ELSEVIER

Meat Science, Vol. 42, No. 3, 315–324, 1996

0309-1740/96/$15.00+.00

0309-1740(95)00040-2

Physical Characteristics of Lamb Primals Packaged Under Vacuum or Modified Atmospheres

Alice M. Doherty,[a]* J. J. Sheridan,[a] P. Allen,[a] D. A. McDowell[b] & I. S. Blair[b]

[a]The National Food Centre, Teagasc, Dunsinea, Castleknock, Dublin 15, Ireland
[b]University of Ulster at Jordanstown, Co Antrim BT37 OQB, Northern Ireland, UK

(Received 19 April 1995 revised version received 31 July 1995; accepted 8 August 1995)

ABSTRACT

Lamb primals (shoulders) were packaged under vacuum, 80% O_2/20% CO_2, 50% CO_2/50% N_2 or 100% CO_2 and stored at 5 or 0°C. Pack contents were examined at 7 day intervals to determine the composition of the pack atmosphere, drip loss, colour (muscle and fat) and pH (surface and internal). The composition of the gas atmospheres changed very little during storage. The only significant differences between developed head space compositions above primals stored at the two different temperatures (5 and 0°C) were noted in packs stored for 28 days under 80% O_2/20% CO_2. Low levels of drip loss (<0.5%) were noted in all packs stored under the modified gas atmospheres. In contrast, significantly higher levels of drip loss (0.5–1.1%) were noted in vacuum packaged lamb stored at 5 and 0°C. Acceptable muscle colour was observed 2 hr after opening of all packs. The only significant differences between atmospheres for lean muscle colour were noted after 28 days storage. Fat colour did not generally change during storage in any of the atmospheres, apart from a slight bleaching effect at 7 days. There were no significant differences between the surface or internal pH values noted after storage under any of the atmosphere/temperature combinations. In general, higher pH values were observed at the surface of the meat than in the interior. This pattern was noted before and after storage.

INTRODUCTION

Modern meat packaging techniques aim to maintain the sensory characteristics of the product, of which colour is one of the most important, and to extend product shelf life by inhibiting or retarding the growth of the resident undesirable microflora (Walker, 1992). These twin objectives can be achieved by a number of methods, of which strategies based on the manipulation of the meat microenvironment, i.e. vacuum packaging and modified atmosphere packaging (MAP) are among the most widely used. MAP systems most frequently use mixtures of carbon dioxide (CO_2), oxygen (O_2) and/or nitrogen (N_2), in which

*Author to whom correspondence should be addressed.

each gas has a specific role to play in extending the shelf life and/or maintaining the appearance of packaged meat (Young *et al.*, 1988). When meat is packaged in MAP, as in any environment, interactions and exchanges occur between and among the product, the microenvironment, and any microorganisms present on the meat; or introduced during packaging. Such interactions can alter the composition of the gases present in the pack (Taylor & MacDougall, 1973) promoting or suppressing microbial growth. To gain an understanding of the effect of such changes on the overall shelf life and keeping quality of meat, it is, therefore, important to examine and in the long term predict the gas composition throughout storage.

In addition to microbial growth and the production of off-odours, a range of concomitant physical changes, i.e. drip loss, colour changes and/or pH changes during storage can reduce the overall appearance and acceptability of packaged meat. Drip loss, the extraction of liquid from the meat into the free space around the meat, can appear as a red watery liquid either on the surface of packaged meat or within the pack, affecting the appearance and acceptability of meat and reducing the weight of saleable final product. Meat colour, an important attribute of meat quality because it strongly influences the consumer's purchase decision (Faustman & Cassens, 1990) is principally dictated by the concentration and chemical state of the muscle pigment, myoglobin (Williams, 1987). Myoglobin, which is purple in low O_2 conditions, binds reversibly with available O_2 to form bright red oxymyoglobin giving the desirable colour of fresh meats. Longer term exposure to O_2, particularly at lower concentrations leads to the irreversible oxidation of oxymyoglobin and myoglobin to metmyoglobin, which imparts an undesirable brown colour to the product (Young *et al.*, 1988; Egan *et al.*, 1990). Changes in meat pH which occur during meat maturation and storage can have significant effects on all of the above aspects of meat quality, enhancing or suppressing microbial growth, drip loss and colour changes with implications for the overall appearance and shelf life of packaged meat.

