Effects of Heat and Water Transport on the Bagel-Making Process: Conventional and Microwave Baking[1]

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ABSTRACT

Bagels were baked by conventional forced-air (CVFA) and microwave heating methods after the boiling step. Differences in temperature histories and water loss rates for bagels heated by the two modes of heating were found. The bagel structure was examined by scanning electron microscopy after boiling and compared with structures observed in the unheated dough. Starch granules appeared most changed near the surface and least changed near the center of the bagel ring. Water was absorbed in the surface area of the boiled bagel but the ^2H relaxation rates were not different from the dough. The bagel structure examined by microscopy after baking showed differences in cell structure matrix development and starch swelling as a function of location or heating method. Differences were found in moisture content in the sampled areas within and between heating methods, however ^2H R_l values were not different above 34.1% moisture content.

A dough heated by conductive heat transfer undergoes structural transformations and mass transfer of water as the sample is heated from the outer surface inwards. In contrast, microwave radiation interacts under ambient oven conditions with the molecules that are coupled, such as water (including its dissolved solutes and ions), producing heat, which then results in structural changes and water movement. Localized heating can result because of the manner by which microwave radiation enters the sample, and it results in an unevenly baked product. Some studies have examined cakes (Brand 1987, Evans 1982), starch (Zylema et al 1985), and gluten (LePage et al 1989) heated in conventional versus microwave ovens. Little work on the behavior of water in microwave-baked dough products has been reported.

During the bagel-making process (dough formation, boiling, and baking), water movement will influence the bagel structure. Structural changes to starch and matrix can be observed with scanning electron microscopy (SEM). Overall and localized moisture contents can provide information on the extent of movement of water, and nuclear magnetic resonance (NMR) can give an indication of the behavior of water nuclei.

Pulsed NMR experiments have been used to examine the relaxation of the water nuclei in various food systems. R_1 relaxation is an averaged value for the type of nucleus being studied in the system, with the relative population of each phase of water having its proportionally weighted influence on the result (Zimmerman and Brittin 1957). Hydrated flour or its components (starch and gluten) have been studied with ^1H (Belton et al 1988, Richardson et al 1986, Wynne-Jones and Blanshard 1986) and ^2H (Leung et al 1983) nuclei. These studies of water nuclei interpreted an increased rate of relaxation of the nuclei as relating to a decreased mobility of the water molecules. Protons are often used to evaluate systems containing water because an adequate signal can be obtained. However, Edzes and Samulski (1978) showed that ^1H cross-relaxation can give inaccurate NMR results. Therefore ^2H NMR can be used to obtain more accurate results (Edzes and Samulski 1978).

In this study, bagels were heated in a controlled environment oven by conventional and microwave heating methods.

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Temperature profiles and water loss rates (WLRs) were recorded. Starch, matrix, and crumb cell structure changes were observed by scanning electron microscopy (SEM). Localized and overall moisture contents were determined. ^2H NMR was used to examine the mobility of the nuclei at various stages of the bagel-making process for bagels made with D_2O.

MATERIALS AND METHODS

Bagel Formula

The bagel formulation and method of preparation (Fig. 1) were based on those of Petrofsky (1986). Ingredient quantities were based on a percentage of the flour, as follows: bread flour 100%, sucrose 0.60%, NaCl 2.00%, H_2O/D_2O 54.49/60.53% (calculated on an equimolar basis), and yeast 0.73%. All the ingredients were of a household type, except the deuterium oxide (D_2O) (99.8% D, Aldrich Chemical Company, Inc., Milwaukee, WI). An equivalent amount of D_2O was substituted for water in bagels for NMR experiments. No differences in dough behavior or handling were observed when an equal number of moles of D_2O was substituted for water. A hybrid microwave and conventional forced-air oven (Hung 1980) was used during baking with conditions given in Figure 1. Baking times were predetermined in preliminary experiments by conventional forced-air heating. Microwave baking times were chosen so that similarly shaped temperature profiles were obtained for both modes of heating, although the total time of baking was different.

