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The storage life of beef and pork packaged in an atmosphere with low carbon monoxide and high carbon dioxide

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Abstract

Ground beef, beef loin steaks and pork chops were packaged in modified atmospheres of 0.4% CO/60% CO_2/40% N_2 and 70% O_2/30% CO_2. In addition ground beef was packaged in clipped chub packs, beef loin steaks were vacuum packaged, and pork chops were packaged in an atmosphere of 60% CO_2/40% N_2 with each pack containing an O_2 absorber. The packs were stored in the dark at 4 or 8°C for up to 21 days. Meat in 0.4% CO/60% CO_2/40% N_2 had a stable bright red colour that lasted beyond the time of spoilage. The storage lives in this gas mixture at 4°C, as limited by off-odours, were 11, 14 and 21 days for ground beef, beef loin steaks and pork chops, respectively. The 70% O_2/30% CO_2 atmosphere resulted in an initially bright red to red colour of the meat, but the colour was unstable and off-odours developed rapidly. The off-odours probably were caused by *Brochothrix thermosphacta*, which grew in all meat types, or by pseudomonads in ground beef. Meat stored in chub packs, vacuum packs or 60% CO_2/40% N_2 with an O_2 absorber developed off-odours and microflora similar to those of meat in 0.4% CO/60% CO_2/40% N_2, but with less acceptable appearances. These results show that a low CO/high CO_2 atmosphere is effective for preserving retail-ready meat.

1. Introduction

The main reasons for modified atmosphere packaging (MAP) of red meats for retail sale are to prolong the microbiological shelf life and to maintain an attractive red colour of the product. Modified atmospheres (MA) usually consist of carbon dioxide (CO_2) for inhibiting microbiological growth, oxygen (O_2) for enhancing colour and, occasionally, nitrogen (N_2) as a filler. The most common gas mixture for retail-ready meat contains approximately 70% O_2 and 30% CO_2, and gives the product an extended shelf life compared to air (Gill, 1996). The shelf life and colour stability of meat stored in this gas mixture is still limited. To obtain a stable red colour for the meat, low concentrations ($<1\%$) of carbon monoxide (CO) can be introduced in the MA. Then, O_2 can be removed from the gas mixture and the concentration of bacteriostatic CO_2 can be increased. Anaerobic conditions extend the shelf life of meat considerably compared to air and O_2-enriched atmospheres (Gill & Molin, 1991). CO binds strongly to the meat pigment myoglobin to form stable carboxymyoglobin which has a cherry red colour (El-Badawi, Cain, Samuels, & Angelmeier, 1964). Low concentrations of CO have little effect on the microflora of meat (Clark, Lentz, & Roth, 1976; Gee & Brown, 1978; Luño, Beltrán, & Roncalés, 1998).

The Norwegian meat industry has for the past decade been using a gas mixture of approximately 0.3–0.5% CO, 60–70% CO_2 and 30–40% N_2 in retail-ready packages of beef, pork and lamb. Packages with this gas mixture now have a 50–60% share of the domestic, retail, red meat market. The technological, hygienic and toxicological aspects of using CO in MA for meat have recently been reviewed with the conclusion that CO used in concentrations up to 1% does not present a toxic hazard to the consumer (Sørheim, Aune, & Nesbakken, 1997a). However, CO may mask spoilage, because the stable cherry red colour can last beyond the microbiological shelf life of the meat (Kropf, 1980).

The inclusion of CO in MA for meat is controversial. CO is presently not allowed in MA for meat in the USA and in the EU (Cornforth, 1994; European Parliament and Council Directive, 1995). However, Norwegian food control authorities have up to now not opposed

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the use of up to 0.5% CO in MA for meat. This would change with an adoption of EU food regulations in Norway. Consequently, the Norwegian meat industry is seeking amendments of current EU food regulations relating to the use of CO in MAP of red meats. If the use of CO should be disallowed, other means of maintaining the long shelf life and the attractive red colour of the meat will have to be sought.

