid esters of monoglycerides (DATEM) and 5 parts sodium stearoyl lactylate (SSL).

Preparation of Bread

Ingredients were mixed in a mixer (Stephan u Söhne, GmbH & Co., Hameln, Germany) for 30 sec at level I and then 90 sec at level II. Batches with increased mix times were mixed for 30 sec at level I and then for the specified mix time at level II. After mixing, the dough was allowed to rest in a proofer (Koma, Koeltechnische Industrie B.V., Netherlands) at 30°C, 85% rh for 20 min. The dough was then divided into 500-g pieces, molded, and pan proofed at 30°C, 85% rh for 60 min. The bread was baked in a deck oven at 230°C top and bottom heat for 30 min. The loaves were allowed to cool for 60 min on cooling racks at room temperature.

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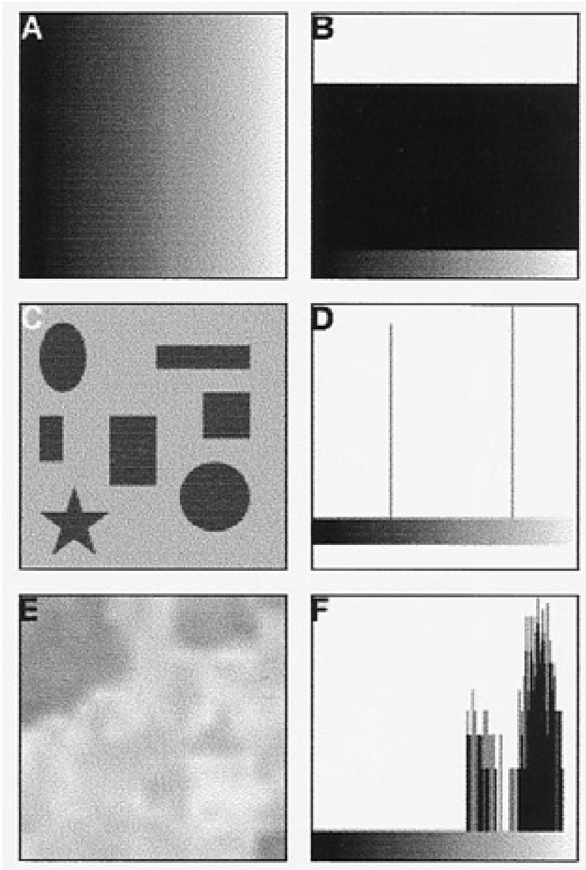

Fig. 1. Gray scale images (**A, C, E**) and corresponding gray level histograms (**B, D, F**). Lightness increases from left to right across the histograms. Uniform transition from dark to light produces a flat histogram (**A, B**). Objects of uniform intensity on a background of uniform intensity produce a histogram with sharply defined intensity peaks (**C, D**). Rapid transition from dark to light as observed in a section of a slice of wheat bread results in a histogram with bimodal characteristics (**E, F**).

Evaluation of the Bread

Tristimulus (L^*, a^*, and b^*) color values were measured using a chromameter (CR300, Minolta, Osaka, Japan). The bread volume was measured 1 hr after baking by the rapeseed displacement method. Bake loss (%), product yield (g/100 g of flour) and volume yield (mL/100 g of flour) were calculated. Bread was sliced transversely using a slice regulator and bread knife to obtain slices 25 mm thick. Both sides of two central slices of each of the three loaves were used for crumb grain measurements. Images were taken 75 min after baking. A single 60- × 60-mm square field of view (FOV) was evaluated for each image. This FOV captured the majority of the crumb area of each slice. Images were taken from the center of the slice. Twelve digital images were processed and analyzed for each batch. This gave a total of 60 images.

