Available online at www.sciencedirect.com
SCIENCE DIRECT®
Meat Science 68 (2004) 649–658
MEAT SCIENCE
www.elsevier.com/locate/meatsci

Display life of sheep meats retail packaged under atmospheres of various volumes and compositions

C. Kennedy, D.J. Buckley, J.P. Kerry *

Department of Food and Nutritional Sciences, University College Cork – National University of Ireland, Cork, Ireland

Received 10 July 2003; received in revised form 20 April 2004; accepted 28 May 2004

Abstract

Longissmus dorsi loins were removed from Suffolk cross-breed lambs (4–9 months) and hoggets (15–20 months). The effect of package gas composition was investigated by packaging loins with gas mixtures containing 80:20:0, 60:20:20 and 60:40:0/O_2:CO_2:N_2 with a 2:1 headspace to meat volume ratio. The most effective gas mixture for prolonging shelf-life was used to study the effect of different headspace to meat volume ratios. Loins were packaged with a headspace to meat volume ratio of 2:1, 1.5:1 or 1:1. All modified atmosphere (MA) packs were held under refrigerated display conditions (4 °C, 616 lx) for 12 days. Loins were assessed for microbial, oxidative and colour stability and headspace composition every 3 days. The 80:20:0/O_2:CO_2:N_2 gas composition and the 2:1 headspace to meat volume ratio was the most effective packaging combination at maintaining and prolonging the attractive red colour of MA packaged lamb and hogget meat. 80:20:0/O_2:CO_2:N_2 resulted in significantly ($p < 0.01$) higher Hunter *a* values in lamb. The 2:1 ratio gave higher visual assessment values in lamb and higher Hunter '*a*' values for hogget meat throughout the trial. The 2:1 ratio was the most effective at decreasing *Pseudomonas* and increasing the numbers of lactic acid bacteria in the total microbial load in both lamb and hogget meat. Lipid oxidation in lamb and hogget meat occurred at a slower comparative rate than discolouration or microbial growth and was not the major determinant of shelf-life. The 2:1 headspace to meat volume ratio was most effective at maintaining the initial gas mix in both lamb and hogget MA packs.

Keywords: Modified atmosphere; Headspace to meat ratio; Shelf-life; Sheep meat

1. Introduction

Although some deterioration of meat will occur in the absence of microorganisms, such as the enzymatic breakdown of tissues and other chemical changes, microbial growth is the most important factor in relation to the keeping quality of fresh meat (Lambert, Smith, & Dodds, 1991). Modified atmosphere packaging (MAP) is designed primarily to preserve the bright red appearance of meat (Taylor, Down, & Shaw, 1990), although lipid oxidation and microbial growth are also important factors for the shelf-life and consumer acceptance of fresh meat (Jakobsen & Bertelsen, 2000). However, when MAP reduces the other deteriorative mechanisms in meat, lipid oxidation might limit shelf-life (McMillin, 1993). Colour is the most frequently used criterion for judging shelf-life quality and acceptability of fresh meats by consumers even though the correlation between colour and overall quality is of limited value (Walker, 1980). Meat colour is controlled by the concentration and chemical state of the muscle pigment, myoglobin (Williams, 1987). Myoglobin, which is purple in anoxic 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 oxidation of oxymyoglobin to metmyoglobin, which imparts the undesirable brown colour associated with non-saleable meat (Kerry, Buckley, & Morrissey, 2000).

In order to optimise shelf-life, sensory quality and microbiological safety using MAP, the packaging system applied is highly product specific (Church & Parsons, 1995). Beef and lamb are both red meats and share similar properties but considerable differences in shelf

* Corresponding author. Tel.: +353-21-490-3798; fax: +353-21-427-6318.
E-mail address: joe.kerry@ucc.ie (J.P. Kerry).

0309-1740/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.meatsci.2004.05.018

lives are apparent between them due to their relative susceptibility to chemical and microbial spoilage. Gill (1989) noted that the pH of beef muscle was lower than that of lamb and consequently less conducive to growth of spoilage organisms. As a result beef can be preserved by vacuum packaging, whereas with lamb, the bacteriostatic effect of CO_2 is necessary in order to achieve a comparable shelf-life. In addition, product shelf-life properties of colour, oxidative stability and microbial growth are largely influenced by interactive effects of initial meat traits, internal packaging parameters and environmental storage conditions.

MAP of lamb has been investigated in carcass and primal format. Results from carcass investigations are not directly comparable to results obtained from primal examination. It is not possible to completely evacuate a carcass pack prior to the injection of gas, resulting in an ill-defined packaging atmosphere (Sheridan et al., 1997). Limited work on lamb primals has been published (Shaw, Harding, & Taylor, 1980). From an extensive review of the scientific literature, no reports, on the effect of different packaging atmospheres on the microflora and shelf-life of lamb or hogget meat were found.

The objectives of this study were to investigate the effect of MAP with different gas compositions and headspace to meat volume ratios on lamb and hogget meat quality and to compare lamb and hogget meat under the different storage conditions.

2. Materials and methods

2.1. Chemicals

All chemicals used were 'AnalaR' grade obtained from British Drug House, Poole, Dorset, UK; Sigma Chemical Co., Ltd., Dorset, UK and Rathburn Chemical Co., Ltd., Walkerburn, Peableshire, Scotland.

2.2. Meat samples

Longissmus dorsi muscles were obtained from factory lambs (4–9 months Suffolk cross-breeds) and hoggets (15–20 months Suffolk cross-breeds). Both lambs and hoggets were examined as lambs are milk-fed and finished on grass, while hoggets are fed either winter/spring grass with concentrates or finished indoors on a hay-based diet. Therefore, the composition of lamb and hogget meat should be very different from each other due to age, physiology and diet. Muscles were removed from carcasses chilled over a period of 24 h post-slaughter. Muscles were trimmed of external fat and cut into steaks of different sizes (see packaging Trials 1 and 2) depending on packaging requirements. Prior to packaging, all samples were allowed to bloom for 1 h at 4 °C.

2.3. Modified atmosphere packaging

Each loin (*M. longissmus dorsi*) selected at random, was divided into five (one for each sampling day, 0, 3, 6, 9 and 12) and placed on CPET trays (BXL Plastics Ltd., Thermoformed Containers Division, 79a Park Lane, Croydon CRO 1JG, UK) and sealed with a low O_2 permeable (65 cm^3/m^2/24 h at STP) laminated 12 μm polyester/adhesive/17 μm clear coated polyester lidding material for MAP using packaging machine type: 100BS Gustav Muller and Co. (Zum Wingert 5, 6380 Bad Homberg, Germany).

