Modified atmosphere packaging of hen table eggs: Effects on functional properties of albumen

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ABSTRACT The aim of this study was to compare technological properties (gel hardness, foam drainage, and meringue crispness) of albumen of nonpacked table eggs (control) with those of eggs packed in high-barrier plastic pouches with 3 modified atmosphere packaging (MAP) conditions (air, 100% N_2, and 100% CO_2) during 28 d of storage at 25°C. The values of gel hardness for the control sample showed an increasing trend, demonstrating the highest values throughout the experiment duration compared with the other samples. This behavior was probably attributable to the pH increase detected only for this sample during storage (from 8.82 ± 0.06 for fresh egg to 9.96 ± 0.06 at the end of the experiment). Air and N_2 samples showed constant and similar hardness values during storage. The hardness of coagulated albumen showed a strict correlation with raw albumen pH ($r^2 = 0.929$; $P < 0.001$). Other than reducing albumen pH during storage, MAP with CO_2 caused the formation of a soft and puffy coagulum with very low hardness, reaching the lowest value of 1.26 ± 0.38 N after 4 d of storage, that slowly increased to 2.11 ± 0.49 N at the end of the experiment. Foam stability decreased during storage for all samples, but CO_2 eggs showed a significantly ($P < 0.05$) higher foam stability than fresh eggs until 15 d, reaching values similar to those of the other samples only at the end of the storage time. Packing eggs in CO_2 promoted an improvement of meringue crispness. The application of this atmosphere could ameliorate the quality characteristics of albumen-based food products. Commercially, CO_2 MAP could provide an albumen-based ingredient tailored to maximize the characteristics needed in the final product (e.g., fresh shell eggs special for meringue preparation) that could give an added value to the product.

Key words: shell egg, modified atmosphere packaging, albumen, functional property

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INTRODUCTION

From a technological point of view, the egg may be considered a multifunctional ingredient because it can perform several functions by means of its coagulating, foaming, emulsifying, coloring, flavoring, anticrystallizing, and nutritional properties (Yang and Baldwin, 1995). Products of egg albumen are important food commodities because they are used in a vast number of food formulations (Liang and Kristinsson, 2007).

Heat coagulation is one of the most important functional properties of egg white (Hermansson, 1979). This phenomenon is a multistage process that plays a key role in determining the rheological and textural properties of products such as cakes, egg-based creams, confectionery, and surimi seafood (Raikos et al., 2007). Coagulation is described as the random aggregation of already-denaturated protein molecules (Hermansson, 1979). Hydrogen bonds are broken, polypeptide chains are uncoiled, and reactive groups are then exposed during protein denaturation (Powrie and Nakai, 1985).

In addition to coagulation, egg albumen proteins are responsible for different functional properties such as foaming, whipping, and viscosity building (Hsieh and Regenstein, 1989). The foam properties are determined by the ability to rapidly adsorb at the air–liquid interface during whipping or bubbling and to form a cohesive viscoelastic film by way of intermolecular interactions (Mine, 1995). The foam collapse is described by 3 principal mechanisms: 1) liquid drainage, where liquid flows from the foam as a consequence of gravity force and the foam dries out; 2) bubble coalescence, where rupture of the film between 2 bubbles causes them to merge into 1 large bubble; and 3) bubble disproportionation, where gas diffusion from small bubbles, because of a higher gas pressure in large bubbles, results in shrinkage of small bubbles and growth of large bubbles in the

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course of time (Bisperink et al., 1992; Hammershøj et al., 1999). Whereas a model interface can be observed for hours or days to establish equilibrium, a foam made with egg white proteins starts changing within minutes of formation (Foegeding et al., 2006). The excellent foaming capacity of egg white proteins and the stability of the resulting foams (even when subjected to heating) are applied in the food industry in the preparation of, among others, cakes and meringues (Van der Plancken et al., 2007). For these products, conditions become more complex because stability must be maintained during additional formulation and processing.

The first part of this research work published in a previous paper showed experimental results concerning the MAP effects on freshness indices of eggs and on physicochemical properties of egg components (Rocculi et al., 2009). The aim of this study was to compare functional properties (gel hardness, foam drainage, and meringue crispness) of albumen of nonpacked hen's table eggs (control) with that of eggs packed in high-barrier plastic pouches with 3 modified atmosphere packaging (**MAP**) conditions (air, 100% N_2, and 100% CO_2) during 28 d of storage at 25°C.