Image Acquisition and Analysis

All measurements used a customized PC IA system. Images were captured using a flatbed scanner (HP ScanJet 4c, Hewlett Packard) and supporting software (DeskScan II, Hewlett Packard). Brightness was adjusted to 150 units and contrast to 170 units using software controls. Images were scanned full scale in 256 gray levels at 150 dots per inch (dpi) each comprising 355 columns by 355 rows of picture elements (pixels). Data was processed using a Pentium II 233MHz PC with 64MB RAM supporting Jandel SigmaScan Pro and Microsoft Excel V 7. A threshold method was used for image segmentation (conversion to a binary image). The increased rate of change of gray level (intensity) at the interface between cell and noncell is such that a dip occurs in the gray level frequency histogram of the image. The minimum point of this dip was selected as the gray level threshold. This is illustrated in Figs. 1 and 2. The analysis was performed independently for each image. To determine whether the system selected a suitable consistent threshold for each entire image, random images were divided into nine subimages each of 20- × 20-mm, and the threshold method was conducted to select the gray level threshold for the particular subimage. Crumb cell detection was conducted on the binary images. Seven crumb grain features were isolated from the FOV, analyzed, and a crumb grain profile generated for each bread type. The crumb grain features chosen were total number of cells, number of cells smaller than 4 mm^2, total cell area, mean cell area, number of cells/cm^2, and cell to total area ratio. Cell shape was analyzed using a shape factor. This measurement calculates circularity of an object. A perfect circle has a shape factor of 1, and a line has a shape factor approaching 0. Cell shape analysis for the different bread types was performed by counting the percentage of cells that fell into a particular shape factor category: $0.00 < X \leq 0.20$, $0.20 < X \leq 0.50$, $0.50 < X \leq 0.80$ and $0.80 < X \leq 1.00$. To investigate the sensitivity of the system, images were compared with classification photographs (Porentabelle) (Dallmann 1958). Visual estimation of the number of cells/cm^2, cell to total area ratio, and mean cell area (mm^2) was conducted on random slices during the trial (results not shown).

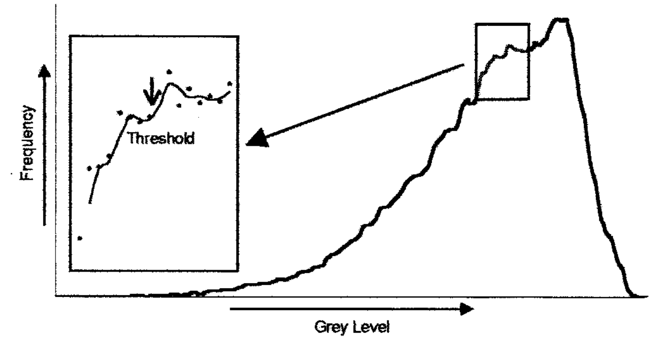

Fig. 2. Gray level histogram of digital gray scale image of a single slice of standard wheat bread. Lightness increases from left to right. Magnified portion indicates rapid transition from dark to light at a cell-noncell interface producing a dip. Lowest point on a two-period trendline drawn through this region was selected as the threshold gray level intensity.

Statistical Evaluation

ANOVA was conducted on data obtained from baking tests, crust color measurements, and image texture data using a statistical software package (SPSS V8.0.0). Tukey's honestly significant difference (HSD) posthoc test was used to detect significant differences at $P < 0.05$.

RESULTS AND DISCUSSION

Baking Tests

Standardized baking tests were performed to ensure uniformity in baking characteristics from bread loaves within a treatment group. Table I compares baking characteristics of three loaves from each of three standard batches and three batches containing fat. Bread mixed for 150 or 240 sec was not significantly different from standard bread with respect to baking tests. Also, bread containing fat or emulsifiers was not significantly with respect to baking test results. Generally, product yield and bake loss were not affected by different treatments. Volume yield increased by ≈13% compared with standard bread when fat or emulsifiers were added. Crust color was not significantly affected by any of the variables.

Crumb Grain Features in Standard Bread and Data Reproducibility

When the images were classified using Porentabelle (Dallmann 1958), almost all the images were given the same classification (5–6), with the result that the different bread types could not be