2.4. Packaging Trial 1

Loins (*M. longissmus dorsi*) ($n = 15$) were selected at random, and divided into three groups ($n = 5$) and packaged with gas mixtures containing either 80:20:0, 60:20:20 or 60:40:0/O_2:CO_2:N_2, with a 2:1 gas volume to meat ratio in each pack.

2.5. Packaging Trial 2

Loins (*M. longissmus dorsi*) ($n = 15$) were selected at random, and divided into three groups ($n = 5$) and were packaged with 80:20:0/O_2:CO_2:N_2 and a gas volume to meat ratio of either 2:1, 1.5:1 or 1:1.

2.6. Storage conditions

MA packs were held under refrigerated display conditions (4 °C) using fluorescent light (Osram L30W/76, Natura Delux, Germany) (616 lx) for up to 12 days.

2.7. Determination of microbial load

All microbiological procedures were carried out in a Class 2 hood (Quality Air Systems, Warrington, England). The microbiology of the meat was analysed using a method modified from Holley et al. (1994). Using a sterile scalpel, 3×3.33 g of meat was aseptically sampled from representative parts of each steak and pooled to give a total of 10 g. Each 10 g sample was stomached for 2 min at high speed with 90 ml 0.1% peptone sterile water, in a Seward stomacher 400 laboratory blender (Seward, London SE1 1PP, UK). A 10-fold serial dilution was made using 0.1% sterile peptone water and a 0.1 ml aliquot from the appropriate dilution was plated in duplicate onto four types of media.

Total viable counts (TVC) were determined using plate count agar (PCA) and inoculated plates were incubated at 35 °C for 48 h. Lactic acid bacteria (LAB) were determined by plating on deMan, Rogosa, Sharpe (MRS) agar and incubating at 35 °C for 48 h. Coliforms were determined using violet red bile agar (VRBA) and inoculated plates were incubated at 35 °C for 24 h.

Pseudomonads were determined by plating on *Pseudomonas* selective agar (PSA), and incubating at 30 °C for 48 h. Plates were removed from the incubator and viable numbers were determined from plates bearing 20–200 colony forming units and results were expressed as CFU/g meat.

2.8. Measurement of oxidative stability

The extent of lipid oxidation was assessed by measuring thiobarbituric acid reacting substances (TBARS) using the method of Tarladgis, Watts, Younathan, and Dungan (1960) as modified by Ke, Ackman, Linke, and Nash (1977). TBARS were expressed as mg malonaldehyde/kg muscle. Lipid oxidation was measured in duplicate from each of the five packs for each treatment in each trial on days 0, 3, 6, 9 and 12.

2.9. Determination of colour

Surface meat colour (Hunter *L*, *a*, *b* values) was measured using a Minolta Chromameter CR-300 (Minolta Camera Co., Chuo-Ku, Osaka 541, Japan). Hunter *L*, *a*, *b* values of meat steaks (*M. longissmus dorsi*) were measured through packaging material on days 0, 3, 6, 9 and 12.

2.10. Visual assessment of sheep meat colour

A semi-trained colour assessment panel of fifteen people was asked to examine the meat colour on the same days as instrumental colour analysis was carried out. Three displays of meat were shown to panelists, one display for each of the different packaging conditions examined in the different trials. Panelists were asked to assess meat colour using a 10 point scale, on which a rating of 10 indicates excellent colour and a rating of zero indicates extremely poor colour. The mid-point of this scale (rating 5) was designated as the lowest score at which panelists would purchase the product under normal retail display conditions.

2.11. Determination of headspace composition

O_2 and CO_2 concentrations in the headspace of 2:1, 1.5:1 and 1:1 MA packs of trial 2 were measured using a PBI Dansensor (PBI Dansensor A/S, Ronnedevej 18, DK-4100 Ringsted, Denmark). A small volume of headspace gas was removed from MA packs through a medical type needle (0.8 mm × 40 mm) (Thermo Europe N.V., 3001 Leuven, Belgium) inserted through an adhesive backed rubber septum (PBI Dansensor A/S, Ronnedevej 18, DK-4100 Ringsted, Denmark), placed on packaging material to prevent pack leakage between measurements. O_2 and CO_2 concentrations were measured on days 0, 3, 6, 9 and 12.

2.12. Statistical analysis

An initial parametric analysis of the data indicated that the normality and constant variance assumptions were violated. Thus, non-parametric tests were conducted where the observations for each response were ranked in ascending order and the appropriate parametric tests were performed on the ranked data (Neter, Wasserman, & Kutner, 1990). The responses analysed were Hunter '*a*' colour, TBARS, TVC's, LAB's, coliforms and *Pseudomonas* counts and O_2 and CO_2 in headspace. For each response (ranked data), a full repeated measures analysis of variance (ANOVA) was conducted to investigate the effects of meat, gas type, and day. Meat and gas type were treated as between-subjects factors and day was treated as a within-subjects factor. For all responses the three way interaction, meat × gas type × day was statistically significant. Thus all subsequent analyses were performed for each day. That is, for each day, 2 × 3 ANOVAs were performed to investigate the effects of meat, gas type and their interaction on the responses (ranked data). Tukeys test was used to adjust for multiple comparisons. The level of significance was determined as $p < 0.05$. Friedman's two-way ANOVA was conducted for visual assessment data to investigate the difference between the six groups; 80:20:0, 60:20:20 and 60:40:0/O_2:CO_2:N_2 with lamb and 80:20:0, 60:20:20 and 60:40:0/O_2:CO_2:N_2 with hogget in trial 1, or 2:1, 1.5:1 and 1:1 with lamb and 2:1, 1.5:1 and 1:1 with hogget in trial 2. All analyses were performed for each day separately. The analyses were performed using SPSS for Windows (SPSS, Chicago, IL, USA) version 10.0.