The aim of the present experiments was to compare a commercial Norwegian $CO/CO_2/N_2$ mixture with alternative gas mixtures and packaging methods for their effects on the off-odour, microflora and colour of ground beef, beef loin steaks and pork chops stored at 4 or 8°C for up to 21 days.

2. Materials and methods

2.1. Preparation of meat

2.1.1. Ground beef

Twenty cow and bull carcasses of Norwegian Red Cattle, which weighed on average 275 kg, were electrically stimulated with 90 V and were chilled using programmed air temperatures between 12 and −5°C. Two days after slaughter the carcasses were deboned, and trimmings with 14% fat were ground through a 4 mm plate. The batch of ground beef was divided into 500 g portions.

2.1.2. Beef loin steaks

Loins (*m. longissimus lumborum et thoracis*) with ultimate pH values below 5.8 were deboned from 25 bull carcasses of Norwegian Red Cattle. These carcasses, which weighed on average 275 kg, were stimulated, chilled and deboned the same way as the carcasses used in the preparation of ground beef. The loins were vacuum packaged and aged for 11 days at 3°C. Thereafter, the loins were cut into steaks 2.5 cm thick, and were randomly assigned to retail packs which each contained two steaks.

2.1.3. Pork chops

Thirty pig carcasses of Norwegian Land Race, which weighed on average 75 kg, were blast-chilled. Four days after slaughter, bone-in loins were removed and crust-frozen in liquid N_2 at −50°C for 20 min to facilitate cutting of chops. The chops, which were 1.6 cm thick, were randomly assigned to retail packs which each contained two chops.

2.2. Packaging

Ground beef, beef loin steaks and pork chops were packaged in 0.4% CO/60% CO_2/40% N_2 (CO mixture) and 70% O_2/30% CO_2 (high O_2). In addition, ground beef was packaged in clipped chub packs, beef loin steaks were vacuum packaged and pork chops were packaged in 60% CO_2/40% N_2 with one Ageless® FX-100 O_2 absorber (Mitsubishi Gas Chem. Co. Inc., Tokyo, Japan) in each pack (mixture with O_2 absorber).

The meat was packaged at a commercial meat plant within 2 h of grinding or cutting. Meat in the CO mixture, the high O_2 mixture and the mixture with O_2 absorber was packaged in an Ilapak Delta 2000 flow-packaging machine (Ilapak Machine Auto S.A., Grancia, Switzerland). The CO mixture was a blend of 1% CO/99% N_2 with 100% CO_2. The high O_2 mixture was used as a preblend. The mixture with O_2 absorber was a blend of 100% N_2 with 100% CO_2 (all gases, Hydrogas, Porsgrunn, Norway). The initial gas volume to meat weight ratio in the packs was approximately 1.5 to 1. The packs consisted of polyethylene trays (Færch Plast, Holstebro, Denmark) wrapped in Cryovac BDF 550 shrinking film (Cryovac, Milan, Italy) with an O_2 transmission rate of 19 $cm^3/m^2/24$ h/atm at 23°C and 0% RH. Chub packs of ground beef were packaged in a clipping machine (Poly-Clip, Frankfurt, Germany) using a red, fishingnet-patterned, polyethylene film (SFK, Vidovre, Denmark) with an O_2 transmission rate of 500 $cm^3/m^2/24$ h/atm at 23°C and 0% RH. Beef loin steaks were vacuum packaged in a Multivac 5100 thermo-forming machine (Multivac, Wolfertschwenden, Germany) using a terephtalate/polyethylene upper film and polyamide/polyethylene lower film with O_2 transmission rates of 10 and 16 $cm^3/m^2/24$ h/atm at 23°C and 0% RH, respectively (Danisco, Horsens, Denmark).

2.3. Storage and sampling of meat

Five samples were collected from the ground beef batch, beef loins and pork loins before packaging, for pH measurements and microbiological analyses.

