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Effect of stunning systems on meat quality of Manchego suckling lamb packed under modified atmospheres

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Abstract

The effects of the type of stunning (TS) [electrically *vs.* gas] and packing in modified atmospheres (MA) [MA-A: 30% CO_2/70% O_2; MA-B: 30% CO_2/69.3% N_2/0.7% CO; MA-C: 40% CO_2/60% N_2] on meat quality (pH), drip losses (DL), water holding capacity (WHC), shear force (SF) and instrumental colour (L^*, and C^* *chroma*) of suckling lamb of the Spanish Manchego breed at 7, 14 and 21 d post-packing was studied. Acceptance of meat samples (on the basis of colour and odour) was determined. In general neither the TS nor the MA affected the pH values. Meat from the gas stunned lambs had the lowest DL ($P < 0.001$ at 14 d post-packing), but lower WHC (more water expelled; $P < 0.01$ at 14 and 21 d post-packing), was more tender ($P < 0.01$) and had higher L^* ($P < 0.001$ at 14 d post-packing) and C^* values ($P < 0.001$) than the electrically stunned group. Similar values of WHC and SF were observed for all MA types but the use of CO in the packs (MA-B) caused less DL, gave the highest C^* values, acceptability and colour stability with time of storage.

Keywords: Lamb meat; Stunning; Electrical; Carbon dioxide (CO_2); Modified atmospheres; Carbon monoxide (CO)

1. Introduction

In the Castilla-La Mancha region, meat from suckling lamb, ‘‘lechal’’ or ‘‘lechazo’’ has its own official label of quality (*‘‘Suckling Manchego Lamb’’*, as of 3 April 2001) which justifies its elevated price in the market and guarantees its organoleptic characteristics. However, the increased price factor is of secondary importance on purchase, since consumers are more influenced by such factors as image and quality (Bernabéu & Tendero, 2005). In addition, colour, tenderness and juiciness are the most significant factors at purchase (Vergara, Gallego, García, & Landete-Castillejos, 2003) and these parameters depend on pre- and post-mortem factors (Sañudo, Sánchez, & Alfonso, 1998). These authors suggested that ante-mortem factors such as pre-slaughter handling and type of stunning can alter lamb meat quality. Although electrical stunning is the usual method, some studies (Vergara, Linares, Berruga, & Gallego, 2005) found that meat from suckling lambs stunned with CO_2 was more tender and had lower drip losses than meat from lambs electrically stunned or non-stunned. In other species, studies showed significant changes at the onset of rigor mortis, i.e. in poultry (Savenije et al., 2002) and pigs (Hambrecht et al., 2004) subjected to different stunning methods, factors which are crucial in the ageing of meat.

Among post-mortem factors, the type of gas mixture used in modified atmosphere packaging, and their effect

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on lamb meat quality has been studied (Berruga, Vergara, & Gallego, 2005; Doherty, Sheridan, Allen, McDowell, & Blair, 1996; Kennedy, Buckley, & Kerry, 2004; Shay & Egan, 1990; Vergara & Gallego, 2001). Methods of preservation are also important in the decision to purchase the product by consumers (Barreiro, 2005).

Eilert (2005) confirmed that from 2002 to 2004 the use of modified atmosphere packaging increased from 9% to 13%, mainly due to lifestyle trends that reduce the time available for meal preparation. Also, the effects of the gases normally used in meat packing (O_2, CO_2 and N_2) have been described (Church, 1994; Jeremiah, 2001) including some of their disadvantages, i.e. surface meat discolouration (Luño, Beltrán, & Roncalés, 1998) or acceleration of oxidative processes (Berruga et al., 2005; Jeremiah, 2001). In order to alleviate some of the problems of the gas mixtures currently used, some authors propose incorporation of carbon monoxide (CO) in low concentrations to pack fresh meat (Luño, Roncalés, Djenane, & Beltrán, 2000; Sorheim, Nissen, & Nesbakken, 1999). Using less than 1% of CO in modified atmospheres, means the meat maintains an attractive colour, spoilage from bacterial growth is retarded (Knut & Nolet, 2006) as are oxidative processes (Linares, Berruga, Bórnez, & Vergara, 2007). CO is harmful at high levels, but a concentration of 0.4–1% added to a modified atmosphere is considered to be completely safe for human consumption (Sorheim et al., 2006). Therefore, the *Union Européenne du Comerce du Betail et de la Viande* (UECBV) has proposed a strategy within the European Union to permit the use of this gas in modified atmospheres to preserve fresh meat (Knut & Nolet, 2006). The use of CO was recently allowed (as of July 2004) in primary packages in the USA (Seyfert, Mancini, Hunt, Tang, & Faustman, 2007).