Weigh ingredients; dissolve salt and sugar in 2/3 the water; dissolve yeast in remaining 1/3; add water mixtures to flour

↓

Combine with household mixer: paddle - speed 2, 1 minute; dough hook - speed 4, 9 minutes

↓

Rest 10 minutes in mixing bowl

↓

Roll 1.5 cm thick; cut into bagel shape (outer diameter 7 cm; hole diameter 3 cm)

↓

Rest ambient temperature (23°C) and humidity (30-80%) 30 minutes; wrap in waxed paper

↓

Boiling water (1.5% sugar) 2.25 minutes

↓

Dry on rack approximately 5 minutes

↓

Bake

Conventional-forced air	Microwave
metal non-stick sheet	teflon sheet
10 SCFM air flow	still air
196 °C, 15 minutes	2450 MHz, 300 Watts
	90 seconds

Fig. 1. Bagel-making process.

Temperature Profiles and Gravimetric WLRs

Fiber optic temperature probes (Luxtron 1000A or 750 fluoroptic temperature sensor) were used to obtain the temperature profiles. The end of the probe was positioned in the geometric center of the bagel ring opposite the side where the microwaves entered the oven. Temperatures were recorded every minute during conventional forced-air baking and every 10 sec during microwave baking.

The bagel weight during baking was recorded at the same time intervals as the temperature profiles. Average WLRs over three recorded measurements were calculated by equations 1 and 2. Average WLRs for the microwave-baked bagels were multiplied by six so the y-axis of the two plots would be on the same scale.

$$\mathrm{WLR}_n = \mathrm{weight}_{n-1} - \mathrm{weight}_n \quad (1)$$

$$\text{Average } \mathrm{WLR}_n = (\mathrm{WLR}_{n+1} + \mathrm{WLR}_n + \mathrm{WLR}_{n-1})/3 \quad (2)$$

Sampling Method

The bagel was evaluated at the end of distinct heating stages of the bagel-making process: the boiling step, the conventional forced-air (CVFA) baking period, and the microwave baking period (subdivided into two regions—baked, microwave-B, and doughy, microwave-D). The two regions of the microwave-heated bagel were visually selected because the bagel did not heat evenly. Three positions of each heating stage were examined, as shown in Figure 2: the crust, midway, and center positions. The midway and center positions will be referred to as the crumb.

Microscopy

Samples for SEM were cut in the shape of an isosceles triangle in order to identify the position of the area observed. They were affixed to aluminum stubs with silver paint and left to dry overnight in a desiccator over calcium carbonate. After coating with gold/palladium (Denton evaporator), the samples were viewed by a Philips SEM (model PSEM 500) at 6 kV.

Moisture Content

Localized moisture contents were determined in triplicate for each of three or four replications of each treatment with the vacuum oven method (AACC 1983). Overall moisture contents were determined gravimetrically.

Nuclear Magnetic Resonance

NMR experiments were performed on an NT-300 WB Technologies, Inc. (General Electric, Fremont, CA) spectrometer at 46.06 MHz deuteron resonance frequency using Nicolet 1280 software (version 50728). The number of acquisitions required for an adequate signal-to-noise ratio was 40 for all samples except the CVFA crust, which required 100 scans. A spectral width of ±10,000 Hz was used. Samples were cut small enough to fit easily and without excessive compression into 5-mm NMR tubes and run within 1–2 hr of baking.

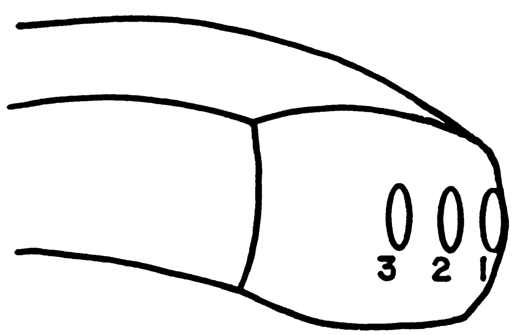

Fig. 2. Cross section of a bagel showing positions sampled: **1** = crust, **2** = midway, **3** = center.

The longitudinal relaxation rates (R_1) were obtained using an inversion recovery pulse sequence of $180°_x$–delay–$90°_x$. The 90° pulse used was 125 μsec, the 180° pulse used was 250 μsec, and the delays ranged from 0.75 to 200 msec with a 1 sec delay used to obtain the maximum signal. The areas under these resultant peaks were obtained using GEN software (version 7.03, General Electric Company). The method of Martin et al (1980), with the aid of the program Cricket Graph (version 1.3, Cricket Software), was used to obtain the value for the longitudinal relaxation time (T_1). R_1 is the inverse of T_1.