The packaged meat was stored in dark chilling rooms at 4 ± 0.5 or 8 ± 0.5°C for up to 21 days at least until off-odours developed. Five packs were removed per product, packaging method, storage temperature and sampling day after the following storage times:

- ground beef: 2, 4, 6, 8 or 11 days;
- beef loin steaks: 3, 7, 10 or 14 days; and
- pork chops: 3, 7, 10, 14, 17 or 21 days.

2.4. Gas analyses

The atmospheres of packs with MA were analysed for O_2 and CO_2 immediately after packaging (approximately every tenth pack) and at sampling (all packs). O_2 was determined using a Toray LC 700-F gas analyser (Toray Engineering, Osaka, Japan) and CO_2 using a Toray PG-100 gas analyser (Toray). The threshold levels for the O_2 and CO_2 analyses were 0.05 and 1%, respectively. Gas samples of 10 cm^3 were removed with a syringe through selfsealing patches on the packs.

2.5. pH

The pH measurements were made directly in the meat with an Ingold Xerolyt gel electrode (Mettler-Toledo A.G., Greifensee, Switzerland).

2.6. Odour

The meat was evaluated for odours by a three member trained panel between 0.5 and 1 min after opening of the packs. The off-odour scale used was: 1 = none, 3 = slight and 5 = extreme. Scores of 3 or below were considered acceptable.

2.7. Microbiology

Ten gram meat samples were collected from portions of the ground beef, and diluted in 90 g peptone water. A sample 25 cm^2 and 2–3 mm thick was removed from the surface of each beef loin or steak and pork loin or chop with a scalpel, and diluted in 100 ml peptone water. Each sample was macerated in a Stomacher for 1 min. Serial 10-fold dilutions of each Stomacher fluid were prepared, and 20 μl volumes of appropriate dilutions were plated in duplicate on the following media:

- plate count agar (PCA; Difco, Difco Laboratories, Detroit, MI, USA) for total viable counts;
- de Man, Sharpe and Rogosa agar (MRS; Oxoid, Unipath Ltd., Basingstoke, Hampshire, UK) adjusted to pH 5.7 for lactic acid bacteria (de Man, Rogosa, & Sharpe, 1960);
- streptomycin thallous acetate actidione agar base (STAA; CM 881 with selective supplement SR 151; Oxoid) for *Brochothrix thermosphacta*;
- pseudomonads agar base (CFC; CM 559 with selective supplement SR 103; Oxoid) for pseudomonads;

In addition, 1 ml portions of appropriate dilutions were plated in duplicate on petrifilm coliform count plates (3M Microbiology Products, St. Paul, MN, USA) for enumeration of coliforms and *Escherichia coli*.

Plates of PCA, MRS, STAA and CFC were incubated at 20°C for four days, and petrifilm plates at 30°C for up to 2 days, all aerobically. Counts were expressed as colony forming units (CFU) per g or cm^2.

2.8. Colour

A six-member trained panel evaluated the colour of the meat in intact packs under 1200 ± 200 lux Warmton Lumilux L36W/31 yellow–white light (Osram, Drammen, Norway). The colour was assessed on a scale where 1 = bright red (ground beef and beef loin steaks) or light bright red (pork chops), 2 = red (ground beef and beef loin steaks) or light red (pork chops), 3 = slightly brown, grey or green, 4 = moderately brown, grey or green and 5 = extremely brown, grey or green (National Live Stock and Meat Board, 1991).

A Minolta Chroma Meter CR-300 (Minolta Camera Co., Osaka, Japan) with 8 mm viewing port and illuminant D_{65} was used for measuring CIE a^* values (redness). The colour was measured directly at the meat surface within 1 min of opening of each pack.

Ground beef in chub packs was not included in the colour analyses because the red packaging film hides the colour of the product. With pork chops, the colour of only the *m. longissimus lumborum et thoracis* was analysed.

2.9. Statistics

Analysis of variance by Tukey's multiple comparisons test was performed using the Systat programme, version 6 (Systat Inc., Evanston, IL, USA).