In this study, lamb primals were packaged under vacuum and three modified atmospheres (80% O_2/20% CO_2, 50% CO_2/50% N_2 or 100% CO_2) and stored at 5 or 0°C for up to 28 days. During storage, changes in the above physical characteristics i.e. drip loss, colour and pH were monitored in relation to each atmosphere/temperature combination. The results of a parallel study which examined the microbiological aspects of storing lamb primals under the above conditions, are presented and discussed in a companion paper (Sheridan *et al.*, 1996).

MATERIALS AND METHODS

Packs

Animals were selected, slaughtered and derived primals were prepared as described previously (Sheridan *et al.*, 1996).

Headspace gas analysis

A gas chromatograph (Spectra 250, Gow-Mac Instrument Co. Ltd., Industrial Estate, Shannon, Co. Clare, Ireland) fitted with an Alltech Speciality CTRI column, was used to analyse all gas mixtures. A CI-4100 Integrator (Milton Roy, LDC Division, Building 89, Industrial Estate, Shannon, Co. Clare, Ireland) was used to plot the chromatographs and calculate the gas percentages from the areas under the curves using the normalisation method (Anon., 1987). Gas mixtures were analysed after initial packaging and periodically throughout storage to monitor any changes in the gases present in the packs.

Measurement of drip loss

The amount of drip obtained from each lamb primal during storage was calculated by weighing the primal before packaging and again after packaging and storage. Drip was expressed as a percentage of the initial weight of the primal.

Colour measurement

Lean
Prior to packing, a 2.5 cm thick section of the *m. longissimus dorsi* (LD) was taken from each loin (i.e. two samples per lamb) at the cutting line between the shoulder and loin and wrapped in a high O_2 permeability film (9600 $cm^3/m^2/24$ hr/atm). Samples were placed on a tray with the exposed cut face uppermost and chilled for 2 hr at 5°C to allow maximum oxymyoglobin development. Colour determinations were made on the uppermost surface using a Hunterlab digital colour difference meter (Model D25D2A, Hunter Associates Laboratory Inc., 9529 Lee Highway, Fairfax, VA, USA). The meter was fitted with a 1" diameter aperture and calibrated using a red standard tile. Colour values *a* and *b* were measured and the hue angle (arctan *b*/*a*) calculated. A rising *a* value indicates an increase in redness. Hue angle combines the *a* and *b* values to specify the actual colour in terms of the angle between the pure red (hue angle = 0°) and pure yellow (hue angle = 90°) axes of the colour space. A rising hue angle indicates a browning of the meat due to metmyoglobin formation. Sample material from stored primals was analysed in a similar manner.

Fat
Prior to packing, a sample of subcutaneous fat was taken from the breast region of each primal (i.e. two samples per lamb), wrapped in a high O_2 permeability film (9600 $cm^3/m^2/24$ hr/atm) and placed on a tray, outer surface uppermost. Colour determinations were then made on the outer surface using a Hunterlab digital colour difference meter (Model D25D2A) fitted with a 1" diameter aperture and calibrated with a white standard tile. The yellowness of the fat was measured in terms of Hunter *b* values, with a rising *b* value indicating an increase in yellowness. Sample material from stored primals was analysed in a similar manner.

pH measurement

The surface pH of the LD of each primal was measured before packaging, and again after packaging and storage using a combination electrode (Type EC-2110, Amagruss, Unit 4, Industrial Estate, Castlebar, Co. Mayo, Ireland) attached to a portable Knick meter (Portamess 751, Elektronische Messgeräte, GmbH and Co., Berlin, Germany). The internal pH of the LD of each primal was measured before packaging and again after packaging and storage using a spear glass electrode (Type EC-2010, Amagruss) attached to an Orion portable meter (Model 201, ATI Orion Europe, Cambridge, UK).