MATERIALS AND METHODS

Egg and Sample Preparation

Experiments were replicated twice; each experiment was carried out on 1,170 eggs (average weight: 68.05 ± 4.23 g) obtained from Hyline Brown hens of about 32 wk of age. During each experiment, clean shell eggs laid the day before were placed on 140 plastic supports (Celplast Srl, Padova, Italy). Each support consisted of a receptacle with 8 cups, formed from transparent thermoplastic material, that enclosed and firmly held 8 eggs. A total of 105 filled supports were packed in 105 high-barrier multilayer (polyethylene-poliammide-polyethylene) pouches (20 × 30 cm, 105 μm thick; Reber Snc, Reggio Emilia, Italy) commonly used for undervacuum packaging. The samples were packed using a quaternary gas mixer (KM100-4, Witt-Gasetechnik, Witten, Germany) and a gas-flushing welding machine (Multiple 315, Orved Srl, Venezia, Italy). The following samples were prepared: control (not packed), air (packed in air), N_2 (packed in 100% N_2), and CO_2 (packed in 100% CO_2). A total of 50 table eggs were used for zero-time evaluations and 35 packages/sample were prepared and stored at 25 ± 2°C. Albumen of fresh eggs (zero time) and egg samples after 1, 2, 4, 8, 15, 21, and 28 d of storage were analyzed for pH, hardness after thermal coagulation, foam drainage after whipping, and meringue crispness after baking. Every sampling day, eggs of 5 packages for each sample were analyzed. Before analyses, albumen was separated from yolk, taking care to avoid contamination by the yolk content, particularly at the later stage of storage when for some samples the vitelline membrane was very weak and easily breakable.

Determination of pH

The pH of egg white was measured using a pH meter (Cyberscan 510, Lennox, Dublin, Ireland) at controlled temperature after gentle mixing to avoid foam formation and to homogenize thin and thick albumen layers. Two measurements per egg per package were performed.

Determination of Albumen Gel Hardness

Coagulation properties of egg albumen were determined following the method described by Hammershøj et al. (2001) with some modifications. Heat-coagulated albumen gels were prepared in triplicate for each sample by inserting about 40 g of gently mixed albumen, obtained from 1 shell egg, into a cylindrical glass jar (40 mm i.d., 35 mm height). The jars were closed with glass caps and submerged in a water bath at 90 ± 2°C for 30 min. Samples were allowed to cool on ice for 30 min. From each jar, 3 cylindrical samples of coagulated albumen (15 mm diameter, 10 mm height) were taken using a core borer and then subjected to texture profile analysis using a texture analyzer (HD500, Stable Micro Systems, Surrey, UK) equipped with a 50-kg load cell and a cylindrical probe (model P/25; 25 mm diameter). The gel cylinders were neither glued nor lubricated to the compression plate. Test speed was 0.5 mm/s and the samples were compressed twice to 50% of the original thickness (5 mm). Results were expressed as hardness, corresponding to the height of the force peak (N) on the first compression cycle (Bourne, 1982; HammershØj et al., 2001). Three eggs per sample from 3 packages for each sampling time were analyzed.

Determination of Foam Drainage

Foam drainage of the albumen was determined following the method described by Lechevalier et al. (2005) with some modifications. Foam was obtained at room temperature by whipping 100 g of gently mixed albumen, obtained from about 3 eggs from 3 packages, with a stand mixer (KSM90, Kitchenaid, St. Joseph, MI) at maximum speed for 2 min. A glass cylinder (45 mm i.d., 60 mm height) was filled with about 9.50 g of the obtained foam and placed in a funnel inserted in a graduated cylinder. The liquid amount (g) drained into the cylinder was weighed every 10 min during 60 min of analysis at 25 ± 2°C. The rate of liquid drainage (**RLD**) was calculated by linear regression of the liquid drainage values versus time. The measurements were performed in triplicate on the foam obtained from 3 eggs for each sample and sampling time.

Determination of Meringue Crispness

Hard meringues were prepared following the procedure described by Scholtyssek et al. (1994) with some modifications, with an albumen:sugar ratio of 1:2 (wt/

wt) and a whipping time of 8 min. Icing sugar was added to 120 g of albumen, obtained from 3 shell eggs, at 2 times: 120 g to raw albumen and 120 g gently after 7 min of whipping. The whipping process was performed with a stand mixer (KSM90, Kitchenaid) at maximum speed for 2 min. Aluminum pans (28 mL capacity, 45 mm diameter, 60 mm height) were then filled with fractions of 11 g of raw meringue and cooked in an oven at 90°C for 210 min. Three meringues per sample were prepared at each sampling time. Texture analysis was performed at 25 ± 2°C about 2 h after removing meringues from the oven, when they reached ambient temperature. A texture analyzer (TA-HDi500, Stable Micro Systems) equipped with a 50-kg load cell and a 3-point bending rig (HDB/3PB, support span of 16 mm) was used. One test was performed for each meringue using the following setting: pretest speed, 1.0 mm/s; test speed, 1.0 mm/s; posttest speed, 10 mm/s; data acquisition, 200 points/s; distance, 20 mm.