3. Results and discussion

3.1. Microbial load

TVC's from MAP lamb meat showed significant differences ($p < 0.05$) early on in storage between the different gas composition packs during retail display but all had exceeded the microbiological guidelines for meat (Department of Irish Health, 1992) of 2.0×10^6 CFUs/g meat after day 6 (Table 1). TVC's in the same study using hogget meat also increased during retail display and had exceeded the same limit after day 3 (Table 1). The initial microbial load on day 0 in hogget meat packaged in different gas compositions was significantly ($p < 0.001$) higher compared with those in the lamb packs of the same study. Shelf-life is inversely proportional to initial microbial load (Christopher, Seideman, Carpenter, Smith, & Vanderzant, 1979; Kraft, 1986). Low initial loads of spoilage bacteria can extend the storage life by altering the composition of the spoilage flora (Gill, 1996). In both lamb and hogget meat pack-

Table 1
Microbiological counts in lamb meat (*M. longissmus dorsi*) packaged in different gas compositions and stored in a refrigerated (4 °C) display cabinet, 616 lx lighting for 12 days

Sample	Bacterial types	Atmosphere O_2:CO_2:N_2	Time (days)				
			0	3	6	9	12
			CFUs/g	CFUs/g	CFUs/g	CFUs/g	CFUs/g
Lamb	TVC	80:20:0	3.1×10^{2c}	3.5×10^{4b}	1.1×10^{6c}	1.7×10^{7b}	3.2×10^{6c}
		60:20:20	3.1×10^{2c}	2.3×10^{5b}	5.6×10^{6b}	4.2×10^{6c}	7.2×10^{6c}
		60:40:0	3.1×10^{2c}	4.4×10^{4}	4.5×10^{6}	1.2×10^{7c}	4.6×10^{6c}
Hogget	TVC	80:20:0	6.5×10^{4}	2.8×10^{5}	1.5×10^{7}	3.7×10^{7}	6.3×10^{7}
		60:20:20	6.5×10^{4}	2.2×10^{4}	1.4×10^{7}	5.8×10^{7}	5.8×10^{7}
		60:40:0	6.5×10^{4}	3.9×10^{4}	3.2×10^{6}	3.6×10^{7}	1.5×10^{7}
Lamb	LAB	80:20:0	TFTC	1.3×10^{2}	5.1×10^{3}	1.4×10^{4}	2.2×10^{4}
		60:20:20	TFTC	4.2×10^{2}	6.4×10^{3}	9.6×10^{3}	1.8×10^{4}
		60:40:0	TFTC	1.2×10^{2}	1.1×10^{4}	1.5×10^{4}	8.1×10^{3}
Hogget	LAB	80:20:0	TFTC	TFTC	1.1×10^{6}	1.0×10^{5}	9.5×10^{4}
		60:20:20	TFTC	TFTC	4.9×10^{5}	3.3×10^{4}	9.4×10^{5}
		60:40:0	TFTC	TFTC	2.4×10^{5}	7.8×10^{4}	1.9×10^{5}
Lamb	Coliforms	80:20:0	TFTC	1.6×10^{2}	9.6×10^{2}	1.4×10^{4}	1.4×10^{3}
		60:20:20	TFTC	1.0×10^{2}	8.6×10^{3}	1.7×10^{3}	5.2×10^{3}
		60:40:0	TFTC	TFTC	2.6×10^{3}	TFTC	TFTC
Hogget	Coliforms	80:20:0	TFTC	6.5×10^{3}	1.4×10^{5}	1.3×10^{6}	1.2×10^{6}
		60:20:20	TFTC	2.3×10^{3}	1.3×10^{7}	9.3×10^{5}	3.9×10^{5}
		60:40:0	TFTC	1.5×10^{3}	2.0×10^{4}	1.0×10^{5}	8.1×10^{4}
Lamb	*Pseudomonas*	80:20:0	TFTC	1.5×10^{2}	7.8×10^{2}	1.3×10^{4}	7.7×10^{2}
		60:20:20	TFTC	1.6×10^{2}	3.7×10^{4}	1.4×10^{3}	1.3×10^{3}
		60:40:0	TFTC	TFTC	6.7×10^{2}	TFTC	TFTC
Hogget	*Pseudomonas*	80:20:0	TFTC	7.2×10^{3}	2.6×10^{5}	1.4×10^{6}	9.8×10^{5}
		60:20:20	TFTC	2.9×10^{3}	2.1×10^{5}	5.1×10^{6}	5.3×10^{5}
		60:40:0	TFTC	7.5×10^{2}	4.0×10^{4}	1.2×10^{5}	1.0×10^{5}

Mean values for five analyses.
Mean TVC lamb value significantly different to hogget [b] $^{**}p < 0.01$, [c] $^{***}p < 0.001$.
TFTC, too few to count.

aged in different gas compositions, lactic acid bacteria counts increased while coliforms and pseudomonads counts decreased and were inhibited after day 9. In the case of hogget meat with its higher initial total microbial load, there was a higher proportion of pseudomonads (ranging from 0.67–8.79% of TVC counts) on days 6, 9 and 12 compared with that of the lamb (0–0.66% of TVC counts). These results concur with Gill (1996) assertion that the spoilage flora of meat will usually be dominated by the bacteria which grow most rapidly under the storage conditions applied to the meat, because there are no interactions between bacteria until the flora reaches high numbers. Since the shelf-life of fresh meat is limited by the growth and biochemical activities of the *Pseudomonas* species (Lambert et al., 1991), this suggests that the initial hygenic condition of the meat prior to packaging has a large influence on the shelf-life and that the effectiveness of the packaging system subsequently applied may be reduced due to the altered composition of the spoilage flora. In both lamb and hogget packs, 60:40:0/O_2:CO_2:N_2 was the most effective at inhibiting coliform and *Pseudomonas* growth although all gas compositions inhibited their growth after day 9. This agrees with the findings of Sahoo and Anjaneyulu (1995) that the optimal inhibition of meat spoilage bacteria is achieved at 40–60% CO_2. Other researchers found the optimal CO_2 concentration of MAP meat to be generally below 40% (Satomi, 1990; Selman, 1987) and Gill (1996) reported that increasing the CO_2 concentration above 20% produced little additional inhibition.

TVC's in lamb meat packaged in different headspace:meat volume ratios increased throughout the 12 days of the trial but showed no significant differences between the different ratio packs on days 9 and 12 (Table 2). All packs remained below the microbiological guidelines for meat maximum limit (Department of Irish Health, 1992) up until day 6. The total microbial load in packaging trial 2 using hogget meat also increased throughout the 12 days but TVC's in hogget packs with a 2:1 ratio were lower than the other ratio packs on day 12 (Table 2). CO_2 both increases the duration of the lag phase and reduces the bacterial growth rate during the logarithmic phase (Farber, 1991). However, the former effect is the greater and therefore as bacteria move from the lag to log phase of growth the inhibitory effects are

Table 2
Microbiological counts in lamb and hogget meat (*M. longissmus dorsi*) packaged in a modify atmosphere of 80:20/O_2:CO_2 using different headspce:meat volume ratios and stored in a refrigerated (4 °C) display cabinet (616 lx) for 12 days

