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Destructuration mechanisms of bread enriched with fibers during mastication

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ABSTRACT

Three breads of different densities and salt contents were chewed by 16 healthy subjects, with controlled physiological characteristics, for three different stages of mastication until swallowing. The distribution of chewed bread particle size was determined by imaging of the boluses at each stage, for the 3 breads and all subjects. Bread piece was reduced into an increasing number of small particles with a median size, function of mastication time, taking an average value of 1.9 mm at swallowing. Bolus moisture content could be predicted from theoretical salivary flow and particle median size. Bolus consistency was derived from the apparent viscosity measured by capillary rheometry. It decreased with chewing time, and this decrease was linked to bolus moisture by a plasticization coefficient, which varied with the individual ($12 < \alpha < 30$). A basic model involving hydration and fragmentation could be suggested to predict bread destructuration, defined by the ratio of consistency of the bolus on that of initial bread.

1. Introduction

Bread is a staple foodstuff, made and eaten in most countries around the world. It is recognized that the nutritional properties of breads could be improved by the addition of dietary fibers and the reduction of salt content (Poutanen, Sozer, & Della Valle, 2014; Saulnier, Micard, & Della Valle, 2014). However, both recommendations lead to a loss of sensory properties, which challenge consumer's acceptance for new foods with improved nutritional properties. In addition, an increase of bread density, or reduction of bread volume, has also been shown to reduce the glycemic index (GI) (Burton & Lightowler, 2006; Saulnier et al., 2014), while the full explanation of this result is still to be determined.

So, in regard to these nutritional stakes, the studies on bread bolus formation during chewing have been increased, because mastication is the first important step of the digestion process, implying complex oral processing to prepare food for swallowing. Some studies have focused on the links between the structure and composition of bread with salt release and saltiness perception, combining in vitro (mastication simulation) and in vivo (sensory panel) analyses. Tournier, Grass, Zope, Salles, and Bertrand (2012), and Tournier, Grass, Septier, Bertrand, and Salles (2014) confirmed the significance of bolus formation strategies according to subjects and bread texture, and their influence on sodium release, thanks to an image analysis method to evaluate bolus heterogeneity. Pflaum, Konitzer, Hofmann, and Koehler (2013) showed that bread with coarse crumb texture, but lower density, led to more enhanced salty taste than a bread with finer crumb, but higher density. Panouillé, Saint-Eve, Déléris, Le Bleis, and Souchon (2014) confirmed Pflaum's results by showing that denser bread was found less salty, and also found that bolus viscoelastic moduli were not key variables in swallowing. Due to the importance of α-amylolysis on starchy foods digestion (Butterworth, Warren, & Ellis, 2011), some studies on bread chewing have focused on the factors involved in bolus hydrolysis, including the role of salivary α-amylase. Hoebler, Devaux, Karinthi, Belleville, and Barry (2000) first stressed the role of the size of bread pieces, smaller ones favoring saliva impregnation. Bornhorst and Singh (2013) underlined the role of α-amylase on bread bolus texture, during simulated gastric digestion. In line, Pentikaïnen et al. (2014) showed that hydrolysis kinetics of chewed boluses significantly differed at times larger than oral residence time. Their results also confirmed the importance of composition (wheat, endosperm and whole rye flours) and bread texture (density, cellular structure). Gao, Wong, Lim, Henry and Zhou (2015) underlined the role of this last factor on oral processing, by studying the chewing of breads processed under various conditions leading to different densities and cellular structure.

Whatever the methods used to assess bread destructuration (imaging, rheology), these studies agree that two main mechanisms control

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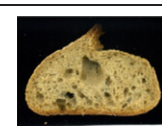
Nomenclature

AM	Amylase activity in saliva (UI.mL^{-1})
EM	Masticatory efficiency (%)
GI	Glycaemic index (—)
K, K_0	Consistency index of bolus and bread crumb, respectively (Pa.s^n)
n	Bolus flow index (—)
n_1, n_2	Adjusted exponents for fragmentation and salivation, respectively (—)
N	Chewing cycle (—)
Q_s	Stimulated salivary flow, function of the individual (mL.min^{-1})
T	Total chewing time before swallowing, function of the individual (s)
V_s	Theoretical amount of saliva in the mouth, function of the individual (mL)
w_{50}	Median particle width (mm)
WC	Moisture content (total wet basis)
ΔWC	Water uptake from saliva (%, wet basis)
α	Plasticization coefficient (—)
β	Adjusted coefficient for salivation (—)
η_{app}	Apparent viscosity (Pa.s)
ρ^*	Crumb density (g.cm^{-3})
$\dot{\gamma}_{app}$	Apparent shear rate (s^{-1})