As an index of crispness, linear distance ($\mathbf{L_d}$) was determined, using the "linear distance" function within Texture Expert Exceed software (version 2.61, Stable Micro Systems), on a plot force (F) in newtons versus distance (D) in millimeters (Stable Micro Systems, 2000; Gregson and Lee, 2003) according to the following equation:

$$L_d = \sum_{x=1}^{x=n} \sqrt{\left[F(x+1) - F(x)\right]^2 + \left[D(x+1) - D(x)\right]^2}.$$

This function automatically calculates the line length by summing the lengths computed between consecutive data points using the Pythagoras equation. The software calculates L_d by summing the length of the straight segments connecting each point acquired (200 points/s) between selected times or distances. Although a "length" is calculated, distance units cannot be used because one axis has force units. Generally, an increase of L_d corresponds to an increase of crispness.

Statistical Analyses

The data were subjected to ANOVA and to the test of mean comparisons according to Fisher's least significant difference, with a level of significance of 0.05 (SAS Institute, 1988). Pearson correlation coefficients (r), regression model (R^2), and probabilities were calculated to evaluate the relationship between pH, hardness, RLD, and crispiness.

RESULTS AND DISCUSSION

Table 1 reports the hardness behavior of the heat-coagulated albumen samples. In general, the average values of hardness detected in our experiments (from 1.26 ± 0.38 to 6.18 ± 0.69 N) are comparable with those obtained by Hammershøj et al. (2001) on fresh eggs (from 4 to 7.5 N) laid by White Leghorn hens at different ages. The values of hardness for the control sample trendily increased, showing the highest hardness ($P < 0.05$) levels until the end of the experiment compared with the other samples. Actually, starting from fresh shell eggs with an average hardness value of coagulated albumen of 4.09 ± 0.20 N, this sample reached 5.19 ± 1.65 N after just 4 d of storage, maintaining values between 5.19 ± 0.61 and 6.18 ± 0.69 N until the end of the experiment. This behavior was probably attributable to the pH increase detected for this sample during storage, which showed values of 8.82 ± 0.06 at zero time and 9.96 ± 0.06 at the end of the storage period (Table 2), confirming previous observations (Rocculi et al., 2009). Beveridge et al. (1980) observed that in the pH range from 7 to 9 a higher firmness of albumen coagulum was found, in terms of shearing force measured by a multiple blade shear compression cell. This firmness increase as a consequence of pH increase was attributed to sulfhydryl-disulfide exchange, which was accelerated at pH 9. Our results agree with those of Chang et al. (1999) who showed that the hardness of albumen gel significantly increased ($P < 0.05$) as the adjusted pH increased from 7.5 to 10. Such an intense modification of coagulated albumen hardness was not detected for samples packed in air and in 100% N_2 (Table 1). These samples showed constant and similar values of hardness during storage that ranged from 3.13 ± 0.38 to 4.19 ± 0.61 N. These values were not much different from those of the fresh eggs (time 0 d) for the entire storage period. A similar behavior was observed for the albumen pH that for these samples remained close to the initial value (8.82 ± 0.06) for the entire storage period, confirming previous findings (Rocculi et al., 2009). A relationship between pH and hardness results was observed also for the sample packed in 100% CO_2. This sample showed a fast and marked pH decrease, reaching a value of 7.03 ± 0.14 after 8 d of storage as a consequence of CO_2 solubilization in the albumen (Li et al., 1985). This significant reduction in pH value was roughly maintained until the end of the storage period, and the albumen pH of this sample showed a value of 7.57 ± 0.09 after 28 d of storage (Table 2).

Nevertheless, the original pH of the albumen can be maintained by the addition of a proper concentration of CO_2 to the air. According to Aggarwal (2008), shell egg MAP with 20% CO_2 showed better maintenance of table egg functional quality. Actually, the fundamental cause of the increase in pH value, or increase in alkalinity in albumen and yolk, is the loss of CO_2 through the eggshell pores (Romanoff and Romanoff, 1949).