Sample	Bacterial types	Headspace:meat volume ratio	Time (days)				
			0	3	6	9	12
			CFUs/g	CFUs/g	CFUs/g	CFUs/g	CFUs/g
Lamb	TVC	2:1	1.2×10^3	2.6×10^5	2.8×10^5	7.0×10^6	1.7×10^7
		1.5:1	1.2×10^3	5.7×10^4	5.0×10^5	5.9×10^6	1.5×10^7
		1:1	1.2×10^3	1.5×10^5	1.6×10^5	6.2×10^6	1.5×10^7
Hogget	TVC	2:1	7.0×10^4	2.2×10^5	2.1×10^6	7.7×10^6	9.1×10^6
		1.5:1	7.0×10^4	1.0×10^4	2.4×10^6	9.4×10^6	1.4×10^7
		1:1	7.0×10^4	3.1×10^4	4.5×10^5	4.6×10^6	1.5×10^7
Lamb	LAB	2:1	1.6×10^2	5.3×10^{3b}	1.0×10^5	1.3×10^{6a}	1.7×10^{6a}
		1.5:1	1.6×10^2	1.4×10^3	1.4×10^5	4.6×10^5	6.0×10^5
		1:1	1.6×10^2	1.9×10^3	9.5×10^{4b}	3.5×10^5	4.6×10^5
Hogget	LAB	2:1	7.6×10^3	5.8×10^3	4.0×10^4	3.0×10^5	4.2×10^5
		1.5:1	7.6×10^3	7.5×10^3	8.6×10^4	4.1×10^5	2.1×10^5
		1:1	7.6×10^3	2.3×10^{4b}	6.8×10^{3b}	5.0×10^{4a}	8.9×10^5
Lamb	Coliforms	2:1	1.6×10^2	6.5×10^2	5.5×10^3	4.2×10^4	4.4×10^3
		1.5:1	1.6×10^2	5.6×10^3	1.8×10^4	3.2×10^5	3.3×10^4
		1:1	1.6×10^2	2.4×10^4	3.7×10^3	4.8×10^5	4.9×10^4
Hogget	Coliforms	2:1	TFTC	5.3×10^2	8.8×10^4	6.9×10^4	1.8×10^5
		1.5:1	TFTC	4.5×10^2	5.9×10^4	7.9×10^4	1.8×10^5
		1:1	TFTC	2.9×10^2	2.1×10^3	9.9×10^3	1.4×10^5
Lamb	*Pseudomonas*	2:1	TFTC	2.3×10^4	4.0×10^3	4.2×10^5	2.4×10^4
		1.5:1	TFTC	3.6×10^3	1.4×10^4	3.2×10^5	1.9×10^4
		1:1	TFTC	2.3×10^4	7.2×10^4	2.5×10^5	1.5×10^4
Hogget	*Pseudomonas*	2:1	TFTC	6.3×10^2	5.2×10^4	4.5×10^4	3.8×10^4
		1.5:1	TFTC	5.4×10^2	6.3×10^4	4.2×10^4	6.4×10^4
		1:1	TFTC	2.4×10^2	2.3×10^2	2.4×10^4	4.1×10^4

Mean values for five analyses.
Mean LAB headspace:meat volume ratio value significantly different to other ratio values of the same meat type: [a] $^*p < 0.05$, [b] $^{**}p < 0.01$.
TFTC, too few to count.

reduced. Shelf-life is directly related to contact area between product and atmosphere as this determines gas dissolution (Church & Parsons, 1995). This may suggest that the larger volume of CO_2 available for interaction in hogget packs with a 2:1 ratio extended the lag phase of the microbial population in the meat. LAB counts in lamb packs with a 2:1 ratio were significantly ($p < 0.01$) higher than in packs with a 1:1 ratio on day 12 and highest of all packs on days 9 and 12. There was also a greater decrease in coliform and *Pseudomonas* numbers between days 9 and 12 in packs with a 2:1 ratio, suggesting that the 2:1 ratio was more effective at inhibiting coliforms and *Pseudomonas*. This may be due to the LAB dominating over the spoilage flora; inhibiting competing organisms by producing bacteriocins as they reached high numbers (Gill, 1996). LAB counts also increased in all hogget meat packs but only the 2:1 ratio packs were effective at inhibiting *Pseudomonas* over the 12 days of retail display. There was no observed inhibition of coliforms in hogget meat in all ratio packs during retail display compared with the lamb meat. Since coliform counts represented a mixture of different bacterial species, the proportions of each species in a meat sample may differ from one sample to the next. This may account for the differences observed in effectiveness of the same headspace gas and volume ratio in lamb and hogget meat packs.

3.2. Oxidative stability

There were no significant difference between TBARS values from lamb packaged under three different gas mixtures, with the exception of day 6 (Table 3), and hogget packaged under three different gas mixtures, up to day 9 (Table 3). TBARS values remained below 2.0 for lamb and hogget meat, for all gas mixtures throughout the trial. TBARS values were higher in lamb and hogget meat packaged in 80:20:0/O_2:CO_2:N_2. This is probably due to the higher oxygen concentration in these MAP packs. Increased lipid oxidation has been reported for meat stored at elevated O_2 concentrations (Jensen et al., 1997; Kerry et al., 2000), although other researchers did not find any increase in lipid oxidation under similar conditions (Asenio, Ordonez, & Sanz,

Table 3
Effect of packaging gas composition and headspace to volume ratio on the oxidative stability of lamb and hogget steaks (*M. longissmus dorsi*) packaged in modified atmosphere and held in a refrigerated (4 °C) illuminates (616 lx) display cabinet

Sample	Atmosphere O_2:CO_2:N_2	Time (days)						Headspace to volume ratio	Time (days)				
		0	3	6	9	12			0	3	6	9	12
		TBARS values	TBARS values	TBARS values	TBARS values	TBARS values			TBARS values	TBARS values	TBARS values	TBARS values	TBARS values
Lamb	80:20:0	0.05 ± 0.0	0.06 ± 0.0	0.40 ± 0.1	0.48 ± 0.0	1.32 ± 0.2		2:1	0.05 ± 0.0	0.16 ± 0.0	0.72 ± 0.1^{b}	1.36 ± 0.2	1.71 ± 0.4
	60:20:20	0.05 ± 0.0	0.04 ± 0.0	0.22 ± 0.0	0.28 ± 0.0	0.86 ± 0.0		1.5:1	0.05 ± 0.0	0.22 ± 0.0	0.44 ± 0.1	1.43 ± 0.1	1.65 ± 0.2
	60:40:0	0.05 ± 0.0	0.02 ± 0.0	0.11 ± 0.0^{a}	0.42 ± 0.1	1.03 ± 0.1		1:1	0.05 ± 0.0	0.04 ± 0.0	0.21 ± 0.0	1.08 ± 0.1	1.63 ± 0.2
Hogget	80:20:0	$0.06 \pm 0..0$	0.07 ± 0.0	0.35 ± 0.1	0.61 ± 0.2	4.14 ± 1.4		2:1	0.05 ± 0.0	0.06 ± 0.0	0.44 ± 0.0^{c}	0.48 ± 0.3	1.32 ± 0.7
	60:20:20	0.12 ± 0.0	0.11 ± 0.0	0.34 ± 0.1	0.72 ± 0.1	3.2 ± 0.6		1.5:1	0.05 ± 0.0	0.04 ± 0.0	0.22 ± 0.0^{c}	0.28 ± 0.3	0.86 ± 0.4
	60:40:0	0.07 ± 0.0	0.02 ± 0.0	0.24 ± 0.0	0.57 ± 0.1	2.15 ± 0.1^{a}		1:1	0.05 ± 0.0	0.02 ± 0.0	0.11 ± 0.0	0.42 ± 0.1	1.03 ± 0.4