bread breakdown and bolus formation: fragmentation of the food pieces and lubrication by saliva, that lead to particle agglomeration. This is in accordance with Hutchings and Lillford (1988) who suggested that a certain "degree of structure" (particle size) and a certain "degree of lubrication" (amount of saliva), as well as a certain "time" (time in the mouth) must be reached for a comfortable deglutition. During chewing, the fragmentation of the food into smaller particles increases their surface area exposed to saliva and air, in order to release flavor compounds in the mouth and to facilitate further breakdown in the stomach. Depending on mechanical characteristics of the foods, fragments would reach a critical particle size (i.e., 0.8–3 mm for various solid foods) prior to bolus formation; this critical size tends to be similar among subjects (Hoebler et al., 2000; Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007; van der Bilt & Fontijn-Tekamp, 2004). For brittle foods, the bolus particle size decreases mostly during the first third of the masticatory sequence (Hedjazi, Guessasma, Yven, Della Valle, & Salles, 2013; Peyron et al., 2011). In the case of a ductile food like bread, this mechanism is more difficult to assess since particle size measurements require bolus dispersion in alcoholic solvents.

Saliva plays an important role on taste, mastication, bolus formation, enzymatic digestion and swallowing (Pedersen, Bardow, Jensen, & Nauntofte, 2002). The production of sufficient saliva is indispensable for good chewing. The volume of saliva incorporated during chewing can vary from 0.4 to 1.7 mL, before swallowing, according to Müller et al. (2010). The salivary impregnation increases with chewing time and the bolus water content largely contributes to swallowing (Panouillé et al., 2014). More saliva is required for mastication of crispy

Table 1
Composition and texture properties of the three bread and crumbs.

Bread	Salt content (%, w/w)	Crumb density (g.cm^{-3})	Crumb water content (%, wet basis)	Apparent modulus (10^5.Pa)	Residual stress (10^5.Pa)	Consistency index (K_0, Pa.s^n)	Image of bread cross section
B1	1.4%	0.34 ± 0.02 ^{b}	50.9 ± 0.4 ^{b}	13.1 ± 1.2 ^{a}	2.8 ± 0.5 ^{b}	7.3 ± 0.1 ^{a}	
B2	1.8%	0.25 ± 0.01 ^{a}	49.2 ± 0.5 ^{a}	13.1 ± 1.0 ^{a}	2.4 ± 0.1 ^{a}	11.3 ± 0.2 ^{c}	
B3	1.4%	0.26 ± 0.01 ^{a}	48.5 ± 0.4 ^{a}	12.3 ± 1.0 ^{a}	2.1 ± 0.3 ^{a}	9.9 ± 0.1 ^{b}	

All bread characteristics were measured six times on different crumb samples, and an average value and standard deviation were derived. Letters a, b, c indicate means that significantly differ at $p < 0.05$ (Student–Newman–Keuls test). Apparent modulus (E_{bread}) and apparent stress (σ_r) are determined from the initial slope of the force-displacement curve and the resistance at the end of relaxation step, respectively, after the multi-indentation test, according to Chaunier et al. (2014). Consistency index was determined by capillary rheometry and derived from the power law of apparent viscosity, as explained in Section 2.3.1.

Table 2
Physiological parameters, chewing time and cycles until swallowing, for the 3 breads and 16 subjects.

	Units	Mean value ± SD	Minimum value	Maximum value	Values from literature [References]	[References]
Stimulated saliva flow	mL/min	1.9 ± 0.8	0.7	3.5	0.4–4.1	[1] [2]
Masticatory efficiency	%	52.5 ± 13.3	25.9	73.7	25–82	[3] [4]
Amylase activity	UI/mL in saliva	51.1 ± 34.1	2.6	109.5	30–307	[2] [4]
Chewing time T	(s)	B1: 21.1 ± 10 ^{a}	10.0	52.1	10–27	
		B2: 20.7 ± 12 ^{a}	7.5	55.8		[4]
		B3: 20.5 ± 10 ^{a}	8.4	53.1		
Chewing cycles N	(—)	B1: 30.8 ± 14 ^{a}	17.3	75.3	14–28	
		B2: 29.4 ± 14 ^{a}	17.3	71.7		[5]
		B3: 29.0 ± 15 ^{a}	15.7	76.0		

[1] Chen (2009); [2] Neyraud et al. (2003); [3] van der Bilt and Fontijn-Tekamp (2004); [4] Panouillé et al. (2014); [5] Engelen et al. (2005). Bread values (means) associated with the same letter are not significantly different (p-value >0.05).