Statistical analysis

The data were analysed using SYSTAT (SYSTAT. Intelligent Software, Evanston, IL, USA) as a split-plot design in which pack type and storage temperature were examined as main plot effects and time, a repeated measure, as a sub-plot effect. The trend over storage time was analysed by regression analysis. Models with linear and quadratic coefficients were examined. As the quadratic term was not significant in any of the atmosphere/temperature combinations, the significance of the linear model is presented where a linear relationship was observed.

RESULTS

Gas atmosphere

Overall, changes in the composition of the modified atmospheres during storage were relatively minor (Table 1). Storage temperature significantly affected gas composition at 28 days in 80% O_2/20% CO_2 packs where there was a small but significant difference between temperatures for O_2 and CO_2 ($p < 0.05$). Significant linear relationships between gas percentages and time at 28 days were observed in some of the atmospheres at 5 and 0°C ($p < 0.05$). However, these effects were small as the relative percentages of each gas did not vary by more than 6% in any of the atmosphere/temperature combinations.

Packs filled with 80% O_2/20% CO_2 showed the greatest changes in the composition of the atmosphere during storage. In packs containing 50% CO_2/50% N_2 or 100% CO_2, pack collapse was observed. This did not occur to the same extent in 50% CO_2/50% N_2 as in 100% CO_2. A small amount of N_2 was evident in the 80% O_2/20% CO_2 packs at all storage times. Since the calibration method for this atmosphere did not include N_2, the actual amount could not be measured. Small amounts of O_2 (< 0.3%) were detected in both the nominally anoxic atmospheres at all storage times.

Drip loss

The mean percentage (%) drip losses during storage in each atmosphere at 5 and 0°C are shown in Table 2. Similar percentage drip losses (< 0.5%) were noted in the three

TABLE 1
Mean Percentages (%) of Carbon Dioxide (CO_2), Oxygen (O_2) or Nitrogen (N_2) over 28 Days, in Gas Packs Containing Lamb Shoulders Stored at 5 or 0°C

Gas atmosphere	*Gas type*	*Storage temperature (°C)*	*Storage time (days)*[a] 7	14	21	28	*Linear trend*[b]
80% O_2/20% CO_2	CO_2	5	26.6	25.4	28.3	30.7[a]	**
		0	24.5	24.5	30.8	25.0[b]	NS
	O_2	5	73.4	74.6	71.7	69.3[a]	**
		0	75.5	75.5	69.2	75.0[b]	NS
50% CO_2/50% N_2	CO_2	5	50.2	47.8	49.4	48.0	NS
		0	50.5	46.8	47.2	46.9	*
	O_2	5	0.02	0.14	0.16	0.00	NS
		0	0.05	0.04	0.08	0.01	NS
	N_2	5	49.8	52.2	50.5	52.0	NS
		0	49.4	53.2	52.7	53.1	*
100% CO_2	CO_2	5	97.8	96.9	95.1	96.3	NS
		0	98.2	98.0	96.7	96.3	**
	O_2	5	0.07	0.06	0.25	0.01	NS
		0	0.08	0.09	0.04	0.13	NS
	N_2	5	2.10	3.10	4.69	3.67	NS
		0	1.71	1.96	3.25	3.55	**

[a]The *t*-test was used to determine significant differences between means at 5 and 0°C for each gas within an atmosphere. Means with different superscripts are significantly different ($p < 0.05$).
[b]Significance of linear regression coefficient: $^{*}p < 0.05$; $^{**}p < 0.01$; NS, non-significant.