Also in terms of hardness, the coagulated albumen of the 100% CO_2 sample showed a fast and significant reduction, reaching a value of 2.20 ± 1.19 N after the first day of storage and maintaining this trend until the end of the experiment (2.11 ± 0.49 N at 28 d). As reported in previous investigations, this phenomenon is caused by the formation of a soft and puffy coagulum, which is attributed to the expansion of CO_2 during heating (Beveridge et al., 1980; Chang et al., 1999). According

Table 1. Hardness (N) of coagulated albumen cylinders obtained from shell egg samples during 28 d of storage at 25°C[1,2]

Time (d)	Control	Air	N_2	CO_2
0	4.09 (0.20)^{B,a}	4.09 (0.20)^{A,a}	4.09 (0.20)^{A,a}	4.09 (0.20)^{A,a}
1	4.85 (0.47)^{A,a}	3.18 (0.46)^{B,b}	3.74 (0.67)^{AB,b}	2.20 (1.19)^{B,b}
2	5.14 (0.60)^{A,a}	3.39 (0.97)^{AB,b}	3.47 (0.41)^{AB,b}	2.25 (0.74)^{B,b}
4	5.19 (1.65)^{AB,a}	3.71 (0.90)^{AB,a}	3.93 (0.48)^{AB,a}	1.26 (0.38)^{B,b}
8	5.82 (0.78)^{A,a}	3.34 (0.40)^{B,b}	3.83 (0.63)^{AB,b}	1.44 (0.48)^{B,c}
15	5.30 (0.60)^{A,a}	3.43 (0.39)^{B,b}	3.13 (0.38)^{B,b}	1.81 (0.66)^{B,c}
21	6.18 (0.69)^{A,a}	3.80 (0.50)^{AB,b}	4.19 (0.61)^{AB,b}	2.41 (0.63)^{B,c}
28	5.19 (0.61)^{A,a}	3.28 (0.41)^{B,b}	3.79 (0.33)^{AB,b}	2.11 (0.49)^{B,c}

^{A,B}Means within a column with different superscripts are significantly different ($P < 0.05$).

$^{a–c}$Means within a row with different superscripts are significantly different ($P < 0.05$).

[1]Mean (n = 6), with SD in parentheses.

[2]Control: not packed; air: packed in air; N_2: packed in 100% N_2; CO_2: packed in 100% CO_2.

to this finding, from a visual examination of the heat-coagulated albumen, control, air, and N_2 samples had a typical compact structure whereas the CO_2 sample was very soft and puffy (Figure 1). Beveridge et al. (1980) showed that this phenomenon occurs at a pH value <7. Chang et al. (1999) observed the formation of a denser structure in albumen gels as pH increased from 7.5 to 10 and a more porous structure at lower pH values. Hammershøj et al. (2002) stated that for food use, the optimal texture of albumen gel is obtained with table eggs stored for 14 d at 4°C because, due to the high CO_2 content, fresh albumen expands during heating and water-holding capacity tends to reduce. This happens also because the pH is closer to the isoelectric point of most albumen proteins. Correlation results (Table 3) confirmed this strict dependence between the hardness of coagulated albumen and its pH, showing a strong positive correlation between these 2 parameters ($r = 0.929$; $P < 0.001$).

Figure 2 shows the liquid drainage results versus time of analysis of albumen foam of fresh shell eggs and egg samples after 1 d of storage. At the end of the analysis, control, air, and 100% N_2 samples showed a similar amount of liquid drained (in the range from 3.27 ± 0.50 to 3.58 ± 0.23 g) that was more than the double of that of the fresh sample (1.68 ± 0.43 g). On the contrary, the foam obtained from the albumen of the CO_2 sample after 1 d of storage lost only 0.39 ± 0.18 g of liquid throughout the period of analysis (60 min). As reported by Liang and Kristinsson (2007), liquid drainage is inversely proportional to foam stability: the higher the liquid drainage, the lower the foam stability. When pH increases, a part of the egg white n-ovalbumin is transformed into s-ovalbumin, which is less hydrophobic than n-ovalbumin. This phenomenon interferes with the formation of a cohesive film at the water–air interface, causing a decrease in foam stability and thus the correlation between the pH and the volume of drained liquid is positive (Lomakina and Mìkovà, 2006). The pH decrease caused by CO_2 MAP promoted the increase of the foam stability obtained using albumen of the CO_2 sample. It is worth noting that altering the pH of a protein medium is a well-known method for unfolding proteins (Chang and Chen, 2000; Liang and Kristinsson, 2007). Few studies have recently shown that moderate unfolding of egg albumen using a simple pH-induced unfolding and refolding regimen could significantly improve its foaming capacity, foam stability, and general foam rheological properties in the pH range in which albumen is normally used (Liang and Kristinsson, 2005; Mleko et al., 2007). This is because moving to the pH region near the protein isoelectric point, the net charge is zero and electrostatic forces between molecules are minimal. This can favor nonelectrostatic intermolecular bonding and thereby increase the stability of the foam (Kato et al., 1985; Hammershøj et al., 2001;