On the other hand, one of the main consumer fears relating to the use of CO is the possible loss of quality due to a break in the cold chain causing deterioration in spite of its attractive appearance (Wilkinson, Janz, Morel, Purchas, & Hendriks, 2006). CO, however, permits the development of off-odours which may warn consumers of possible loss of quality (Knut & Nolet, 2006).

Since the effects of different types of stunning and gas mixtures on the ageing process of lamb meat packed in modified atmospheres is unknown, the objectives of this study were (1) to evaluate the effect of different of stunning systems (electrical *vs.* gas) on the quality of lamb meat packed in three modified atmospheres [high O_2 (MA-A); high CO_2/low CO (MA-B) and no oxygen (MA-C)] and (2) to suggest a packaging atmosphere/stunning method that best preserves quality in Manchego suckling lamb meat.

2. Materials and methods

The research protocol used in this work was previously approved by the Animal Ethics Committee of the University of Castilla-La Mancha, according to guidelines of the Executive Committee 86/609/CEE of 2 November 1986 regarding the protection of animals used in research and for scientific purposes.

2.1. Animals

A total of 25 Spanish Manchega suckling lambs (fed exclusively with milk) and slaughtered at 12.8 ± 0.2 kg of weight from the flock at the Experimental Farm of Castilla-La Mancha University (Albacete, Spain) were used in this study. Lambs were distributed into two groups according to the type of stunning (TS):

- ESL, $n = 15$: at 110 V, 50 Hz for 5 s (electrodes applied on both sides of the head, behind the ears) (Electronarcosis Panel, MAC-01, Bernard, S.L.).
- GSL, $n = 10$: using CO_2, in groups of five in the box, 90% CO_2 for 90 s at the bottom of the well (G. Van Wijnsberghe & Co n.v., Veurne, Belgium) usually used for stunning pigs in the slaughterhouse.

Immediately after stunning, lambs were slaughtered using standard commercial procedures. After 2 h post-dressing, all carcasses were chilled at 4 °C in a conventional chiller for 24 h. Then the *Longissimus dorsi* muscle from both sides of the carcasses was removed and cut into nine portions to determine meat quality.

2.2. Sampling

An ULMA Packaging machine model Smart 500 (Guipuzcoa, Spain) was used for packing. Samples were placed in clear trays (Linpac, Plastic, West Yorkshire, UK), with an oxygen permeability rate of 3.2 $cm^{-3}\,m^{-2}\,d^{-1}$ at 1 atm and 23 °C, and covered by a film with transmission rates of 1 $cm^{-3}\,m^{-2}\,d^{-1}$ for oxygen (23 °C; 50% RH); 5.5 $cm^{-3}\,m^{-2}\,d^{-1}$ for CO_2 (23 °C; 0% RH) and 2.2 $g\,m^{-2}\,d^{-1}$ for H_2O (25 °C; 90% RH). The following modified atmospheres (MA) were compared:

MA-A: 70% O_2 + 30% CO_2.
MA-B: 69.3% N_2 + 30% CO_2 + 0.7% CO.
MA-C: 60% N_2 + 40% CO_2.

Samples from each lamb were used in all three treatments (MA-A, MA-B and MA-C) and all the packs kept at 2 °C. Meat quality was assessed at 7, 14 and 21 d post-packing (i.e. 8, 15 and 22 d post-slaughter).

Before opening the packs:

- Gas composition was checked for all packs and for all storage times using a ChecMate PBI Dansensor (Denmark) gas analyzer. To achieve this, gas samples were drawn into a syringe by inserting a needle through the adhesive foam plastic tape on the lid.
- A panel of five experts evaluated the colour based on overall appearance. Samples were evaluated on a 1–3 scale where 1 = unacceptable (very bad colour or discol-

oured meat), 2 = acceptable (good colour or negligibly discoloured meat) and 3 = very acceptable (excellent colour). A score of 2 or above was considered acceptable, whereas scores below 2 were unacceptable.