TABLE 2
Mean Percentage (%) Drip Loss over 28 Days, from Lamb Shoulders Packaged in Different Gas Atmospheres at 5 or 0°C

Gas atmosphere	*Storage temperature (°C)*	*Storage time (days)*[a] 7	14	21	28	*Linear trend*[b]
Vacuum pack	5	0.51	0.84[a]	1.03[a]	0.88[a]	*
	0	0.50	0.84[a]	1.03[a]	0.96[a]	**
80% O_2/20% CO_2	5	0.27	0.38[b]	0.32[b]	0.46[b]	NS
	0	0.32	0.35[b]	0.39[b]	0.39[bc]	NS
50% CO_2/50% N_2	5	0.27	0.30[b]	0.32[b]	0.39[bc]	NS
	0	0.22	0.28[b]	0.27[b]	0.39[bc]	NS
100% CO_2	5	0.14	0.25[b]	0.19[b]	0.27[bc]	NS
	0	0.20	0.28[b]	0.19[b]	0.19[c]	NS

[a]Pairwise comparisons between means at each storage time were made using the Tukey–Kramer test. Within a column, means with different superscripts are significantly different ($p < 0.05$).
[b]Significance of linear regression coefficient: $^{*}p < 0.05$; $^{**}p < 0.01$; NS, non-significant.

modified atmospheres at 5 and 0°C, with little variation during storage from 7 to 28 days. A significant difference in drip loss was recorded at 28 days between primals stored under 80% O_2/20% CO_2 at 5°C (0.46) and under 100% CO_2 at 0°C (0.19) ($p < 0.05$). No correlations were noted between drip loss and storage time in any of these modified atmosphere/temperature combinations. In contrast, drip loss in vacuum packs at 5 and 0°C increased with time up to 21 days. Vacuum packs stored at 5 or 0°C had significantly higher drip losses ($p < 0.05$) than the other atmospheres at all storage times on almost all sample occasions, with the exception being at the 7 day sampling point. The relationship between drip loss and storage time up to 28 days was significant in vacuum packs at 5°C ($p < 0.05$) and at 0°C ($p < 0.01$).

Lean colour

In all cases, except at 28 days, there were no significant differences between the *a* values (redness) noted in the different atmospheres or temperatures at any of the storage times (Table 3). At 28 days, meat stored in vacuum packs at 0°C had higher values than that stored in 80% O_2/20% CO_2 at 5 or 0°C ($p < 0.05$). The linear increase in redness with storage time, measured 2 hr after pack opening, was significant in vacuum packs stored at 5°C ($p < 0.05$) and at 0°C ($p < 0.01$).

Hue angle

The hue angle variation for each of the gas atmospheres at 5 and 0°C is shown in Fig. 1. Small differences in hue angle were observed between some of the packaging treatments at 28 days only ($p < 0.05$). Despite the observed increase in hue angle in some of the atmosphere/temperature combinations, the linear trend was not significant in any case.

TABLE 3
Lean Colour (Hunter *a* Values)[a] over 28 Days, Measured 2 hr after Pack Opening from Lamb Shoulders Packaged in Different Gas Atmospheres at 5 or 0°C

Gas atmosphere	*Storage temperature (°C)*	*Storage time (days)*[b] 7	14	21	28	*Linear trend*[c]
Vacuum pack	5	11.4	14.3	13.9	16.9[ab]	*
	0	11.3	14.7	14.8	18.9[a]	**
80% O_2/20% CO_2	5	12.2	10.9	11.8	11.2[b]	NS
	0	12.0	13.0	12.8	10.1[b]	NS
50% CO_2/50% N_2	5	11.9	10.6	14.0	12.8[ab]	NS
	0	11.9	12.0	15.0	11.6[ab]	NS
100% CO_2	5	10.5	11.3	14.0	13.5[ab]	NS
	0	13.4	11.8	12.4	13.3[ab]	NS

[a]Mean Hunter *a* value at time zero = 12.4; standard error = 0.26.
[b]Pairwise comparisons between means at each storage time were made using the Tukey–Kramer test. Within a column, means with different superscripts are significantly different ($p < 0.05$).
[c]Significance of linear regression coefficient: $^*p < 0.05$; $^{**}p < 0.01$; NS, non-significant.