Mean values ± SEM (mg malonaldehyde (MDA)/kg meat).
Mean TBARS value (for lamb) of 80:20:0/O_2:CO_2:N_2 significantly different to ^{a}60:40:0/O_2:CO_2:N_2: $^{*}p < 0.05$.
Mean TBARS value (for hogget) of 80:20:0/O_2:CO_2:N_2 significantly different to ^{a}60:40:0/O_2:CO_2:N_2: $^{a*}p < 0.05$.
Mean TBARS value (for lamb and hogget) of ^{b}2:1 and ^{c}1.5:1 significantly different to 1:1: $^{b**}p < 0.01$, $^{c***}p < 0.001$.

1988; Ordonez & Ledward, 1977). However, it must be noted that samples remained below 2.0 mg malonaldehyde/kg muscle up until day 9. This level may be considered as the threshold for rancid off-flavours in meat (Watts, 1962). The results presented here are similar to those reported by Jakobsen and Bertelsen (2000) who found that a reduction in O_2 concentration in the headspace from 80% to 55% did not have much influence on the lipid oxidation of MA packaged beef. A further decrease in O_2 concentration below 55% is required to obtain reduced lipid oxidation in beef at 3 °C (Jakobsen & Bertelsen, 2000). The significantly ($p < 0.001$) higher TBARS values of hogget meat compared with those of lamb on day 12 is at variance with the observations of Cifini, Napolitano, Pacelli, Riviezzi, and Girolami (2000) who reported that as sheep slaughter age increased, TBARS values tended to decrease. The significantly ($p < 0.001$) higher TBARS values of hogget meat may be due to the significantly ($p < 0.001$) higher microbial load (Table 1) which may accelerate metmyoglobin formation (Butler, Bratzler, & Mallmann, 1953) and subsequent lipid oxidation (Rhee & Ziprin, 1987) compared with those of lamb (Table 1). The formation of metmyoglobin and the production of lipid oxidation products have been linearly related and positively correlated (Faustman, Cassens, Schaefer, Buege, & Scheller, 1989).

There were no significant differences between TBARS values from lamb meat held under all MAP headspace to meat volume ratios on days 9 and 12 and TBARS values remained below 2.0 up to day 12 (Table 3). There was also no significant difference between TBARS values from hogget meat held under all MAP ratios on days 0, 3, 9 and 12 and values also remained below 2.0 up to day 12 (Table 3). In this case TBARS values for lamb meat were higher compared with those from hoggets on days 9 and 12. This again may be due to the slightly higher total viable counts in the lamb compared to those of the hogget (Table 2). It should be noted in both the lamb and hogget meat that TBARS values were lowest in the meat packaged in the 1:1 ratio during retail display. This may suggest that the lower volume of O_2 in the 1:1 ratio hogget packs reduced the O_2 available for interaction with the lipids present in the meat.

4. Colour

There were no significant difference in Hunter '*a*' values of lamb in the different MAP gas conditions for the first 6 days of retail display (Table 4) but Hunter '*a*' values were significantly ($p < 0.01$) higher at day 9 and 12 in lamb packaged with 80:20:0/O_2:CO_2:N_2 compared with other MAP conditions. It was also observed that Hunter '*a*' values of lamb meat packaged under 80:20:0/O_2:CO_2:N_2 were higher than lamb

Table 4
Effect of packaging gas composition on the colour (Hunter '*a*' and visual assessment) of lamb and hogget steaks (*M. longissmus dorsi*) packaged in modified atmosphere and held in a refrigerated (4 °C) illuminates (616 lx) display cabinet

Sample	Atmosphere O_2:CO_2:N_2	Time (days)									
		0		3		6		9		12	
		Hunter '*a*'		Hunter '*a*'		Hunter '*a*'		Hunter '*a*'		Hunter '*a*'	
			Visual		Visual		Visual		Visual		Visual
Lamb	80:20:0	12.5 ± 0.0	12.0 ± 0.3	10.8 ± 0.4	11.0 ± 0.4	9.3 ± 0.3	9.3 ± 0.3[b]	7.1 ± 0.7[b]	7.1 ± 0.7[b]	6.7 ± 0.8[b]	6.7 ± 0.8[b]
	60:20:20	11.5 ± 0.2	11.0 ± 0.2	9.6 ± 0.2	9.6 ± 0.2	8.1 ± 0.4	8.1 ± 0.4	5.1 ± 0.8	5.1 ± 0.3	3.9 ± 0.2	3.9 ± 0.2
	60:40:0	11.8 ± 0.1	12.0 ± 0.1	10.4 ± 0.4	10.0 ± 0.4	8.6 ± 0.5	8.6 ± 0.4	3.7 ± 0.2	3.7 ± 0.2	2.7 ± 0.1	2.7 ± 0.1
Hogget	80:20:0	12.7 ± 0.2	12.0 ± 0.2	11.5 ± 0.1	7.8 ± 0.2	9.1 ± 0.6	7.3 ± 0.3	7.9 ± 0.4	6.0 ± 0.3	6.8 ± 0.2	5.7 ± 0.5
	60:20:20	13.2 ± 0.1	9.0 ± 0.2	10.8 ± 0.3	7.4 ± 0.3	7.1 ± 0.2	7.3 ± 0.3	7.1 ± 0.3	4.7 ± 0.3	7.2 ± 0.6	4.5 ± 0.4
	60:40:0	12.3 ± 0.1	8.8 ± 0.2	10.9 ± 0.3	7.0 ± 0.2	9.4 ± 0.5	6.6 ± 0.4	8.4 ± 0.0.5	6.0 ± 0.3	7.2 ± 0.5	5.0 ± 0.6