Next, the packs were opened and the following parameters were assessed:

- *Odour*, on a 1–3 scale, where 1 = unacceptable (very strong off-odour), 2 = acceptable (slight off-odour) and 3 = very acceptable (no off-odour).
- *Colour coordinates* ($L^*a^*b^*$ values) were measured on the surface of the LD muscle, immediately after the packs were opened, with a colorimeter Minolta CR400 (Osaka, Japan) calibrated against a standard white tile and *Chroma* was also calculated [$C^* = (a^{*2} + b^{*2})^{1/2}$].
- *pH* was then determined using a penetrating electrode adapted to a portable Crison 507 pH meter.
- *Drip loss* (DL), expressed as a percentage of the initial weight of the half carcass, was assessed by the following procedure (Vergara et al., 2003): (1) weight of pack before opening; (2) weight of dry meat (using a blotting paper); (3) weight of pack after washing and drying. Water expelled (We) = (1) − (2 + 3); DL = (We × 100)/[We + (2)].
- *Water holding capacity* (WHC) was determined as percentage of free water (Grau & Hamm, 1953).
- *Shear force* (SF) was measured using a TA.XT2 texture analyser (Surrey, England) equipped with a Warner–Bratzler device. For this analysis, each meat sample was individually placed in polyethylene bags in a water bath at 70 °C for 15 min. After drying the cooked samples with filter paper, they were cut into three (1 cm^2 cross-section and 2–3 cm length) and the SF was recorded (Vergara & Gallego, 2000).

2.3. Data analysis

All data were analyzed with the SPSS 11 version statistical package. A General Lineal Model was used to determine the significance of effects (type of stunning and the type of modified atmosphere packaging) and their interactions on the following parameters of meat quality: pH, colour as L^* and Chroma values, WHC, DL and SF. Tukey's test was used to measure differences among means. Differences were considered significant at the $P < 0.05$ level.

3. Results and discussion

3.1. Sensory analysis

Table 1 shows the acceptance of lamb meat with regard to colour and odour sensory evaluation. Acceptance was similar in each type of MA (A, B) for the different stunning groups (electrically *vs.* gas). However, the TS seemed to affect the acceptance of MA-C since the gas-stunned group reached a higher score in both parameters (colour and odour) than the electrically stunned lambs. In agreement with some authors (Verbeke, Van Oeckel, Warnants, Viaene, & Boucqué, 1999), the type of stunning could affect the sensory properties of meat.

Table 1
Mean percentage (%) of packs considered acceptable by sensory analysis of colour[a] and odour[b]

	Modified atmosphere					
	MA-A		MA-B		MA-C	
	ESL	GSL	ESL	GSL	ESL	GSL
Colour						
7	100	100	100	100	35	96
14	39	36	100	100	30	83
21	33	25	98	100	30	96
Odour						
7	83	82	80	100	60	79
14	47	25	80	93	0	79
21	28	14	83	46	0	50

ESL: electrically stunning lambs; GSL: gas stunned lambs. Modified atmosphere: MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2). Samples were categorised (for both colour and odour) as: 1 = not acceptable (discoloured meat, strong off-odour, respectively); 2 = acceptable (good colour, slight off-odour, respectively) or 3 = very acceptable (excellent colour, no off-odour, respectively).
[a] Closed packs.
[b] When packs were opened.

Acceptance of samples was highest in MA-B, intermediate in MA-A, and lowest in MA-C. In other species (beef and pork) (Sorheim et al., 1999) reported that in 0.4% CO, meat samples exhibited more satisfying colour throughout storage than samples packed in a 60% CO_2 + 40% N_2 (MA-C) or 70% O_2 + 30% CO_2 (MA-A). This agrees with our results in lamb, because the carboxymyoglobin pigment promotes a pleasant and stable bright cherry-red colour (Viana, Gomide, & Vanetti, 2005). Some authors such as Luño et al. (1998), reported that CO extends the odour shelf-life of meat (beef) due to its inhibition of bacterial growth and its antioxidant activity (Luño et al., 2000). In contrast, our results showed that at all storage times (7, 14 and 21 d) the percentage of acceptable packs was generally superior for colour and lower for odour for these samples. Wilkinson et al. (2006) stressed that it is critical to control hygienic and cold-chain conditions when CO is used in packing meat.