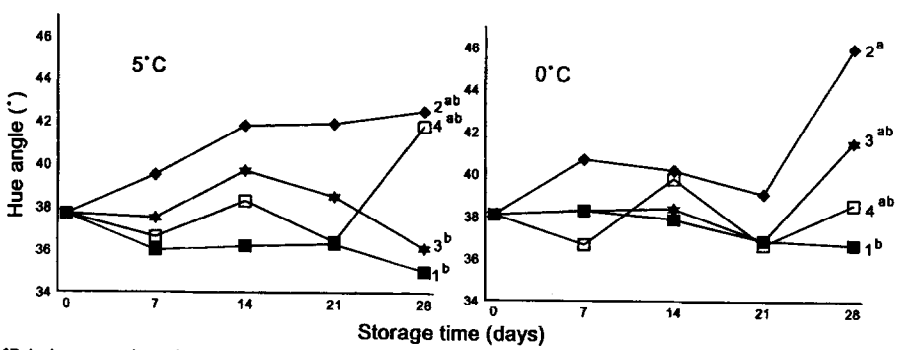

Fig. 1. Hue angle (°) at 2 hr over 28 days storage on lamb shoulders packaged under: (1) vacuum; (2) 80% O_2/20% CO_2; (3) 50% CO_2/50% N_2; or (4) 100% CO_2 and stored at 5 or 0°C.

Fat colour

A decrease in fat yellowness, suggesting that bleaching had occurred, was observed at 7 days in all samples (Table 4). No significant differences in fat colour were noted between primals stored for similar periods of time under the various atmospheres or temperatures. The only change in fat colour over 28 days in any of the atmospheres at 5 or 0°C was in materials stored in 80% O_2/20% CO_2 at 5°C, where a small but significant linear relationship between fat colour and storage time was noted ($p < 0.05$).

TABLE 4
Fat Colour (Hunter *b* Values)[a] over 28 Days, from Lamb Shoulders Packaged in Different Gas Atmospheres at 5 or 0°C

Gas atmosphere	*Storage temperature (°C)*	*Storage time (days)* 7	14	21	28	*Linear trend*[b]
Vacuum pack	5	11.6	10.8	13.0	13.7	NS
	0	9.7	11.2	11.8	11.5	NS
80% O_2/20% CO_2	5	9.3	12.8	12.0	12.9	*
	0	11.9	11.4	11.2	12.2	NS
50% CO_2/50% N_2	5	10.7	12.8	12.1	13.4	NS
	0	11.0	12.9	12.2	11.2	NS
100% CO_2	5	11.0	12.3	11.4	12.4	NS
	0	11.2	11.7	10.9	11.5	NS

[a]Mean Hunter *b* value at time zero = 13.0; standard error = 0.26.
[b]Significance of linear regression coefficient: $^*p < 0.05$; NS, non-significant.

Meat pH

There were no significant differences between mean surface pH values noted in primals stored under the different atmospheres or temperatures at any storage time. A similar result was obtained for mean internal pH values. The mean surface and internal pH values, averaged over 5 and 0°C, are shown in Table 5. It was noted that surface pH was significantly higher ($p < 0.05$) than internal pH in primals before packaging and after storage, and overall the differences were significant. There were linear increases in the surface and internal pH during storage in 50% CO_2/50% N_2 and 100% CO_2 ($p < 0.05$).