Mean values ± SEM for five analysis performed 10 times (Hunter '*a*').
Mean Hunter '*a*' value of lamb in 80:20:0/O_2:CO_2:N_2 significantly ([b]$p < 0.01$) higher than other map treatments.
Mean visual assessment of lamb in 80:20:0/O_2:CO_2:N_2 significantly ([b]**$p < 0.01$) higher than other map treatments.

packaged using other MAP conditions during retail display (Table 4). It has been well established that elevated levels of O_2 prolong colour stability (Asenio et al., 1988; Bartkowski, Dryden, & Marchello, 1982; Taylor, 1972). A major function of O_2 in MAP meats is to maintain myoglobin in its oxygenated form, oxymyoglobin, which imparts the attractive red colour to the meat. It should be noted that as the TBARS values of lamb meat (Table 3) increased from day 6 to 12 there were corresponding decreases in Hunter '*a*' (Table 4) and visual assessment values (Table 4). This suggests that oxidation of lipids and myoglobin to metmyoglobin are in some way related such that an increase in the oxidation of one causes a similar effect in the other. Rhee and Ziprin (1987) showed that lipid oxidation correlated with total pigment and myoglobin content of raw muscle. In this study hogget meat showed no difference in Hunter '*a*' values (Table 4), with the exception of days 0 and 6, and visual assessment values (Table 4) throughout the storage period. However visual assessment values were slightly higher on days 3 and 12 under 80:20:0/O_2:CO_2:N_2 compared with other MAP conditions. This may be due to the preferred brick red colour for lamb observed by the panel reflecting the consumers perception of quality. Hunter '*a*' values detected by the colormeter is a quantitative measurement of red colour and does not distinguish between subtle differences in appearance. Hunter '*a*' values of hogget meat (Table 4) in the different MAP conditions was highest for meat packaged in headspace 60:20:60/O_2:CO_2:N_2 on day 0, 80:20:0/O_2:CO_2:N_2 on day 3 and 60:40:0/O_2:CO_2:N_2 on days 6, 9 and 12. Comparison of total microbial populations in both lamb and hogget (Table 1) showed significantly ($p < 0.001$) higher counts in hogget meat during storage under all MAP conditions. Stringer, Bilskie, and Naumann (1969) noted that surface discolouration was a function of the number of bacteria on the meat surface. It was also observed that Hunter '*a*' values of hogget packaged in headspace 60:40:0/O_2:CO_2:N_2 were highest and *Pseudomonas* counts lowest on days 6, 9 and 12 compared with other MAP gas conditions suggesting the relationship between microbial growth and discolouration may be due to the high proportion of bacteria such as *Pseudomonas*. Robach and Costilow (1961) claimed that aerobic bacteria such as *Pseudomonas geniculata*, *P. aeruginosa* and *P. fluorescens* consumed O_2, thereby reducing oxygen tension on the surface of the meat and causing discolouration.

Hunter '*a*' values (Table 5) of lamb packaged at different headspace to meat volume ratios were not significantly different but lamb packaged at a 2:1 ratio had higher visual assessment values (Table 5) throughout the 12 days of retail display. Hunter '*a*' values (Table 5) of hogget meat packaged at 2:1 and 1:1 headspace to meat volume ratios were higher on days 3, 6 and 9 with the 2:1

Table 5
Effect of headspace to meat volume ratio on the colour (Hunter 'a' and visual assessment) of lamb and hogget steaks (*M. longissmus dorsi*) packaged in modified atmosphere and held in a refrigerated (4 °C) illuminates (616 lx) display cabinet

Sample	Headspace to meat volume ratio	Time (days)											
		0		3		6		9		12			
		Hunter 'a'		Hunter 'a'		Hunter 'a'		Hunter 'a'		Hunter 'a'	Visual	Visual	Visual
Lamb	2:1	13.9 ± 0.5		9.8 ± 0.3		8.8 ± 0.2		6.1 ± 0.5		5.1 ± 0.5	8.1 ± 0.3	6.9 ± 0.3	6.3 ± 0.2	5.4 ± 0.2	4.5 ± 0.3
	1.5:1	13.5 ± 0.3		9.8 ± 0.1		9.0 ± 0.2		5.8 ± 0.3		5.2 ± 0.3	7.8 ± 0.3	6.5 ± 0.3	5.9 ± 0.2	4.9 ± 0.1	3.9 ± 0.4
	1:1	13.4 ± 0.4		9.3 ± 0.3		8.2 ± 0.3		5.2 ± 0.5		5.0 ± 0.7	7.7 ± 0.3	5.6 ± 0.3	5.1 ± 0.2	4.3 ± 0.2	3.5 ± 0.4
Hogget	2:1	12.8 ± 0..4		11.0 ± 0.3		9.1 ± 0.2		8.4 ± 0.2		6.5 ± 0.5	9.0 ± 0.1	7.8 ± 0.4	7.3 ± 0.2	7.5 ± 0.4	4.6 ± 0.3
	1.5:1	12.2 ± 0.2		9.6 ± 0.1		8.1 ± 0.2		7.3 ± 0.3		5.4 ± 0.6	8.9 ± 0.1	7.5 ± 0.3	7.0 ± 0.3	6.5 ± 0.3	4.0 ± 0.3
	1:1	13.1 ± 0.4		10.6 ± 0.2		8.9 ± 0.5		8.5 ± 0.3		7.2 ± 0.3	9.1 ± 0.1	7.6 ± 0.3	6.3 ± 0.4	6.5 ± 0.4	5.1 ± 0.3

Mean values ± SEM.

ratio being significantly ($p < 0.01$) higher on day 3 and the higher of the two throughout the 12 days of retail display. Visual evaluation showed a higher colour rating with hogget meat packaged at the 2:1 ratio on days 3, 6 and 9 which was significantly ($p < 0.001$) higher than 1.5:1 ratio on day 9 (Table 5). This suggests that the higher volume of O_2 in the headspace of the 2:1 ratio packs keeps myoglobin in its oxidised form for longer due to the greater availability of O_2 in the headspace.

4.1. Headspace analysis

Oxygen concentrations in 2:1 and 1.5:1 headspace to meat volume ratio packs containing lamb were significantly ($p < 0.05$) higher than those in the 1:1 ratio packs after day 3 (Table 6). In 2:1 ratio hogget packs oxygen concentrations were also significantly ($p < 0.001$) higher than 1:1 and 1.5:1 ($p < 0.01$) ratio packs on days 3, 6, 9 and 12 (Table 6). A high O_2 headspace is dynamic, with CO_2 dissolving in the meat and being formed by tissue and bacterial respiration, with the consumption of O_2 (Gill, 1996). This suggests that the 2:1 headspace to meat volume ratio was more effective at buffering against such changes and better at maintaining the initial gas mix.