Statistical Analysis

The moisture content and R_1 data were analyzed separately by analysis of variance using the general linear model of the Statistical Analysis System (SAS 1987) with a split-plot design. The stage of the bagel-making process (dough, boiled, CVFA, microwave-B, microwave-D) was the main treatment and the position within the bagel was the split-plot (or subplot). When significant values of F ratios (the mean square of the treatment to mean square of error) were found, tests were conducted to compare the means. Dunnett's test (Montgomery 1984) was used to compare the means for each of the three boiled positions to the dough, and Duncan's test (Montgomery 1984) was used to compare the means from all three positions for all four heating methods.

RESULTS AND DISCUSSION

Temperature Profiles and WLRs

Similar appearing temperature profiles were found between the two baking methods even though the actual temperatures were different per fraction of baking time and the total baking time was shorter for microwave heating. Representative time-temperature plots for CVFA and microwave baking are shown in Figure 3A and B, respectively. During the first two-thirds of the baking period the temperatures increase until they reach and remain constant at approximately 102.5°C for the last one-third of each baking period. The major temperature profile difference occurs during the first two-thirds of the baking period. The profiles for the CVFA samples are slightly concave whereas those for the microwave samples are slightly convex. Also, the temperatures are higher for a proportionally longer period of time during CVFA heating. Surface temperatures, however, for CVFA-heated bagels are probably higher than 100°C (LePage et al 1989, Galletti et al 1980). During microwave heating, it is possible that the interior temperature may be greater than the surface temperature, as shown for a model gluten system (LePage et al 1989). The shape difference in the temperature profiles between the two baking methods would be due in part to a difference in the heat transfer mechanisms (Wei et al 1985a,b) and in the way the heating front is moving through the dough ring (Zylema et al 1985).

The WLR data for CVFA baking (Fig. 4A) show an increasing but variable rate of water loss during baking. Once the internal temperature reaches 100°C, the WLR remains constant until the end of the baking period. During microwave heating (Fig. 4B), the WLR is also increasing, but at a much higher rate and with a smoother curve than during CVFA baking; there is no constant WLR period. The lack of a constant WLR at the end is because the surface temperature is less than 100°C. From these results, it can be seen that a large amount of water could be lost within a short period of time during microwave heating of bagels if the heating period were extended past the "point of doneness," even by a few seconds. For example, from the WLR seen at the end of the baking period, at least 1.5 g of water could be lost in 30 sec more of baking. This is equal to almost half of the total water loss during the entire microwave baking period.

After baking, net water loss of 6.0 g for CVFA-heated bagels and 4.0 g for microwave-heated bagels was found (initial weight was 46 ± 3 g before baking).

Scanning Electron Microscopy

Scanning electron micrographs for the first part of the bagel-making process are shown in Figure 5. Wheat starch granules typically exhibit two sizes, and this can be clearly seen in the dough (Fig. 5A), where little matrix masks the starch granules. The surface of the starch granules appears pitted, which is probably due to protein bodies during granule formation (Hoseney et al 1977). Crust, midway, and center position samples (Fig. 5B, C, and D, respectively) from the boiled bagel show decreasing changes in starch granule structure compared with unheated granules. The larger starch granules in the crust have begun to fold, and the smaller starch granules appear dimpled. Larger granules in the middle position are similar to those in the unheated dough and some of the smaller granules are dimpled. There is some matrix development around the granules in the center position, but otherwise no change appears when compared with the dough. Fibrillar appearing structures, which are attributed to gluten strands, were seen in the heated samples but not in the dough. The expansion of the air cells during boiling is evident.

Representative scanning electron micrographs from baked bagels are shown in Figure 6. The crust from the CVFA heated bagel (Fig. 6A) appears compact. Figure 6B shows that the CVFA midway and center positions are similar in appearance. Crust