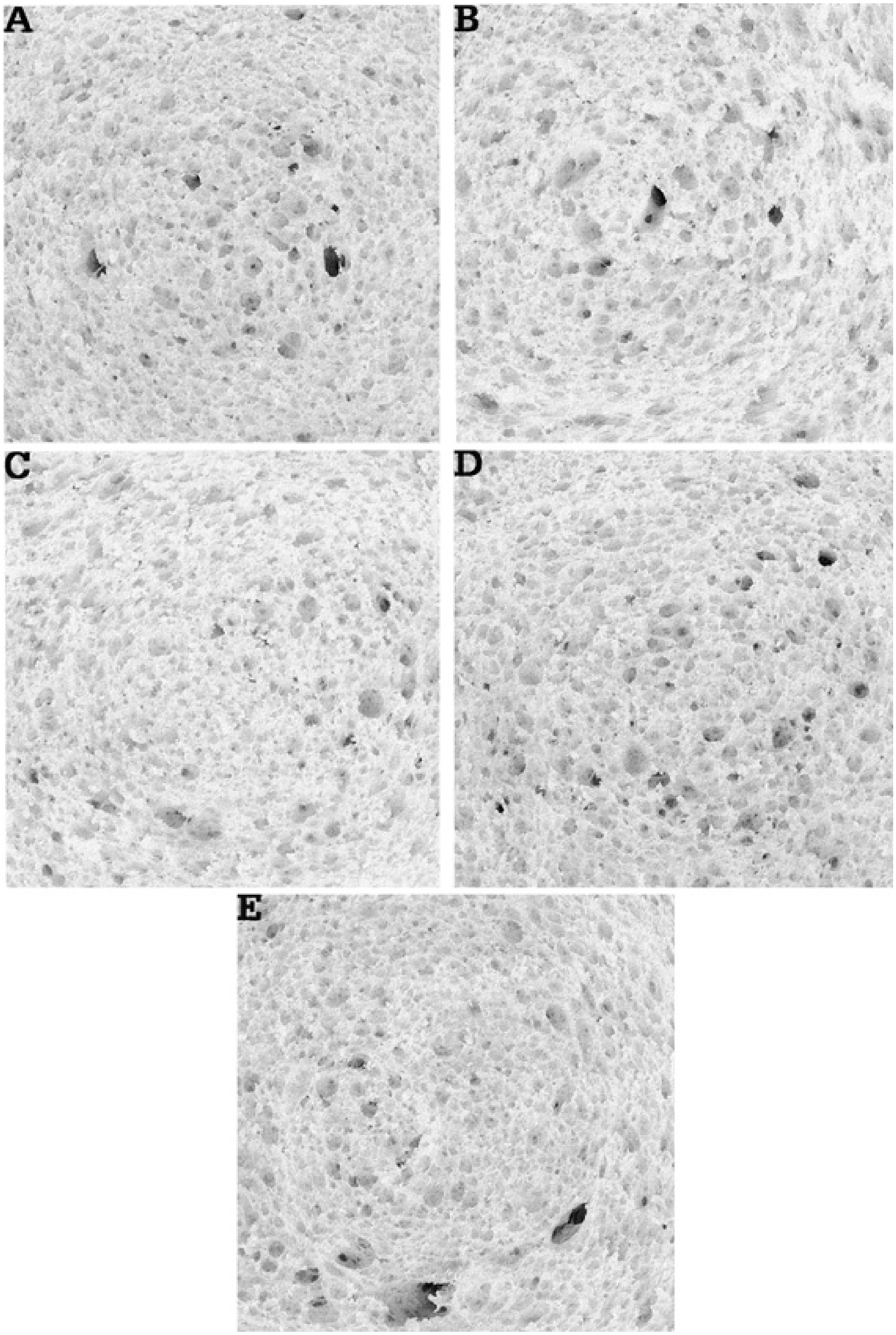

Fig. 3. Sample gray level images of 60- × 60-mm field of view of different bread types. Standard (**A**), standard with fat (**B**), standard with emulsifiers (**C**), standard with 150 sec of mixing time (**D**), standard with 240 sec of mixing time (**E**).

reliably distinguished. Twelve images from each bread type were evaluated using the IA system. This was the minimum number of slices required to accurately compare bread crumb structures and assess the effect of the different additives and mix times. Analysis of the subimages showed that the system selected an identical threshold for each of all the subimages within an image as was selected for the entire image. Typical crumb grain measurements for the 12 individual images from three standard loaves are presented in Table II. ANOVA indicated that with the exception of cell to total area ratio, no significant differences were detected for any of the crumb grain features in slices taken from different loaves of the same bread type. The total number of cells detected was 1,428 ±

TABLE I
Baking Characteristics of Standard Bread and Bread with Added Fat

Batch	Bake Loss (%)	Product Yield (g/100 g of flour)	Volume Yield (mL/100 g of flour)	Tristimulus Color Values		
				*L**	*a**	*b**
Std 1	11.5c[a]	144.7a	481.9b	56.2a	17.6ab	29.9a
Std 2	11.9a–c	144.1a–c	491.1b	58.9a	19.4a	34.6a
Std 3	11.6bc	144.4a	500.4b	57.8a	13.6ab	32.9a
Fat 1	11.8bc	144.2ab	573.9a	57.8a	19.5a	34.3a
Fat 2	12.3ab	143.3bc	562.5a	60.7a	19.5a	35.9a
Fat 3	12.5a	143.1c	558.5a	60.0a	13.3b	34.3a

[a] Values followed by the same letter in the same column are not significantly different ($P < 0.05$). $n = 3$.