CO_2 concentrations in 2:1 headspace to meat volume ratio packs containing lamb were significantly ($p < 0.01$) lower than those of 1:1 ratio packs on days 3, 9 and 12 (Table 6). 2:1 and 1.5:1 ratio MAP lamb packs also maintained their initial gas composition better than 1:1 ratio MAP packs throughout the storage period. Hogget meat in 2:1 ratio packs had significantly ($p < 0.05$) lower CO_2 concentrations than 1:1 from day 3 to 9 and 1.5:1 ($p < 0.01$) from day 3 to 12. 2:1 ratio hogget packs also maintained their initial gas composition better than 1:1 and 1.5:1 ratio MAP packs during retail display. The increase in CO_2 corresponded with a decrease in the O_2 concentration in the headspace of both lamb and hogget packs. Daun, Solberg, Franke, and Gilbert (1971) reported similar results to this study using MA packed beef, suggesting the initial increase in CO_2 was due to tissue utilisation of O_2 while the second increase corresponded to microbial growth. However, the significant increase in CO_2 on days 3, 6, 9 and 12 in the 1:1 ratio lamb packs did not correspond to a significantly larger microbial population in the same packs on the same days.

5. Conclusion

The results show that 80:20:0/O_2:CO_2:N_2 gas composition and 2:1 headspace to meat volume ratio was the most effective packaging combination at maintaining and prolonging the attractive red colour of MA packaged lamb and hogget meat, during storage.

Table 6
Percentage oxygen and carbon dioxide in the package headspace of lamb and hogget steaks (*M. longissmus dorsi*) packaged in modified atmosphere 80:20/O_2:CO_2 at different headspace:meat volume ratios and stored in a refrigerated (4 °C) display cabinet (616 lx) for 12 days

MA pack	Headspace gas	Headspace:meat volume ratio	Time (days)				
			0	3	6	9	12
			% in headspace				
Lamb	O_2	2:1	72.2 ± 0.2	$68.4 \pm 0.7^{\underline{b}}$	$65.1 \pm 1.1^{\underline{a}}$	$53.2 \pm 1.5^{\underline{a}}$	$48.5 \pm 2.3^{\underline{b}}$
		1.5:1	71.9 ± 0.1	$68.8 \pm 0.2^{\underline{a}}$	$65.9 \pm 0.4^{\underline{b}}$	52.7 ± 0.7	$46.7 \pm 0.9^{\underline{a}}$
		1:1	71.4 ± 0.2	66.8 ± 0.5	60.4 ± 1.0	38.4 ± 0.8	27.5 ± 0.7
Hogget	O_2	2:1	73.2 ± 0.5	$70.8 \pm 0.3^{\underline{bc}}$	68.1 $0.6^{\underline{a}}$	65.7 ± 1.0^{b}	$55.6 \pm 0.9^{\underline{c}}$
		1.5:1	73.6 ± 0.5	68.5 ± 0.4	65.7 ± 0.7	60.4 ± 2.6	$49.4 \pm 2.0^{\underline{a}}$
		1:1	72.8 ± 0.4	67.6 ± 0.4	65.0 ± 0.6	62.4 ± 0.9	44.7 ± 2.0
Lamb	CO_2	2:1	24.4 ± 0.1	$26.9 \pm 0.4^{\underline{b}}$	30.0 ± 0.5	$43.3 \pm 1.0^{\underline{b}}$	$48.3 \pm 1.2^{\underline{b}}$
		1.5:1	24.9 ± 0.2	$27.3 \pm 0.3^{\underline{b}}$	29.9 ± 0.4	44.6 ± 0.7	50.8 ± 0.9
		1:1	25.1 ± 0.3	29.1 ± 0.4	32.7 ± 1.7	57.0 ± 0.5	68.8 ± 1.2
Hogget	CO_2	2:1	24.6 ± 0.4	$25.6 \pm 0.3^{\underline{bc}}$	$27.2 \pm 0.4^{\underline{ba}}$	$29.3 \pm 0.4^{\underline{bb}}$	40.1 ± 0.7^{a}
		1.5:1	25.0 ± 0.5	27.7 ± 0.5	30.4 ± 0.7	33.1 ± 1.0	45.3 ± 1.1
		1:1	25.1 ± 0.4	28.3 ± 0.4	30.6 ± 0.6	33.2 ± 1.0	43.8 ± 1.8

Mean values ± SEM.
Mean percentage value significantly different to 1:1 ratio: [a] $*p < 0.05$, [b] $**p < 0.01$, [c] $***p < 0.001$, and 1:1.5 ratio: [a]$*p < 0.05$, [b] $**p < 0.01$.

TBARS values for MA packaged lamb and hogget meat were not significantly increased in 80:20:0/O_2:CO_2:N_2 at a 2:1 ratio. Lipid oxidation in both cases occurred at a slower comparative rate than discolouration or microbial growth and was not the major determinant of shelf-life. The 2:1 ratio was the most effective at decreasing *Pseudomonas* and increasing the numbers of lactic acid bacteria in the total microbial load of both lamb and hogget meat. It was also the most effective at buffering against headspace gas changes and better at maintaining the initial gas mix in both lamb and hogget MA packs.

The most important determinant of shelf-life in MA packaged lamb and hogget meat was microbial growth and in particular the initial microbial load prior to packaging. This study demonstrated that higher initial microbial loads greatly influenced the growth rate and composition of spoilage flora. In general higher microbial load there was a corresponding increase in TBARS values and decrease in Hunter '*a*' and visual assessment values. The initial hygienic condition of the meat prior to packaging has a large influence on the shelf-life and the effectiveness of the packaging system subsequently applied may be reduced due to the altered composition of subsequent spoilage flora.

Acknowledgements

This research was carried out in association with Irish Country Meats, Camolin, Co. Wexford and Enterprise Ireland under the Applied Research Scheme.

References

Asenio, M. A., Ordonez, J. A., & Sanz, B. (1988). Effect of carbon dioxide and oxygen enriched atmosphere on the shelf life of refrigerated pork packed in plastic bags. *Journal of Food Protection, 51*(5), 356–360.

Bartkowski, L., Dryden, F. D., & Marchello, J. A. (1982). Quality changes of beef steaks stored in controlled gas atmosphere containing high or low levels of oxygen. *Journal of Food Protection, 45*(1), 41–45.

Butler, O. D., Bratzler, L. J., & Mallmann, W. L. (1953). The effect of bacteria on the colour of prepackaged retail beef cuts. *Food Technology, 7*(10), 397–400.

Christopher, F. M., Seideman, S. C., Carpenter, Z. L., Smith, G. C., & Vanderzant, C. (1979). Microbiology of beef packaged in various gas atmospheres. *Journal of Food Protection, 42*, 240–244.