Table 2. pH of albumen obtained from shell egg samples during 28 d of storage at 25°C[1,2]

Time (d)	Control	Air	N_2	CO_2
0	8.82 (0.06)^{D,a}	8.82 (0.06)^{B,a}	8.82 (0.06)^{B,a}	8.82 (0.06)^{A,a}
1	9.23 (0.03)^{C,a}	9.07 (0.19)^{AB,a}	8.92 (0.07)^{AB,a}	8.04 (0.24)^{B,b}
2	9.42 (0.21)^{BC,a}	8.82 (0.19)^{AB,b}	9.11 (0.05)^{A,b}	7.52 (0.07)^{C,c}
4	9.69 (0.03)^{B,a}	8.94 (0.21)^{AB,b}	9.04 (0.25)^{AB,b}	7.58 (0.04)^{C,c}
8	9.88 (0.05)^{A,a}	9.05 (0.34)^{AB,b}	9.09 (0.11)^{A,b}	7.03 (0.14)^{D,c}
15	9.82 (0.08)^{A,a}	8.92 (0.07)^{AB,b}	8.71 (0.21)^{B,b}	7.17 (0.15)^{D,c}
21	9.98 (0.05)^{A,a}	9.04 (0.12)^{A,b}	9.12 (0.09)^{A,b}	7.65 (0.09)^{C,c}
28	9.96 (0.06)^{A,a}	8.81 (0.19)^{AB,b}	8.94 (0.17)^{AB,b}	7.57 (0.09)^{C,c}

$^{A–D}$Means within a column with different superscripts are significantly different ($P < 0.05$).

$^{a–c}$Means within a row with different superscripts are significantly different ($P < 0.05$).

[1]Mean (n = 12), with SD in parentheses.

[2]Control: not packed; air: packed in air; N_2: packed in 100% N_2; CO_2: packed in 100% CO_2.

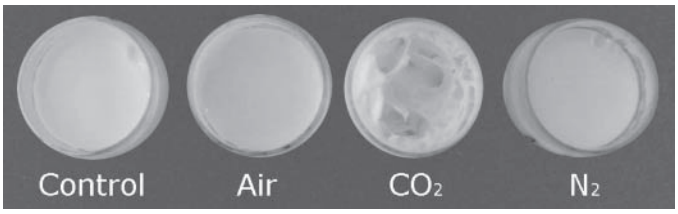

Figure 1. Coagulated albumen obtained from shell egg samples after 1 d of storage at 25°C. Control: not packed; air: packed in air; CO_2: packed in 100% CO_2; N_2: packed in 100% N_2.

Van der Plancken et al., 2007). On the contrary, Chang et al. (1999) showed that foam stability of albumen was not correlated with pH in the range between 7.5 and 10.

To have a more exhaustive parameter linked to foam stability, the slope of the straight line obtained by linear regression of the liquid drainage data (e.g., Figure 2) was calculated as RLD for the fresh shell eggs and various samples analyzed throughout the storage period (Figure 3). All the samples showed an increasing trend of RLD during storage because the stability of the foam became lower and lower as the storage time increased. Compared with fresh eggs, air, control, and N_2 samples showed lower foam stability (higher value of RLD) from the beginning of storage. In general, these samples had similar values of RLD that showed a strong increase from 8 to 15 d of storage. The RLD behavior of the CO_2 sample showed an apparent steady increase throughout the storage period that can be modeled with a simple equation: $y = -0.0002x^2 + 0.0077x + 0.0004$ ($R^2 = 0.998$). The foam stability of albumen of shell eggs packed in 100% CO_2 was significantly higher ($P < 0.05$) than that of the other samples until 15 d of storage, showing values similar to those of the other samples at the end of the experiment.

Table 3. Correlation coefficients between pH, hardness (F_{max}), rate of liquid drainage (RLD), and linear distance (L_d) results (n = 28)

Item	pH	F_{max}	RLD	L_d
pH	—			
F_{max}	0.929***	—		
RLD	0.392*	0.413*	—	
L_d	−0.408*	−0.464*	−0.887***	—

*Significant at 0.05; ***significant at 0.001.

By means of correlation analysis (Table 3) it is possible to note that pH and RLD were positively correlated ($r^2 = 0.392$; $P < 0.05$), suggesting that the pH was not the only factor responsible for the modifications detected on foam stability during storage. In addition, RLD showed a positive correlation with hardness ($r^2 = 0.413$; $P < 0.05$), demonstrating a small and inverse relationship between coagulating and foaming properties of egg albumen. Further investigations on the kind and amount of combined forms of CO_2 (e.g., aggregate of bicarbonate, carbamino, lipoids, unknown forms in which CO_2 is bound to proteins; Romanoff and Romanoff, 1949) present in the albumen of shell egg as a function of CO_2 partial pressure and storage time could clarify these aspects. This could permit a deeper understanding of the modifications of the physicochemical and technological properties caused by shell egg CO_2 exposure, also when conditions become more complex.