3. Results

3.1. Gas composition

The initial O_2 concentrations in packs with the CO mixture and the mixture with O_2 absorber were all below 0.5% immediately after packaging. O_2 was not detected in these packs after 2 or 3 days storage. The level of O_2 in packs of high O_2 was reduced from the initial 70 to 60–65% during storage for up to 21 days. Concentrations of CO_2 in the packs were generally reduced by one fifth after 2 or 3 days storage, and were then stable (data not shown).

3.2. Storage life of ground beef

The time to develop off-odours was 2 to 3 days longer for ground beef stored in the CO mixture and in chub packs than in high O_2, and it was 4 or 5 days longer at 4 than at 8°C for all three packaging methods (Table 1). In high O_2, the total viable counts increased faster and were higher ($p < 0.01$) than for the other two types of packaging after 2 days at either 4 or 8°C [Fig. 1(a)]. The total viable counts were more than 90% lactic acid bacteria (data not shown). The high numbers of lactic acid bacteria in ground beef, up to approximately $\log_{10}$ 8 CFU/g, caused a decrease in the pH value from the initial 5.7 to 5.2 after 6 days when the meat was stored in the CO mixture or chub packs at 8°C (data not shown). At 4°C, the pH value was reduced to 5.5 after 11 days in both those packaging systems. The numbers of *B. thermosphacta* increased, in meat in high O_2 [Fig. 1(b)]. In meat in high O_2 the numbers of pseudomonads increased up to approximately $\log_{10}$ 7 CFU/g, but only to $\log_{10}$ 5 and 6 CFU/g in

meat in the CO mixture or chub packs, respectively (data not shown).

Ground beef in the CO mixture had a stable bright red colour, as shown by both the low colour scores and the high a^* values [Fig. 1(c) and (d)]. Meat in high O_2 was significantly less red ($p < 0.05$) than meat in the CO mixture, with higher colour scores and lower a^* values at day 2 and at later storage times at both 4 and 8°C. The colour of meat in high O_2 deteriorated with time, significantly faster ($p < 0.01$) at 8 than at 4°C.

Table 1
Time for development of off-odours in different types of meat in various packagings at storage temperatures of 4 or 8°C

Product	Packaging[a]	Time of off-odour detection (days)	
		4°C	8°C
Ground beef	CO mixture	11	6
	High O_2	8	4
	Chub packs	11	6
Beef loin steaks	CO mixture	14	7
	High O_2	10	7
	Vacuum packs	14	7
Pork chops	CO mixture	21	14
	High O_2	14	7
	Mixture with O_2 absorber	17	10

[a] CO mixture = modified atmosphere of 0.4% CO/60% CO_2/40% N_2; High O_2 = modified atmosphere of 70% O_2/30% CO_2; Mixture with O_2 absorber = modified atmosphere of 60% CO_2/40% N_2 with an O_2 absorber in the pack.

3.3. Storage life of beef loin steaks

At 4°C, off-odours developed 4 days later in beef loin steaks in the CO mixture and in vacuum packs than in high O_2 (Table 1). At 8°C, no differences in the development of off-odours were observed. Off-odours developed 4 to 7 days earlier in meat at 8 than at 4°C. The type of packaging did not significantly affect ($p < 0.05$) the total viable counts on the meat, but the counts were significantly higher ($p < 0.01$) at 8 than at 4°C after both 3 and 7 days of storage [Fig. 2(a)]. The numbers of *B. thermosphacta* were less than $\log_{10} 4$ CFU/cm^2 in meat in all types of packaging at all times, but were significantly higher ($p < 0.05$) on meat in high O_2 at 7 and 10 days than on meat in the CO mixture and in vacuum packs at equivalent times [Fig. 2(b)]. The numbers of pseudomonads did not exceed $\log_{10} 3.5$ CFU/cm^2 at any sampling time, and were not significantly affected ($p > 0.05$) by the type of packaging or the storage temperature.