There were off-odours under aerobic conditions (MA-A) in both groups (ESL and GSL), mainly from 2 weeks on post-packing, as some organisms produce odourous compounds under high oxygen concentrations (Vergara & Gallego, 2001) in lamb. Jeremiah (2001) proposed that atmospheres containing carbon monoxide extended storage life and maintained normal odour longer than the other packing systems (MA-A and MA-C). Finally, the bacteriostatic effect of CO_2 gas used in the anaerobic system (MA-C) seems to be reinforced by the gas inhaled by animals at stunning. This could explain the better scores for meat samples in the GSL group than the electrically stunned ones. Verbeke et al. (1999) attributed the better quality in meat from CO_2-stunned pigs to less muscle contractions, which implies less energy-consumption and thus better meat quality.

Furthermore, the acceptance of electrically stunned lamb meat samples by panelists decreased with storage time and, while MA-A and MA-C were well scored only up to 14 d post-packing, MA-B (with CO) received high acceptance up to 21 d.

3.2. pH

Table 2 shows the pH variation in the suckling lamb meat samples. In general, there were no differences in pH with type of stunning or modified atmosphere, although there were individual differences according to the Tukey test. The absence of a TS effect on pH values was also observed by Vergara, Linares et al. (2005) in meat packed conventionally (in air).

Forslid and Augustinsson (1988), in pig, pointed out that inhalation of CO_2 is responsible for lower blood pH, due to intense acidaemia, which could finally lead to a lower pH in the meat after slaughter, thus explaining the lower pH value for gas stunned lambs during the first week post-packaging in MA-C ($P < 0.05$) (5.60 ± 0.01 *vs.* 5.67 ± 0.01, in GSL, ESL, respectively; $P < 0.05$). Perhaps the high level of CO_2 in these packs (MA-C) added to the CO_2 used for stunning created an accumulation of gas in the muscle and the drop in pH at this time, as suggested by Fleming, Froning, Beck, and Sosnicki (1991) in turkey.

The type of MA (A, B or C) had no significant effect, although in the electrically stunned group a lower pH ($P < 0.05$) was described in MA-C at 14 d post-packaging in comparison with the other two packing systems (5.76 ± 0.02, 5.71 ± 0.01, 5.68 ± 0.01 at MA-A, MA-B, MA-C, respectively). This fact could be related to a possible increase in absorption of CO_2 by the muscle at this time in the high CO_2 conditions (>30% CO_2) (Jeremiah & Gibson, 2001).

Storage time caused differences in meat pH, with this parameter increasing in all groups but only significantly ($P < 0.05$) in some groups [in MA-A and MA-B for the electrically stunned lambs and in MA-C for the gas stunned group]. Other studies found an increase in pH when meat is packed in modified atmospheres (Moore & Gill, 1987) in lamb; (Rousset & Renerre, 1990) in beef; (Vergara, Berruga, & Linares, 2005) in rabbit, which could be attributed to tissue breakdown over time (Moore & Gill, 1987).

3.3. Drip loss (DL)

DL values ranged between 1.4 and 2.4 (Table 3). Ingolesson and Dransfield (1991) considered a drip loss in fresh lamb meat of about 2.7% to be within acceptable limits.

Other authors such as Moore and Young (1991) and Doherty et al. (1996), described lower values of DL (0.24–1.5% and 0.3–0.5%, respectively) in lamb meat packed under modified atmospheres. These differences could be related to the various techniques used in drip loss determination in addition to the use of different packing systems.

The TS of animals affected DL values and, at 14 d post-packing, DL was always higher in samples from electrically stunned lambs ($P < 0.001$) than samples from the gas stunned group. According to Ingolesson and Dransfield (1991), in lamb; Channon, Payne, and Warner (2000), in pig, faster glycolysis due to the electrical current could be responsible for increases in water loss. Channon et al. (2000) reported higher DL values in refrigerated meat from electrically stunned animals than in those stunned with CO_2.