DISCUSSION

Several factors contribute to changes in gas composition during the low temperature storage of meat products, including permeability of the packaging materials used (Seideman *et al.*, 1979*a*), meat and bacterial respiration (Taylor & MacDougall, 1973; Johnson, 1974) and gas solubility (Daun *et al.*, 1971). Since the permeabilities of the packaging materials used in the present study were very low, particularly at the temperatures used, the exchange of gases from outside the packs are unlikely to have any major effects on internal gas composition. The effects of bacterial and meat respiration on gas compostion were most evident in 80% O_2/20% CO_2 packs stored at 5°C. Under these conditions, the proportion of CO_2 increased while the proportion of O_2 decreased. Other workers have noted similar changes in relation to beef and pork products packaged in high O_2 (75–80%)–low CO_2 (25–20%) gas mixtures (Taylor & MacDougall, 1973; Seideman *et al.*, 1979*a*; Taylor *et al.*, 1986, 1990).

In the high CO_2 atmospheres (50% CO_2/50% N_2 and 100% CO_2), O_2 was detected during storage as the percentage of CO_2 declined and N_2 increased. Small residual levels of air in these packs after packaging may account for the presence of O_2 in both atmospheres and the appearance of N_2 in 100% CO_2.

TABLE 5
Mean Surface and Internal pH[a] Values up to 28 Days, Averaged over 5 and 0°C, from Lamb Shoulders Packaged in Different Gas Atmospheres

Gas atmosphere	*Storage temperature (°C)*	*Storage time (days)*[b] 7	14	21	28	*Linear trend*[c]
Vacuum pack	S	5.82[a]	5.77[a]	5.85[a]	5.75	NS
	I	5.63[b]	5.63[b]	5.67[b]	5.72	NS
80% O_2/20% CO_2	S	5.70	5.83[a]	5.81[a]	5.84	NS
	I	5.62	5.64[b]	5.63[b]	5.69	NS
50% CO_2/50% N_2	S	5.70	5.85[a]	5.84[a]	5.97[a]	**
	I	5.53	5.62[b]	5.60[b]	5.62[b]	**
100% CO_2	S	5.57	5.91[a]	5.95[a]	6.04[a]	***
	I	5.43	5.58[b]	5.57[b]	5.66[b]	*

S, surface; I, internal.
[a]Mean surface pH at time zero = 5.82; standard error = 0.02. Mean internal pH at time zero = 5.51; standard error = 0.01.
[b]Pairwise comparisons between means at each storage time were made using the least significance difference test. Within a column, means with different superscripts are significantly different ($p < 0.05$).
[c]Significance of linear regression coefficient: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; NS, non-significant.

The results obtained in this study for changes in gas composition in 100% CO_2 packs were considerably less than those recorded by Seideman *et al.* (1979*b*). These authors reported that the $O_2 : N_2$ ratio was 3.78 : 16.18 at 28 days. This suggests that air had entered the packs they examined during the storage period. Other workers (Erichsen & Molin, 1981) noted very small changes (0.0–0.1% O_2) in the composition of gases surrounding normal and high pH meat packaged in 100% CO_2 held for up to 51 days. This is probably due to the high gas to meat ratio (10 : 1) used by these authors compared to those used in the present study (2 : 1). Such a high gas to meat ratio would not be practical for commercial purposes.

The extent of drip loss noted in vacuum packaged meat is a major disadvantage in the use of this method. Our studies on vacuum packaged lamb stored at 5 and 0°C confirm the results of a number of previous studies showing that vacuum packaged meat produces higher levels of drip than meat packaged in modified atmospheres (Seideman *et al.*, 1979*b*; O'Keeffe & Hood, 1980–81; Rousset & Renerre, 1991; Schluter *et al.*, 1994). As the values and patterns of observed surface and internal pH values were generally similar across all the storage regimes, it is unlikely that the increased drip loss noted in vacuum packaged lamb was a pH associated effect. The higher drip loss in vacuum packaged products may be due to the physical extraction of water from vacuum packaged meat due to the applied vacuum pressure (Schluter *et al.*, 1994). In contrast to the above results, Taylor *et al.* (1990) reported lower drip loss in vacuum skin packs compared to an atmosphere containing 75% O_2/25% CO_2. These authors attributed the difference to the proximity of the packaging materials to the product, effectively sealing the meat surface.