For instance, the complexity of the system increases in the production of foods such as meringue, where foam stability must be maintained during formulation and additional processing. With this product, the foam must show little expansion or collapse when heat setting causes drying and converts the foam from a liquid to a solid (Foegeding et al., 2006). The addition

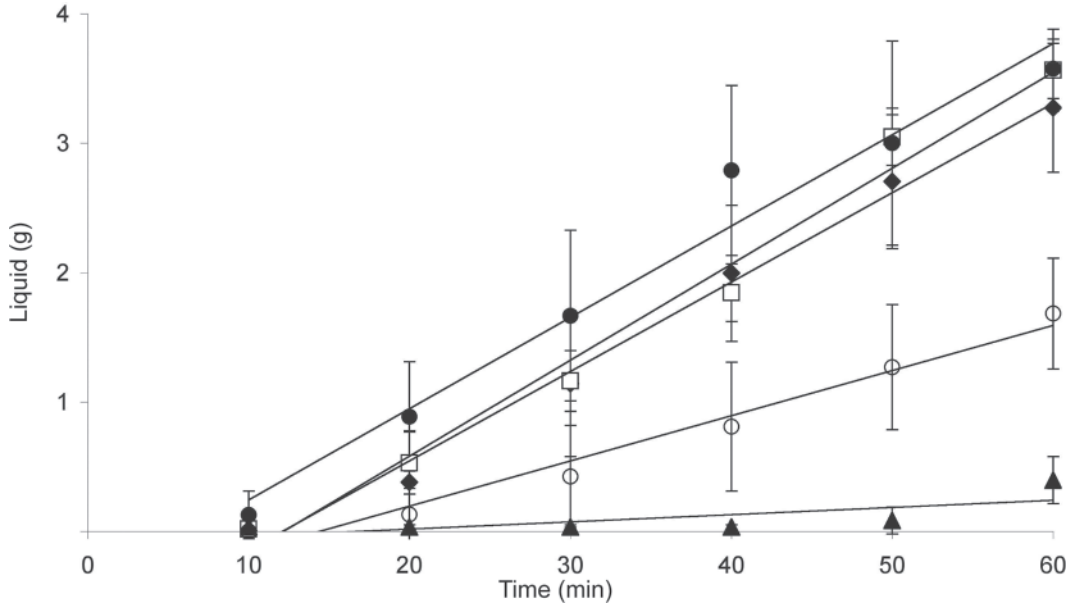

Figure 2. Liquid drainage (g) versus time of analysis of albumen foam obtained from fresh shell eggs and egg samples after 1 d of storage at 25°C. Fresh (○): fresh eggs; control (♦): not packed; air (□): packed in air; N_2 (●): packed in 100% N_2; CO_2 (▲): packed in 100% CO_2.