In agreement with Jeremiah (2001), the type of modified atmosphere affected drip loss ($P < 0.001$ at 7 d and afterwards $P < 0.01$). In general, DL values were lower in sam-

Table 2
pH of the meat of suckling lamb of Manchega Spanish breed stunned by different methods and packed in modified atmospheres

	Type of stunning						Significance		
	Electrically stunned lambs			Gas stunned lambs					
	MA-A	MA-B	MA-C	MA-A	MA-B	MA-C			
7	5.63 ± 0.45^{x}	5.67 ± 0.01^{xy}	5.67 ± 0.01^{w}	5.64 ± 0.04	5.62 ± 0.03	5.60 ± 0.01^{xr}	NS	NS	NS
14	5.76 ± 0.02^{by}	5.71 ± 0.01^{aby}	5.68 ± 0.01^{a}	5.70 ± 0.04	5.70 ± 0.03	5.65 ± 0.01^{y}	NS	NS	NS
21	5.62 ± 0.02^{xw}	5.65 ± 0.02^{x}	5.64 ± 0.02	5.70 ± 0.01^{r}	5.71 ± 0.02	5.68 ± 0.01^{y}	**	NS	NS
Anova	**	*	NS	NS	NS	***			

MA: Modified atmosphere; MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2).
TS: Type of stunning.
[a,b] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different types of MA (A, B and C) at the same time post-packing and the same TS.
NS, not significant; *, **, *** indicates significance levels at 0.05, 0.01 and 0.001, respectively.
[x,y] Values in the same column with different superscripts are significantly different ($P < 0.05$) for the different post-packing times (7, 14 and 21 d) at the same TS and MA.
[w,r] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different TS (electrical and gas) at the same time of post-packing and MA.

Table 3
Drip losses in meat of suckling lamb of Manchega Spanish breed stunned by different methods and packed in modified atmospheres

	Type of stunning						Significance		
	Electrically stunned lambs			Gas stunned lambs					
	MA-A	MA-B	MA-C	MA-A	MA-B	MA-C			
7	1.90 ± 0.16	1.58 ± 0.09^{x}	1.42 ± 0.10^{x}	2.37 ± 0.12^{b}	1.52 ± 0.13^{a}	1.80 ± 0.19^{a}	*	***	NS
14	2.37 ± 0.12^{w}	2.15 ± 0.80^{yw}	2.41 ± 0.07^{yw}	1.98 ± 0.12^{r}	1.55 ± 0.13^{r}	1.95 ± 0.11^{r}	***	**	NS
21	2.18 ± 0.14	2.02 ± 0.12^{yw}	2.32 ± 0.14^{y}	2.38 ± 0.14^{b}	1.56 ± 0.06^{ar}	1.90 ± 0.19^{ab}	NS	**	*
Anova	NS	***	***	NS	NS	NS			

MA: Modified atmosphere; MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2).
TS: Type of stunning.
NS, not significant; *, **, *** indicates significance levels at 0.05, 0.01 and 0.001, respectively.
[a,b] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different types of MA (A, B and C) at the same time post-packing and the same TS.
[x,y] Values in the same column with different superscripts are significantly different ($P < 0.05$) for the different post-packing times (7, 14 and 21 d) at the same TS and MA.
[w,r] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different TS (electrical and gas) at the same time of post-packing and MA.

ples packed with carbon monoxide and higher in samples in MA-A. In agreement with Doherty et al. (1996), a high oxygen concentration can produce an increase in drip losses in lamb meat.

DL increased in the first 14 d after packing but only significantly ($P < 0.05$) in both MA-B and MA-C packed electrically stunned lambs, it then remained constant for all groups. This agrees with other authors (Zarate & Zaritzky, 1985, in beef and Vergara et al., 2003, in deer) who observed that most exudate is lost within the first 2 weeks post-packing.

3.4. Water holding capacity (WHC as percentage of free water)

In Table 4, water holding capacity (WHC) values in Spanish Manchega lamb meat packaged under MA systems are shown.

In spite of the fact that the highest DL was observed in the ESL group, the WHC was lower (more water expelled) in the gas stunned lambs than in the electrically stunned ones (significantly so at 14 and 21 d post-packing, $P < 0.01$). This is in agreement with other authors such as Hambrecht, Eissen, and Verstegen (2003) in pigs subjected to both stunning systems (electrical *vs.* gas). The tendency of meat from gas stunned lambs to release more water implies higher juiciness in these samples (Vergara & Gallego, 2000).