In the present study, drip loss was not significantly affected by the storage temperatures examined. This is in agreement with the findings of O'Keeffe & Hood (1980–81)

where drip loss increased more rapidly with temperature from 5 to 10°C than from 0 to 5°C.

In the present study, acceptable, cherry-red (Faustman & Cassens, 1990) muscle colour was observed in all stored primals 2 hr after packs were opened. Since colour was measured after only a 2 hr blooming period, the effect on colour stability is unknown. Colour stability has been reported to decline during storage (O'Keeffe & Hood, 1980–81).

In the present study, the O_2 concentrations in 50% CO_2/50% N_2 and 100% CO_2 packs after storage were generally below 0.1%, although higher concentrations (0.13–0.25%) were noted in four of the packs. At all these concentrations of O_2, acceptable muscle colour was observed in both atmospheres. This result is at variance with the observations of Penney & Bell (1993), who reported that noticeable browning of lamb occurred in packs containing more than 0.15% O_2. The difference between these two studies may be explained by the fact that Penney & Bell (1993) examined muscle from electrically stimulated carcasses, whereas muscle from non-stimulated carcasses was investigated in the present study. Sleper *et al.* (1983) found that muscle from electrically stimulated carcasses has less metmyoglobin reducing activity than muscle from non-stimulated carcasses. This means that non-stimulated carcasses yield meat with a greater capacity to metabolise brown metmyoglobin and maintain an acceptable red colour.

Apart from a slight bleaching effect at 7 days, fat colour was not seriously affected in any of the packaging treatments in the present study. Although fat colour is less important than lean meat colour, it may also influence consumer acceptability of the product. In general, the consumer regards white as the most acceptable fat colour. High CO_2 atmospheres can cause bleaching of the fat (Egan & Shay, 1988), while drip losses from other parts of the product during storage can stain fat components.

The results of this study showed that for either surface or internal pH, there were no significant differences between packaging treatments during storage. In general, this is in agreement with the findings of other workers (Huffman *et al.*, 1975; Seideman *et al.*, 1979*b*; Anjaneyulu & Smidt, 1986; Moore & Gill, 1987; McMullen & Stiles, 1991; Rousset & Renerre, 1990, 1991). In our study, the observed increase in pH with storage time in the high CO_2 atmospheres was unexpected, based on reports that meat pH declines when packaged in such atmospheres (Ledward, 1970; Egan & Shay, 1988, Gill, 1988). Moore & Gill (1987) however, also recorded an increase in the pH of lamb during storage in CO_2. These authors suggested that tissue breakdown may be responsible.

It has been suggested that a reduced pH derived in high CO_2 atmospheres may inhibit bacterial growth (King & Nagel, 1967; Daniels *et al.*, 1985; Egan & Shay, 1988; Dixon & Kell, 1989). This is at variance with the results of other workers (Huffman *et al.*, 1975; Sheridan *et al.*, 1995). Huffman *et al.* (1975) noted identical surface pHs for beef packaged in atmospheres containing approximately 100% CO_2 and 70% N_2/25% CO_2/5% O_2 while bacterial counts in 100% CO_2 were significantly lower than in 70% N_2/25% CO_2/5% O_2. Similarly, in the present work (Sheridan *et al.*, 1995), bacterial counts in 50% CO_2/50% N_2 and 100% CO_2 were generally lower than in vacuum packs and 80% O_2/20% CO_2, although pH values were broadly similar. Thus it appears that bacterial counts in high CO_2 atmospheres do not directly dictate the observed reduction in pH. Further studies are required to determine the exact relationship between pH and CO_2 concentration.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial assistance of the EEC Food-Linked Agro-Industrial Research (FLAIR) project No. 89055.