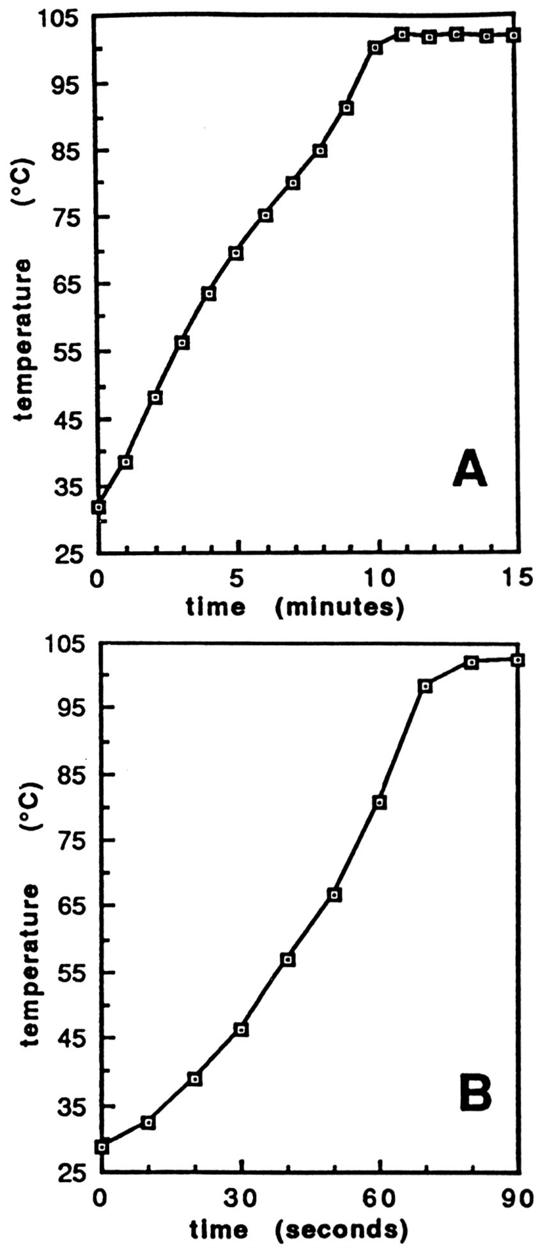

Fig. 3. Temperature profiles for the two baking methods: **A,** conventional forced-air; **B,** microwave.

from the microwave-B region (not shown) was similar in appearance to that of the crust from CVFA baked bagels but was slightly less compact. The two crumb positions of the microwave-B region have a similar appearance (Fig. 6C), containing less ropiness and more matrix development (masking the starch granules) than crumb from CVFA baked bagels. Crust from the microwave-D region (not shown) contained matrix that was developed to the extent that starch granules were difficult to see. Some of the starch granules appeared dimpled. At the midway position of the microwave-D region (not shown), not as many starch granules appeared folded relative to the center position (Fig. 6D). Both of these crumb positions contained ropey structures. Air cells are clearly seen in the crumb position of all three baked regions. Furthermore, the microwave-B region appeared to expand more than the microwave-D region.

Moisture Content and R_1 Data

Localized moisture contents and R_1 data obtained from a single broad Lorentzian shaped peak (with half-height about 200 Hz) are given Tables I, II, and III.

The moisture contents and R_1 values for dough and three positions of boiled samples (Table I) show that the crust contained a significantly larger amount of moisture than the dough but did not differ in R_1.

The localized moisture contents (Table II) in the crust for each of the stages significantly differed from one another. However, at the midway position, the CVFA and microwave-D region samples contained the same amount of water, and the microwave-B region samples had less water; the boiled sample had the most. Samples from the center position of the CVFA bagels had the same water content as the boiled samples, and the CVFA samples had the same moisture content as those of the microwave-D region. Furthermore, for the center position, the microwave-B samples had the least water content of all stages studied; for each stage there was a significant difference between the crust and the two crumb positions.

The CVFA baked bagel lost more water during baking than the microwave-baked bagel. However, crumb from microwave-B samples had lower moisture contents than crumb from CVFA and microwave-D samples. Therefore, it was concluded that the resultant very dry surface produced during CVFA baking was a major contributor to the greater overall water loss seen in those bagels compared with those heated by microwave. Most of the water loss in microwave-heated bagels occurred after the bagels were removed from the oven, and was probably due to the absence