High CO_2 concentrations, as a consequence of inhalation at stunning, can produce an intense breakdown in tissues which could be involved in the easier exit of water from the cells and the subsequent decrease in WHC in the gas stunned lambs (Moore & Gill, 1987).

However, neither the MA nor the time of storage affected the WHC in both groups of lambs, a fact which is contrary to a previous study by Vergara and Gallego (2001) where both factors (MA, storage time) were found to affect the WHC of meat.

3.5. Shear force (SF)

Table 5 shows the shear force (SF) (N/cm^2) at different storage times.

Table 4
Water holding capacity (% water expelled) in meat of suckling lamb of Manchega Spanish breed stunned by different methods and packed in modified atmospheres

	Type of stunning						Significance		
	Electrically stunned lambs			Gas stunned lambs					
	MA-A	MA-B	MA-C	MA-A	MA-B	MA-C			
7	18.33 ± 1.37	22.06 ± 1.31	22.72 ± 3.32	21.44 ± 1.80	24.47 ± 1.52	21.62 ± 1.79	NS	NS	NS
14	21.19 ± 1.70	22.82 ± 0.72	21.62 ± 0.46^{w}	25.01 ± 1.32	25.09 ± 1.89	27.02 ± 1.41^{r}	**	NS	NS
21	21.87 ± 1.19^{w}	24.48 ± 1.10	25.46 ± 1.04	26.22 ± 0.74^{r}	28.24 ± 1.33	25.39 ± 1.38	**	NS	NS
Anova	NS	NS	NS	NS	NS	NS			

MA: Modified atmosphere; MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2).
TS: Type of stunning.
NS, not significant; ** indicates significance level at 0.01.
[w,r] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different TS (electrical and gas) at the same time of post-packing and MA.

Table 5
Shear force (N/cm^2) values in meat of suckling lamb of Manchega Spanish breed stunned with different methods and packed in modified atmospheres

	Type of stunning						Significance		
	Electrically stunned lambs			Gas stunned lambs					
	MA-A	MA-B	MA-C	MA-A	MA-B	MA-C			
7	36.26 ± 0.31^{y}	41.94 ± 0.51^{yw}	48.80 ± 1.00^{w}	31.55 ± 0.65	16.95 ± 0.26^{r}	23.71 ± 0.62^{r}	***	NS	NS
14	25.77 ± 0.31^{xy}	24.20 ± 0.31^{x}	32.43 ± 0.71	24.10 ± 0.42	17.93 ± 0.31	16.66 ± 0.43	*	NS	NS
21	23.12 ± 0.35^{abx}	18.71 ± 0.26^{ax}	31.75 ± 0.87^{bw}	19.89 ± 0.37^{b}	13.23 ± 0.16^{ab}	9.99 ± 0.04^{ar}	***	NS	*
Anova	*	***	NS	NS	NS	NS			

MA: Modified atmosphere; MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2).
TS: Type of stunning.
NS, not significant; *, *** indicates significance levels at 0.05 and 0.001, respectively.
a,b Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different types of MA (A, B and C) at the same time of post-packing and the same TS.
x,y Values in the same column with different superscripts are significantly different ($P < 0.05$) for the different post-packing times (7, 14 and 21 d) at the same TS and MA.
w,r Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different TS (electrical and gas) at the same time of post-packing and MA.

Meat from the gas stunned lambs was more tender at all times ($P < 0.001$ for 7 and 21 d and $P < 0.05$ for 14 d post-packing) than that from the electrically stunned group in all the packing systems.

It seems that CO_2 affects SF values. As a consequence of the gas stunning system, CO_2, which is highly soluble in meat (Gill, 1990), remained at an elevated level in the tissues (through inhalation). It is also known that the perimysium, which is 80% collagen, is denatured at 70 °C and transformed to gelatine (Offer, Restall, & Trinick, 1984). During cooking, the gas binds to the collagen triple helix that is unravelled (Mitsuda et al., 1977). Next, CO_2 gathers at the weakest points of the muscle (perimysial seams) producing pores and fissures which could relate to the increase in tenderness (lower SF values) (Bruce, Wolfe, Jones, & Price, 1996). Lower values of shear force were also found in poultry (Veeramuthu & Sams, 1993) and lamb meat (Vergara, Linares et al., 2005) when electrical *vs.* gas stunning systems were compared at initially (1 h) and at 7 d post-mortem, respectively.