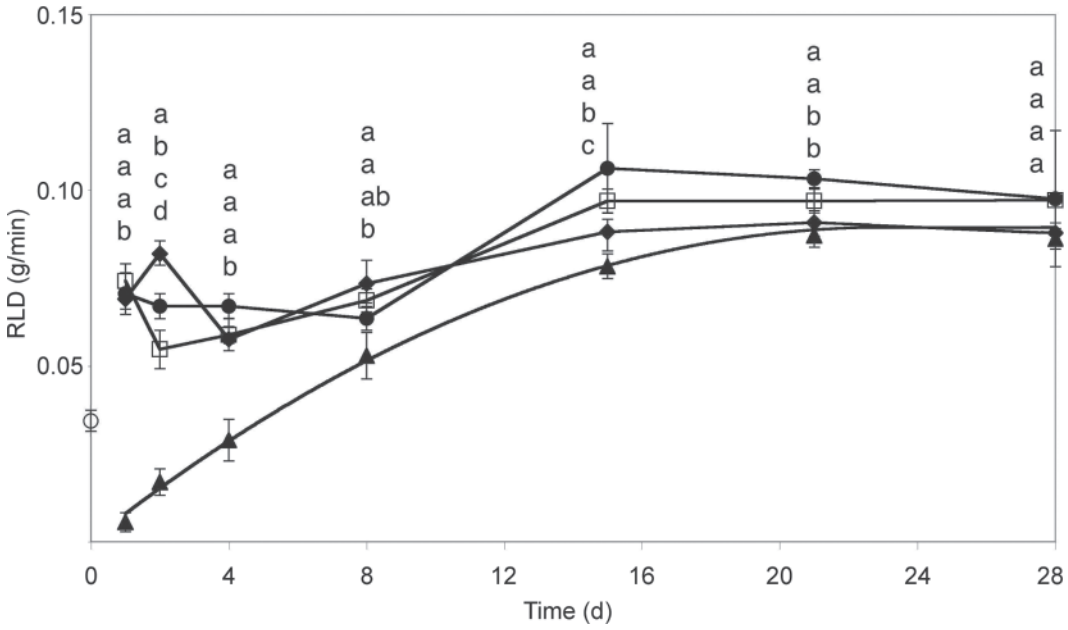

Figure 3. Rate of liquid drainage (RLD; g/min) values (average and SE) of albumen foam obtained from shell egg samples during 28 d of storage at 25°C. Fresh (○): fresh eggs; control (♦): not packed; air (□): packed in air; N_2 (●): packed in 100% N_2; CO_2 (▲): packed in 100% CO_2. Means with different letters for the same sampling time are significantly ($P < 0.05$) different.

of sugar to the albumen to make meringues causes a delay in foam formation. Particularly with 50% sugar, more than 9 min of beating is necessary to incorporate all the liquid into the foam (3–4 min without sugar) containing sugar (Lomakina and Mìkovà, 2006). During processing, foam may undergo heat and mass transfer, along with volume changes when formed into the desired food structure (Foegeding et al., 2006). From a macroscopic point of view, these phenomena are strictly connected with the final quality of the product and to its modification during shelf life.

For an aerated product such as meringue, crispness is one of the most important quality factors. Crispness is an ill-defined sensory parameter describing the textural quality of certain highly fracturable foods. It is associated with the perception of multiple successive rapid fractures resulting from the forces applied during mastication. This is perceived in the mouth through fluctuations in mechanical force and in the ear through the detection of the sounds produced (Gregson and Lee, 2003). According to Gregson and Lee (2003), among the parameters obtained by using instrumental techniques, one of the most useful for crispness assessment of crispy products (e.g., breakfast cereals) is linear distance (L_d).

Figure 4, as an example, shows a typical texture profile (force vs. time) obtained by 3-point bend rig tests of meringues prepared with albumen of the different samples after 2 d of storage. The linear distance estimates the distance traveled by an observer walking from x_1 to x_2 along the graph, for instance, from 0 to 20 s in Figure 4. For smooth graphs, this distance would be less than for jagged graphs (Nalesnik et al., 2007). Products perceived as crispy or crunchy often produce a highly jagged line with fluctuations (peaks) in force because of the many fracture events; L_d is greater for crispy products than for similar "soft" products (Nalesnik et al., 2007). Meringues obtained with eggs packed in CO_2 produced a very jagged force versus time graph with higher force and steep drops, particularly in the first test period (Figure 4). Figure 5 reports L_d values detected for all samples during storage. In general, meringue crispness tended to decrease with the increasing of storage time for all the samples, whereas control, air, and N_2 samples showed a comparable L_d decreasing trend. As happens for foam stability, the meringue crispness of the CO_2 sample was improved from the first day of shell eggs' exposure to CO_2 and was significantly higher ($P < 0.05$) than the other samples until 15 d of egg storage. Actually, in addition to the stabilizing effect on albumen foam, CO_2 exposure improved meringue crispness compared with the other samples. From a visual examination, the final product presented a more uniform and fine structure, demonstrating that the CO_2 effect persisted after the formulation and processing needed for meringue preparation.

In conclusion, the hardness of coagulated albumen showed a strict correlation with raw albumen pH, and 100% CO_2 MAP caused the formation of a soft and puffy coagulum with very low hardness for the entire storage period as a consequence of a fast and marked pH reduction and the expansion of solubilized CO_2 during heating. The foam stability decreased during storage for all samples, but eggs packed in 100% CO_2 showed a more stable foam than fresh eggs until 15 d, reaching values similar to those of the other samples only at the end of the storage period. Our results showed that the decreasing foam stability behavior detected on the al-