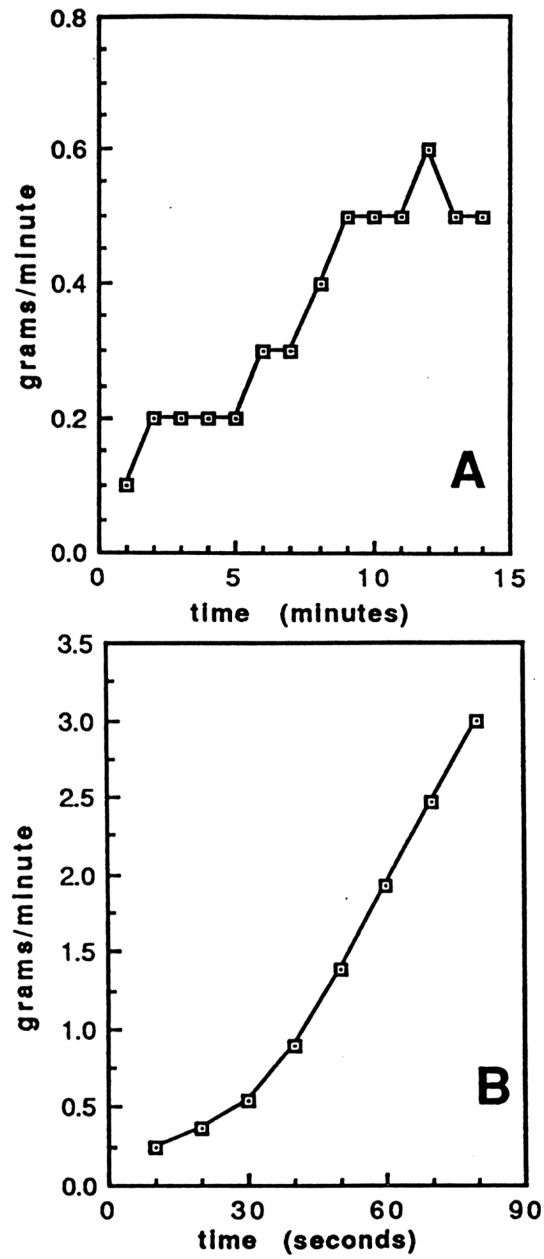

Fig. 4. Water loss rate curves for the two baking methods: **A,** conventional forced-air; **B,** microwave.

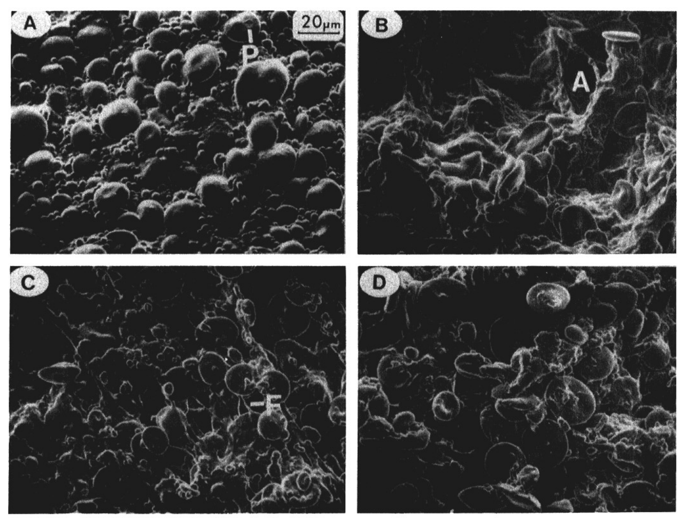

Fig. 5. Scanning electron micrographs of a bagel before baking: **A,** dough; **B,** boiled crust; **C,** boiled midway; **D,** boiled center. Air cell (**A**), fibrillar structure (**F**), pit (**P**).

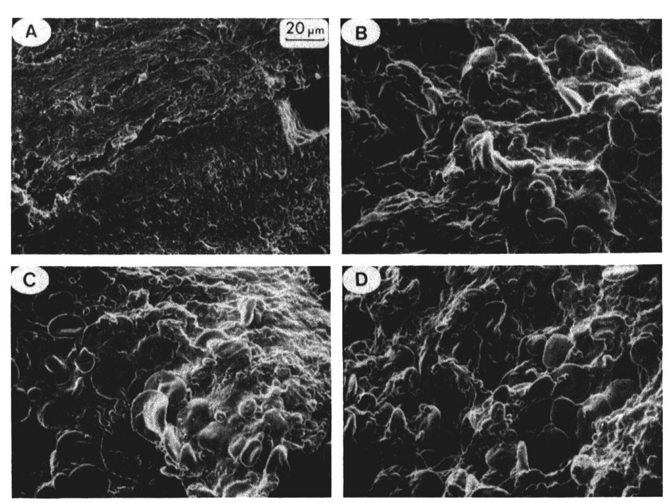

Fig. 6. Scanning electron micrographs of baked bagels: **A,** conventional forced-air crust; **B,** conventional forced-air crumb; **C,** microwave baked crumb; **D,** microwave doughy center.