TABLE II
Typical Crumb Grain Feature Measurements for Images from Standard Bread

Loaf and Image Number	Total Cells	Small Cells[a]	Cell Total Area (mm^2)	Mean Cell Area (mm^2)	Cells/cm^2	Cell to Total Area Ratio
1						
1	1,464	1,426	867	0.59	40.7	0.24
2	1,386	1,336	1057	0.76	38.5	0.29
3	1,412	1,373	985	0.70	39.2	0.27
4	1,406	1,355	1035	0.74	39.1	0.29
Mean	1,417.0a[b]	1,372.5a	986.0a	0.70a	39.38a	0.28b
2						
5	1,412	1,373	985	0.70	39.2	0.27
6	1,395	1,335	1047	0.75	38.8	0.29
7	1,364	1,302	1370	1.00	37.9	0.38
8	1,451	1,380	1288	0.89	40.3	0.36
Mean	1,405.5a	1,347.5a	1172.5a	0.84a	39.05a	0.33ab
3						
9	1,364	1,302	1370	1.00	37.9	0.38
10	1,451	1,380	1288	0.89	40.3	0.36
11	1,583	1,535	1084	0.69	44.0	0.30
12	1,443	1,380	1283	0.89	40.1	0.36
Mean	1,460.3a	1,399.3a	1256.3a	0.87a	40.58a	0.35a
Overall mean	1,428	1,373	1139	0.80	39.7	0.32
Overall std dev	59	62	171	0.13	1.6	0.05

[a] Number of cells >0.05 mm^2 but <4.00 mm^2.
[b] Values followed by the same letter in the same column are not significantly different ($P < 0.05$). $n = 4$.

59 (CV 4.2%). Thus, the number of cells/cm^2 was 39.7 ± 1.6 (CV 4.2%). This value compared well with visual estimation. The number of cells <4 mm^2 was 1,373 ± 62 (CV 4.5%). The calculated total cell area was 1,139 ± 171 mm^2 (CV 15%) with a mean cell area of 0.80 ± 0.13 mm^2 (CV 16.5%). The average cell to total area ratio for standard bread was 0.32 ± 0.05 (CV 15%). Thus, based on the FOV analyzed, ≈32% of the cross-sectional area of the bread is composed of gas cells. This calculated value compared well with visual estimation from the actual bread slices. The calculated value for mean cell area also compared well with visual estimation. These values are distinct from those reported by Sapirstein et al (1994), who calculated a cell to total area ratio of 0.44–0.46 and a mean cell area of 0.48mm^2 in control bread prepared using the GRL Chorleywood procedure as described by Kilborn and Tipples (1981). In this method, mixing is conducted under partial vacuum that has a considerable influence on the crumb grain of the finished product. If the two IA systems are comparably accurate, then the values calculated may be unique to the procedure used to prepare the bread. A high degree of variation in total cell area and mean cell area within a bread type was a feature of the bread type rather than inconsistent measurement. Data was highly reproducible for all other measurements and calculations. A fact that must be taken into consideration when measuring cell area from bread slices is that only a very small proportion of cells in the slice are actually bisected and that larger cells are more likely to be cut than are smaller ones.

Crumb Grain Measurements for Different Bread Types

Examples of images from each bread type are shown in Fig. 3. In line with baking test results, substantial differences were found between many of the crumb grain features extracted from the different bread types. ANOVA showed that differences in image characteristics for the different bread types were significant (Table III). Addition of fat to the standard recipe resulted in a decrease of ≈13% in the total number of cells detected, and addition of emulsifiers resulted in a decrease of ≈19%. Consequently, the number of cells/cm^2 decreased accordingly. The number of cells < 4 mm^2 decreased by ≈14% in bread containing fat and by ≈21% in bread containing emulsifiers. There was an increase of ≈11% in the total cell area and the mean cell area increased by ≈35% compared with standard bread when fat or emulsifiers were added. The observed increase in total cell area was expected, as an increase of ≈13% in volume yield had been observed in bread containing fat or emulsifiers. Given that the amount of dough was equal in the three bread types, any increase in volume had to be attributable to the presence of gas cells in the loaves.