REFERENCES

Anjaneyulu, A. S. R. & Smidt, H. D. (1986). *J. Food Sci. Technol.*, **23,** 88.
Anon. (1987). Milton Roy Technical Manual for C1400 Computing Integrator.
Daniels, J. A., Krishnamurthi, R. & Rizvi, S. S. H. (1985). *J. Food Prot.*, **48,** 532.
Daun, H., Solberg, M., Franke, W. & Gilbert, S. (1971). *J. Food Sci.*, **36,** 1011.
Dixon, N. M. & Kell, D. B. (1989). *J. Appl. Bacteriol.*, **67,** 109.
Egan, A. F., Eustace, I. J. & Shay, B. J. (1990). *Meat Focus Int.*, Oct., 25.
Egan, A. F. & Shay, B. J. (1988). *ICoMST.*, **34,** 476.
Erichsen, I. & Molin, G. (1981). *J. Food Prot.*, **44,** 866.
Faustman, C. & Cassens, R. G. (1990). *J. Muscle Foods*, **1,** 217.
Gill, C. O. (1988). *Meat Sci.*, **22,** 65.
Huffman, D. L., Davis, K. A., Marple, D. N. & McGuire, J. A. (1975). *J. Food Sci.*, **40,** 1229.
Johnson, B. Y. (1974). *CSIRO Food Res. Q.*, **34,** 14.
King, A. D. Jr & Nagel, C. W. (1967). *J. Food Sci.*, **32,** 575.
Ledward, D. A. (1970). *J. Food Sci.*, **35,** 33.
McMullen, L. M. & Stiles, M. E. (1991). *J. Food Prot.*, **54,** 778.
Moore, V. J. & Gill, C. O. (1987). *NZ J. Agric. Res.*, **30,** 449.
O'Keeffe, M. & Hood, D. E. (1980–81). *Meat Sci.*, **5,** 267.
Penney, N. & Bell, R. G. (1993). *Meat Sci.*, **33,** 245.
Rousset, S. & Renerre, M. (1990). *Sci. Des Aliments.*, **10,** 737.
Rousset, S. & Renerre, M. (1991). *Int. J. Food Sci. Technol.*, **26,** 641.
Schluter, A. R., Miller, M. F., Jones, D. K., Meade, M. K., Ramsey, C. B. & Patterson, L. L. (1994). *Meat Sci.*, **37,** 257.
Seideman, S. C., Carpenter, Z. L., Smith, G. C., Dill, C. W. & Vanderzant, C. (1979*a*). *J. Food Prot.*, **42,** 317.
Seideman, S. C., Smith, G. C., Carpenter, Z. L., Dutson, T. R. & Dill, C. W. (1979*b*). *J. Food Sci.*, **44,** 1036.
Sheridan, J. J., Doherty, A., Allen, P., McDowell, D. A., Blair, I. S. & Harrington, D. (1995). *Meat Sci.*, submitted.
Sleper, P. S., Hunt, M. C., Kropf, D. H., Kastner, C. L. & Dikeman, M. E. (1983). *J. Food Sci.*, **48,** 479.
Taylor, A. A., Down, N. F. & Shaw, B. G. (1986). In *Recent Advances and Developments in the Refrigeration of Meat by Chilling.* International Institute of Refrigeration, Commission C2, p. 295.
Taylor, A. A., Down, N. F. & Shaw, B. G. (1990). *Int. J. Food Sci. Technol.*, **25,** 98.
Taylor, A. A. & MacDougall, D. B. (1973). *J. Food Technol.*, **8,** 453.
Walker, S. J. (1992). In *Chilled Foods, A Comprehensive Guide*, eds C. Dennis & M. Stringer. Ellis Horwood, London, p. 147.
Williams, A. C. Jr (1987). In *Food Product—Package Compatibility, Proceedings*, eds J. I. Gray, B. R. Harte & J. Miltz. Technomic Publishing Company, Lancaster, p. 170.
Young, L. L., Reviere, R. D. & Cole, A. B. (1988). *Food Technol.*, Sept., 65.