TABLE I
Moisture Content and Relaxation Rate (R_1) for Dough Before and After Boiling

Sample	(%) Moisture	R_1 (sec^{-1})
Dough	39.6	19.13
Boiled		
crust	44.6[a]	24.75
midway	40.5	22.88
center	40.0	23.50
SD	1.9[b]	3.73[c]

[a] Significantly different ($P = 0.05$) from the dough according to Dunnett's test.
[b] $n = 9$.
[c] $n = 4$ or 5.

TABLE II
Moisture Content for Heat-Treated Samples

	Moisture[a] (%)			
Position	Boiled	CVFA	MW-D	MW-B
Crust	44.6 a	20.2 h	34.1 e	29.9 g
Midway	40.5 b	36.7 d	38.3 cd	32.0 f
Center	40.0 bc	38.1 cd	36.9 d	32.3 ef

[a] Standard deviation: 2.0 ($P = 0.05$; $n = 9$ or 12). Moisture contents followed by different letters indicate a significant difference between means according to Duncan's test. CVFA = conventional forced-air baked, MW-D = microwave doughy region, MW-B = microwave baked region.

of a dehydrated crust which could act as a barrier to moisture transport.

R_1 values for the four treatments and three positions (Table III) showed significant differences in R_1 for the CVFA crust relative to the other crust positions, and the microwave-B midway relative to the other midway positions. Examination of the three positions within a heating method shows that there are differences between the positions in the CVFA and microwave-B samples only. The data show that R_1 values were the same above a moisture content of 34.1%. At about 29.9–34.1% moisture, the R_1 values vary and may be due to slight differences in moisture content rather than critical level for R_1 changes. At 20.2% moisture, the R_1 value is very different and large.

Moisture content values between 30 and 33% were found to be equivalent to the level of bound water by Wynne-Jones and Blanshard (1986) and Wootton and Bamunuarachchi (1979) for starch and Shanbhag et al (1970) for flour. For the purposes of this discussion, bound water is defined as that which is not free (bulk). When the water content of the bagels was greater than 32%, structural changes were evident by SEM, but the mobility (R_1) was not significantly different.

In summary, differences in temperatures, WLRs, and moisture contents were not always reflected in structural changes as seen by SEM or R_1 data for ^2H NMR. We must remember that events that occur at a microscopic level are not always measurable at the more macroscopic level.

CONCLUSION

Conventional forced-air and microwave baking have different heating mechanisms that result in different temperature profiles and WLR curves. During conductive heat transfer in a hot oven, most water loss resulted from the dehydration of the crust. Heating by electromagnetic coupling with individual nuclei in a cool oven resulted in an overall smaller amount of water loss during heating, with most evaporation taking place after removal from the oven. Physical changes observed by SEM for the dough during boiling appeared related to temperature changes and not directly to changes in moisture content and/or relaxation. Also, when samples were examined after the oven heating stages, the scanning electron micrographs showed bagel structural changes that were not directly related to the differences in moisture content or NMR results. With the methods presented here to determine R_1, we were not able to statistically differentiate changes at the molecular level when the water content was greater than 34.1%. We attribute this result to the domination of the signal by the bulk water when its relative quantity was greater than the bound water. Unevenness of microwave heating of the product could be detected by all three methods of examination.

TABLE III
R_1 for Heat-Treated Samples

	Longitudinal Relaxation Rate[a] (sec^{-1})			
Position	Boiled	CVFA	MW-D	MW-B
Crust	24.75 d	128.48 a	38.99 bc	49.62 b
Midway	22.89 d	26.06 cd	29.04 cd	49.70 b
Center	23.50 d	27.65 cd	28.02 cd	34.08 cd

[a] Standard deviation: 7.92 ($P = 0.05$; $n = 3$, 4, or 5). Relaxation rates followed by different letters indicate a significant difference between means according to Duncan's test. CVFA = conventional forced-air baked, MW-D = microwave doughy region, MW-B = microwave baked region.

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