Results for shape factor analysis are presented in Table IV. Generally, the degree of cell elongation is a measure of the strength of the dough and a direct measure of the chewiness of the bread (Hoseney 1994). During molding, the dough is sheeted and then rolled into a cylinder. The cells are elongated around the cylinder. Shape factor analysis shows that mixing for 150 sec results in a significant decrease in cell roundness. Addition of fat or emulsifiers also cause a significant decrease in cell roundness. The crumb grain in bread containing fat or emulsifiers was more open (Fig. 3) with a greater mean cell area, a higher cell to total area ratio, and, therefore, thinner cell walls than standard bread. As expected, addition of fat or emulsifiers to bread had similar effects on crumb grain characteristics, but unlike the other bread types studied, they could not usually be statistically distinguished from each other with a high degree of confidence.

Increasing mixing time in the standard recipe from 90 to 150 sec resulted in a decrease of ≈13% in the number of cells detected.

TABLE III
Crumb Grain Characteristics of Wheat Bread Produced Using Fat, Emulsifiers, or Increased Mixing Times

Bread Type[a]	Total Cells	Small Cells[b]	Total Cell Area (mm^2)	Mean Cell Area (mm^2)	Cells/cm^2	Cell to Total Area Ratio
1	1427.6a[c]	1373.1b	1138.9a	0.80bc	39.7a	0.32a
2	1246.5b	1187.0c	1288.1a	1.05a	34.6b	0.36a
3	1153.6b	1089.0c	1258.3a	1.11a	32.0b	0.35a
4	1244.9b	1190.8c	1151.3a	0.93ab	34.6b	0.32a
5	1516.7a	1482.3a	938.6b	0.62c	42.1a	0.26b

[a] 1 = Standard, 2 = standard with fat, 3 = standard with emulsifiers, 4 = standard with 150 sec of mix time, 5 = standard with 240 sec of mix time.
[b] Number of cells >0.05 mm^2 but <4.00 mm^2.
[c] Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

TABLE IV
Cell Shape Analysis for Standard Bread and Bread Containing Fat or Emulsifiers

Bread Type[a]	Cell Shape Factor (% of total cells)[b]			
	$0.00 < X \leq 0.20$	$0.20 < X \leq 0.50$	$0.50 < X \leq 0.80$	$0.80 < X \leq 1.00$
1	8b[c]	32a	39a	21a
2	11a	31b	37b	21a
3	11a	31b	37b	21a
4	10a	33a	38ab	19b
5	8b	32ab	39a	21ab

[a] 1 = Standard, 2 = standard with fat, 3 = standard with emulsifiers, 4 = standard with 150 sec of mix time, 5 = standard with 240 sec of mix time.
[b] 0 = line → 1.00 = circle.
[c] Values followed by the same letter in the same column are not significantly different ($P < 0.05$). $n = 12$.

However, when mixing time was extended to 240 sec, this effect was reversed, and the number of cells detected increased by ≈6% when compared with standard bread. Of the five bread types studied, bread mixed for 240 sec recorded the highest number of cells/cm^2. The number of cells <4 mm^2 decreased by ≈13% in bread mixed for 150 sec and increased by ≈8% in bread mixed for 240 sec when compared with standard bread. Also, the mean cell area in bread mixed for 150 sec increased by ≈16% but decreased by ≈23% in bread mixed for 240 sec relative to standard bread. Consequently, the bread mixed for 240 sec had the lowest cell to total area ratio of the five bread types studied, being ≈19% lower than standard bread. The cell to total area ratio in bread mixed for 150 sec was similar to standard bread. As dough is mixed to minimum mobility, its resistance to extension increases to a maximum and then begins to decrease. This can be observed from farinograms (Bloksma and Bushuk 1988). Gas cell coalescence occurs during the early part of baking (Haymann et al 1998). In optimally mixed dough, the ability to sustain an open crumb structure is at a maximum. The amount of air incorporated in optimally mixed dough is about half the total amount possible. This amount increases during overmixing (Junge et al 1981) and, consequently, more nitrogen gas is incorporated in the dough. Because of this extra nitrogen, more gas cells are initially present in the mixed dough that act as nuclei for gas cell development from CO_2 produced during fermentation.

In overmixed dough, the tendency to flow is greater (resistance to extension is decreased) (Bloksma and Bushuk 1988), and because the strength of the dough is reduced, its capacity to sustain large cells is also reduced. Gas cell coalescence is reduced and more gas is lost to the atmosphere. Because the cells are less likely to coalesce, they remain discreet and, therefore, smaller with thicker cell walls. Therefore, the number of cells in bread produced from very overmixed dough (240 sec) is greater, but the cell to total area ratio is lower than in standard bread.