Church, I. J., & Parsons, A. L. (1995). Modified atmosphere packaging technology: Review. *Journal of the Science of Food and Agriculture, 67*, 143–152.

Cifini, G. F., Napolitano, C., Pacelli, Riviezzi, A. M., & Girolami, A. (2000). Effect of age at slaughter on lipid oxidation of Apulian lambs. *Small Ruminant Research, 35*, 65–70.

Daun, H., Solberg, W., Franke, W., & Gilbert, S. (1971). Effect of oxygen-enriched atmospheres on storage quality of packaged fresh meat. *Journal of Food Science, 36*, 1011–1014.

Department of Irish Health. (1992). Microbiological guidelines for meat and meat products, milk, cream, ice-cream, eggs and fish.

Farber, J. M. (1991). Microbiological aspects of modified atmosphere packaging: review. *Journal of Food Protection, 54*, 58–70.

Faustman, C., Cassens, R. G., Schaefer, D. M., Buege, D. R., & Scheller, K. K. (1989). Vitamin E supplementation of Holstein steer diets improves sirloin steak colour. *Journal of Food Science, 54*, 485–486.

Gill, C. O. (1989). Packaging for prolonged chill storage: The Captech process. *British Food Journal, 91*(7), 11–15.

Gill, C. O. (1996). Extending the storage life of raw chilled meats. *Meat Science, 43*, S99–S109.

Holley, R. A., Delaquis, P., Rodrigue, N., Doyon, G., Gagon, J., & Gariepy, C. (1994). Controlled-atmosphere packaging of pork under carbon dioxide. *Journal of Food Protection, 57*, 1088–1093.

Jakobsen, M., & Bertelsen, G. (2000). Colour stability and lipid oxidation of fresh beef. Development of a response surface model for predicting the effects of temperature, storage time and modified atmosphere composition. *Meat Science, 54*, 49–57.

Jensen, C., Guidera, J., Skovgaard, I. M., Staun, H., Skibsted, L. H., Jensen, S. K., Møller, A. J., Buckley, J., & Bertelsen, G. (1997). Effects of dietary α-tocopherol acetate supplementation on α-tocopherol deposition in porcine *M. Psoas Major* and *M. Longissmus Dorsi* and on drip loss, colour stability and oxidative stability of pork meat. *Meat Science, 45*, 491–500.

Ke, P. J., Ackman, R. G., Linke, B. A., & Nash, D. M. (1977). Differential lipid oxidation in various parts of frozen mackerel. *Journal of Food Technology, 12*, 37–47.

Kerry, J. P., Buckley, D. J., & Morrissey, P. A. (2000). Improvement of oxidative stability of beef and lamb with Vitamin E. In E. A. Decker, C. Faustman, & C. J. Lopez-Bote (Eds.), *Antioxidants in muscle foods* (pp. 229–261). New York: John Wiley & Sons, Inc..

Kraft, A. A. (1986). Meat microbiology. In P. J. Bechtel (Ed.), *Muscle as food* (pp. 239–278). London: Academic Press.

Lambert, A. D., Smith, J. P., & Dodds, K. L. (1991). Shelf life extension and microbiological safety of fresh meat: Review. *Food Microbiology, 8*, 267–297.

McMillin, K. W., (1993). Dynamic gas exchange of modified atmosphere packaging of fresh meat. In *Conference proceedings (session C-1)*, Chicago, USA, Pack Alimentaire.

Neter, J., Wasserman, W., & Kutner, M. H. (1990). In J. Neter, W. Wasserman, & M. H. Kutner (Eds.), *Applied linear statistical models; Regression, analysis of variance and experimental design* (pp. 1035–1066). Boston, Homewood: Irwin.

Ordonez, J. A., & Ledward, D. A. (1977). Lipid and myoglobin oxidation in pork stored in oxygen and carbon dioxide enriched atmospheres. *Meat Science, 1*, 41–48.

Rhee, K. S., & Ziprin, Y. A. (1987). Lipid oxidation in retail beef, pork and chicken muscles as affected by concentrations of heme pigments and non-heme iron and microsomal enzymic lipid peroxidation activity. *Journal of Food Biochemistry, 11*, 1–15.

Robach, D. L., & Costilow, R. M. (1961). Role of bacteria in the oxidation of myoglobin. *Applied Microbiology, 9*, 529.

Sahoo, J., & Anjaneyulu, A. S. R. (1995). Modified atmosphere packaging of muscle foods: Technology, shelf-life and safety aspects. *Indian Food Industry, 14*(3), 28–36.

Satomi, K. (1990). Gas exchange packaging. In T. Kadoya (Ed.), *Food packaging* (pp. 269–278). London: Academic Press.

Selman, J. (1987). New methods of preservation. *Food Manufacture, 53*, 55–56.

Shaw, B. G., Harding, C. D., & Taylor, A. A. (1980). The microbiology and storage stability of vacuum packed lamb. *Journal of Food Technology, 15*, 397–405.

Sheridan, J. J., Doherty, A. M., Allen, P., McDowell, D. A., Blair, I. S., & Harrington, D. (1997). The effect of vacuum and modified atmosphere packaging on the shelf-life of lamb primals stored at different temperatures. *Meat Science, 45*, 107–117.

Stringer, W. C., Bilskie, M. E., & Naumann, H. D. (1969). Microbial profile of fresh beef. *Food Technology, 23*(1), 97–102.

Tarladgis, B. G., Watts, B. M., Younathan, M. T., & Dungan, L. R. (1960). A distillation method for the quantitative determination of malonaldehyde in rancid foods. *Journal of American Oil Chemist's Society, 37*, 44–48.

Taylor, A. A. (1972). Gases in fresh meat packaging. *Meat World, 5*, 3–6.

Taylor, A. A., Down, N. F., & Shaw, B. G. (1990). A comparison of modified atmosphere and vacuum skin packing for the storage of red meats. *International Journal of Food Science and Technology, 25*, 98–109.

Walker, H. W. (1980). Effects of microflora on fresh meat colour. In *33rd Reciprocal meat conference proceedings* (pp. 33–35). USA: American Meat Science Association.

Watts, B. M. (1962). Meat products. In H. W. Shultz, E. A. Day, & R. P. R. Simhuber (Eds.), *Symposium on food: Lipid and their oxidation* (pp. 202–219). Westport, CT, USA: AVI Publishing Co..

Williams, A. C., Jr (1987). In J. I. Gray, B. R Harte, & J. Miltz (Eds.), *Food product – package compatibility, proceedings* (p. 170). Lancaster, UK: Technomic Publishing Company.