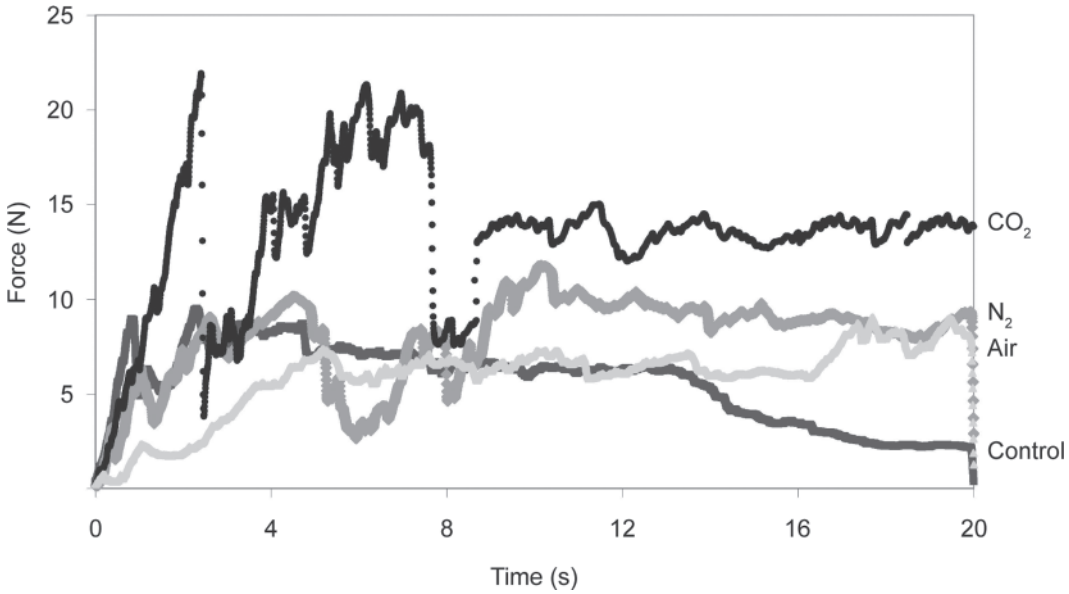

Figure 4. Force versus time generated by 3 point bending rig test of meringues obtained with albumen of shell egg samples after 2 d of storage. Control: not packed; air: packed in air; CO_2: packed in 100% CO_2; N_2: packed in 100% N_2.

bumen of eggs packed with 100% CO_2 can be described by a simple polynomial equation.

In addition to the stabilizing effect on albumen foam, packing eggs in CO_2 improved meringue crispness compared with the other packaging conditions. The final product presented a more uniform and finer structure, showing that the CO_2 effect persisted after the formulation and processing needed for meringue preparation.

The application of this atmosphere could ameliorate the quality characteristics of albumen-based food products. Commercially, CO_2 MAP could provide an albumen-based ingredient tailored to maximize the characteristics needed in the final product (e.g., fresh shell eggs special for meringue) that could give an added value to the product, in terms of both producer profits and consumer needs. It is important to underline that in the European Union eggs are marketed at room temperature whereas in the United States eggs are kept at 7.2°C after washing, grading, and packing. According to previous studies, the storage temperature increase promotes a faster loss of egg freshness and of the technological properties of its constituents (Hammershøj et al., 2002; Estrada et al., 2010). In this direction, the application of CO_2 MAP can represent a protective system against cold chain breaking or temperature abuse or both while promoting the improvement of the quality maintenance of the product. To better understand egg constituent modifications linked to CO_2 absorption, further investigations are currently underway in our laboratory to model CO_2 distribution in shell eggs at different CO_2 partial pressures and storage temperatures and to fully investigate consequent albumen and yolk chemical changes.

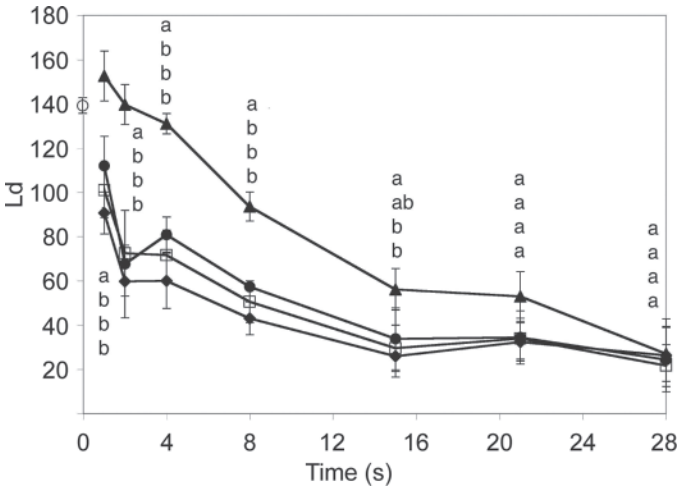

Figure 5. Linear distance (L_d) of meringues obtained with albumen of shell egg samples during 28 d of storage at 25°C. Fresh (○): fresh eggs; control (♦): not packed; air (□): packed in air; N_2 (●): packed in 100% N_2; CO_2 (▲): packed in 100% CO_2. Means with different letters for the same sampling time are significantly ($P < 0.05$) different.

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