From the results observed in standard bread (90 sec mix time), and bread produced from dough mixed for 150 sec, it would appear that optimal mixing time is closer to 150 sec than to 90 sec.

CONCLUSIONS

A simple, objective IA system was developed using two commercially available software packages. The system yielded reproducible results for a variety of bread crumb grain image features. Although the calculated values compared well with visual inspection, the role of this system was to provide objective measurement of features, not to simply mimic human perception. Bread crumb grain features, like traditional baking characteristics, were influenced in different ways and to different extents by the addition of fat or emulsifier or by extending mixing time. Statistical analysis confirmed that there were significant differences between the bread types, and these differences were evaluated using the IA system. Addition of fat or emulsifiers to the recipe had a significant effect on crumb grain features, including reduced number of cells/cm^2, a greater mean cell area, and a greater total cell area. Generally, addition of fat or emulsifiers to the recipe caused the same types of changes in crumb grain features, with the emulsifiers causing a marginally greater effect. Overmixing of dough caused a significant decrease in total cell area, mean cell area, and, consequently, in cell to total area ratio. All the bread types could be distinguished using the crumb grain feature profiles generated. Due to the fact that in optimally mixed dough the ability to sustain an open crumb structure is at a maximum, in the absence of a farinograph, crumb grain IA could be used to calculate optimum mixing time for wheat dough by determining the mixing time that produces bread with the greatest mean cell area.

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LITERATURE CITED

Bertrand, D., Le Guernevé, C., Marion, D., Devaux, M. F., and Robert, P. 1992. Description of the textural appearance of bread crumb by video image analysis. Cereal Chem. 69:257-261.
Bloksma, A. H., and Bushuk, W. 1988. Rheology and chemistry of dough. Pages 131-217 in: Wheat Chemistry and Technology, 3rd ed. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
Dallmann, H. 1958. Porentabelle. Verlag Moritz, Schäfer: Detmold, Germany.
Harrigan, K. A. 1997. Particle size analysis using automated image analysis. Cereal Foods World 42:30-35.
Harrigan, K. A., and Bussmann, S. 1998. Digital speck counting of semolina using automated image analysis. Cereal Foods World 43:11-16.
Haymann, D., Hoseney, R. C., and Faubion, J. M. 1998. bread crumb grain development during baking. Cereal Chem. 75:577-580.
Hoseney, R. C. 1994. Yeast leavened products. Pages 229-273 in: Principles of Cereal Science and Technology, 2nd ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
Junge, R. C., Hoseney, R. C., and Varriano-Marston, E. 1981. Effect of surfactants on air incorporation in dough and the crumb grain of bread. Cereal Chem. 58:338-342.
Kilborn, R. H., and Tipples, K. H. 1981. Canadian test baking procedures. II. GRL-Chorleywood method. Cereal Foods World 26:628-630.

Liu, W., Tao, Y., Siebenmorgen, T. J., and Chen, H. 1998. digital image analysis method for rapid measurement of rice degree of milling. Cereal Chem. 75:380-385.

Noll, B., and Kuhn, M. 1997. Bildanalyse zur Strukturbeschreibung von Lebensmitteln am Beispiel von Brotkrumen und Blätterteiggebäck. Getreide Mehl und Brot 51:98-103.

Rogers, D. E., Day, D. D., and Olewnik, M. C. 1995. Development of an objective crumb-grain measurement. Cereal Foods World 40:498-501.

Saadi, A., Lempereur, I., Sharonov, S., Autran, J. C., and Manfait, M. 1998. spatial distribution of phenolic materials in durum wheat grain as probed by confocal fluorescence spectral imaging. J. Cereal Sci. 28:107-114.

Sapirstein, H. D., Roller, R., and Bushuk, W. 1994. Instrumental measurement of bread crumb grain by digital image analysis. Cereal Chem. 71:383-391.

Zayas, I. Y. 1993. digital image texture analysis for bread crumb grain evaluation. Cereal Foods World 38:760-766.

Zayas, I. Y., and Steele, J. L. 1996. Image texture analysis for discrimination of mill fractions of hard and soft wheat. Cereal Chem. 73:136-142.

Zayas, I., Pomeranz, Y., and Lai, F. S. 1989. Discrimination of wheat and nonwheat components in grain samples by image analysis. Cereal Chem. 66:233-237.

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