In general, the type of MA had no effect on the SF of lamb meat, in agreement with Bell, Penney, and Moorhead (1996) (in beef) and Vergara and Gallego (2001) (in lamb). Also, tenderness increased over time, as observed in other studies (Jeremiah, Tong, & Gibson, 1997). Meat from ESL group packed under a low CO level (MA-B) reached a mean value of 41.94 N/cm^2 at 7 d post-packing which is considerably higher than, for example the mean value of 18.71 N/cm^2 for the 21 d aged group. However, we believe that the consumer would still regard the samples in MA-B for the electrically stunned group to be tender, not tough.

3.6. L^* value and Chroma

Table 6 shows *lightness* and colour saturation (L^*, C^* coordinates) values. Meat from the gas stunned animals was paler (higher L^*) than that from the electrically stunned lambs, and significant differences ($P < 0.001$) were found at 14 d post-packaging. Hamilton, Miller, Ellis, McKeith, and Wilson (2003), in pig, reported greater L^* values in animals with reduced water holding capacities, which agrees with our results (Table 4) as regards the gas stunned group. In contrast, Velarde, Gispert, Faucitano, Manteca, and Diestre (2000) and Velarde et al. (2001) found darker meat in loins from gas stunned pigs, but attributed this to the genotype of the individuals rather than the stunning system.

In addition, TS affected ($P < 0.01$) colour saturation (C^*), which was lower in electrically stunned animals compared with gas stunned ones in MA-C (15.4 *vs.* 20.7, for ESL and GSL, respectively) and also in MA-B, although only at 7 d post-packaging (22.4 *vs.* 24.5, for ESL and GSL, respectively). Decreases in lightness and also in colour saturation were found by Jolley (1990) in rabbit meat due to an elevated glycolytic rate, which could explain our results in the electrically stunned lambs.

According to Albertí (2000), Chroma value depends on the quantity of muscle myoglobin and blood haemoglobin in addition to the their chemical form. Also, some authors (Roça et al., 2001 in beef; Ramos, Gomide, Fontes, Ramos, & Pertenelli, 2005 in frog) observed that muscle haemoprotein concentration can be affected by the type of stunning.

Electrical stunning produces an effective bleed-out after sticking due to an increase in blood pressure (tonic phase) and strong contractions (clonic phase) (Velarde, Gispert, Diestre, & Manteca, 2003) which would imply a subsequent decrease in the amount of haemoglobin and therefore a decrease in colour saturation (lower C^* values) as in our results. In this sense Fleming et al. (1991) (in turkeys) found 0.18 mg/g of myoglobin in meat from electrically stunned poultry and 0.21 mg/g in those stunned by CO_2.

In general, in both groups, at 21 d post-packaging, the L^* value was higher (paler meat) in MA-A (high oxygen content) ($P < 0.001$ and 0.01, in ESL and GSL, respec-

Table 6
Colour coordinates (L^*, Chroma) in meat of suckling lamb of Manchega Spanish breed stunned by different methods and packed in modified atmospheres

	Type of stunning						Significance		
	Electrically stunned lambs			Gas stunned lambs			TS	MA	TS × MA
	MA-A	MA-B	MA-C	MA-A	MA-B	MA-C			
L^*									
7	49.75 ± 0.89^{x}	49.15 ± 0.69	50.57 ± 0.64	50.69 ± 1.42^{x}	50.57 ± 0.79	50.95 ± 1.78	NS	NS	NS
14	49.89 ± 1.21^{xw}	49.75 ± 0.53	50.16 ± 0.64	54.67 ± 0.84^{xyr}	51.75 ± 0.84	52.39 ± 1.18	***	NS	NS
21	54.09 ± 0.77^{by}	50.37 ± 0.51^{a}	50.65 ± 0.78^{a}	55.68 ± 1.42^{by}	50.02 ± 0.58^{a}	51.65 ± 1.29^{ab}	NS	***	NS
	**	NS	NS	*	NS	NS			
Chroma									
7	20.45 ± 0.6^{yb}	22.4 ± 0.43^{wb}	15.24 ± 0.60^{wa}	20.38 ± 0.61^{ya}	24.56 ± 1.11^{rb}	20.21 ± 1.61^{ra}	***	***	*
14	18.72 ± 0.71^{xyb}	22.46 ± 0.61^{c}	15.22 ± 0.80^{wa}	18.53 ± 0.61^{xya}	24.27 ± 1.15^{b}	20.66 ± 1.23^{rab}	**	***	*
21	15.21 ± 1.71^{xa}	22.45 ± 0.53^{b}	15.83 ± 0.53^{wa}	17.95 ± 0.38^{xa}	23.84 ± 1.09^{b}	21.24 ± 1.08^{rb}	***	***	*
	**	NS	NS	*	NS	NS			

MA: Modified atmosphere; MA-A (30% CO_2 + 70% O_2), MA-B (30% CO_2 + 0.7% CO + 69.3% N_2), MA-C (40% CO_2 + 60% N_2).
TS: Type of stunning.
NS, not significant; *, **, *** indicates significance levels at 0.05, 0.01 and 0.001, respectively.
[a,b] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different types of MA (A, B and C) at the same post-packing time and the same TS.
[x,y] Values in the same column with different superscripts are significantly different ($P < 0.05$) for the different post-packing times (7, 14 and 21 d) at the same TS and MA.
[w,r] Values in the same row with different superscripts are significantly different ($P < 0.05$) for the different TS (electrical and gas) at the same time of post-packing and MA.

tively). Seyfert et al. (2007) found that high oxygen levels in the packs delayed the appearance of metmyoglobin at the cut surface, producing paleness in beef loins. Other authors such as Luño et al. (2000) (in beef) also related greater *lightness* to the formation of less metmyoglobin. Previous studies (Linares et al., 2007; Linares, Bórnez, & Vergara, 2006), reported that increased oxidation is strongly related to an increase in the L^* value in lamb meat.

The MA has an effect on colour saturation since the MA-B (low CO-high CO_2) had higher C^* values in both groups (electrically and gas stunned lambs). Binding of CO to the myoglobin produces carboxymyoglobin, which is more stable than oxymyoglobin against oxidative discolouration and thus gives a bright cherry-red colour in meat (Sorheim, Aune, & Nesbakken, 1997). Higher Chroma stability in 1% of CO was also found by Luño et al. (2000) (in beef) and Viana et al. (2005) (in pork). According to Sorheim et al. (1999), 0.4% of CO is enough to produce a good colour stability in meat.

Storage time affects colour coordinates in MA-A ($P < 0.01$ in ESL; $P < 0.05$ in GSL for L^* and C^*, respectively) but not in MA-B or MA-C. In MA-A, L^* increased over time and C^* decreased from 7 to 21 d post-packing, agreeing with results found by Seyfert et al. (2007) in high oxygen systems.

4. Conclusions

In this study, we have determined the effect of the type of stunning, modified atmospheres and their interactions on meat quality of suckling lamb. In general, the type of stunning had an effect on DL, WHC, SF and colour. Thus, meat from gas stunned animals was more tender, juicier (more water expelled) and produced lower drip losses than meat from electrically stunned lambs. A significant interaction ($P < 0.05$) between factors (TS and MA) was observed in C^*, this being higher ($P < 0.05$) in the gas stunned group than in the electrically stunned group packed without oxygen (MA-C), with a high percentage of packs accepted (both for colour and odour) from the gas stunned group. Although the type of MA did not modify the pH, WHC or SF values, some parameters such as sensorial evaluation, DL and colour coordinates were affected. Our results showed that packing under a low CO concentration (MA-B) gave the highest sensorial acceptance and colour saturation in both groups in addition to the lowest drip losses.

In conclusion, stunning by CO_2 gas could be a valid alternative to prevent the negative effects that electro-narcosis systems have on meat quality in lamb apparent with ageing time. Also, the addition of a low CO level into the packs could give the best meat quality characteristics, as even at 3 weeks post-packing in the electrically stunned group more than 80% of packs were acceptable. In addition, in the gas stunned group, it is possible to obtain a product of good tenderness and colour with a post-packing life of 7 d and possibly 2 weeks using CO in the gas mixture.

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