The colour of the beef loin steaks in the CO mixture was stable bright red throughout storage at both 4 and 8°C, as shown by the low colour scores and high a^* values [Fig. 2(c) and (d)]. Steaks in high O_2 were also bright red with high a^* values at day 3, but these steaks discoloured gradually between days 3 and 10, significantly faster ($p < 0.05$) at 8 than at 4°C. Meat in vacuum packs was slightly discoloured with low a^* values throughout storage. The colour scores and a^* values of vacuum packaged steaks were not significantly affected ($p > 0.05$) by the storage temperature.

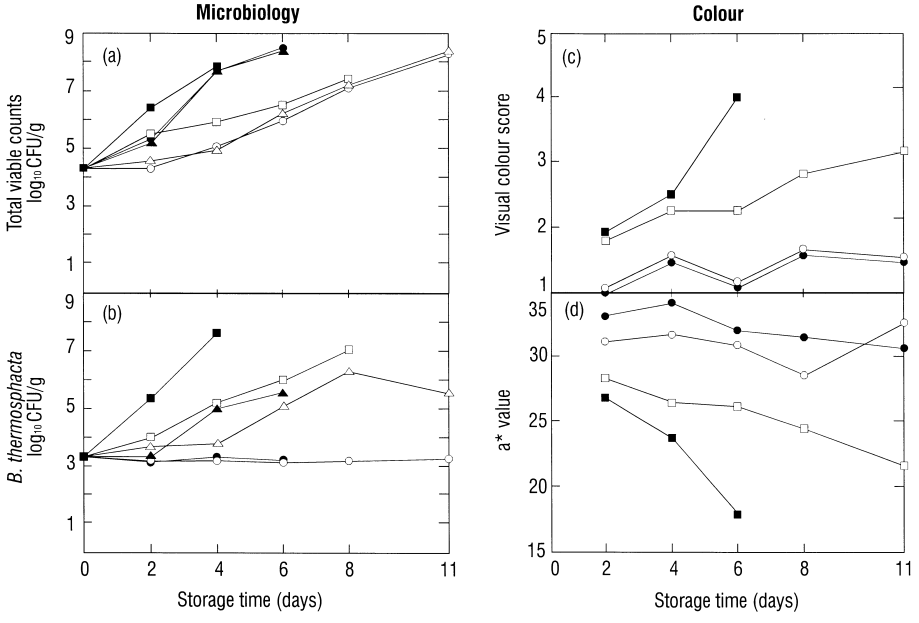

Fig. 1. Mean values ($n = 5$) for (a) total viable counts, (b) numbers of *Brochothrix thermosphacta*, (c) visual colour scores and (d) CIE a^* values for ground beef stored in 0.4% CO/60% CO_2/40% N_2 at 4°C (○) or 8° C (●), in 70% O_2/30% CO_2 at 4°C (□) or 8°C (■), or in chub packs at 4°C (△) or 8°C (▲). Colour was assessed on a scale where 1 = bright red and 5 = extremely discoloured.

3.4. Storage life of pork chops

For pork chops, off-odours developed more slowly in meat in the CO mixture than in meat in the mixture with O_2 absorbers or in high O_2 (Table 1). Off-odours were detected 7 days earlier at 8 than at 4°C for chops in each type of packaging. The type of packaging did not affect the total viable counts on the pork chops [Fig. 3(a)]. However, the counts were greater on meat stored at 8 than at 4°C. The numbers of *B. thermosphacta* on chops in high O_2 were significantly higher ($p < 0.01$) than on chops in the CO mixture or in the mixture with O_2 absorbers after 7 days at 8°C or 10 days at 4°C, and reached approximately $\log_{10}$ 6 CFU/cm^2 [Fig. 3(b)]. The numbers of pseudomonads did not exceed $\log_{10}$ 3 CFU/cm^2 on any of the pork chops.

The colour of pork chops in the CO mixture was light bright red with high a^* values throughout storage [Fig. 3(c) and (d)]. Chops in high O_2 were red at day 3, but discoloured during storage, significantly faster ($p < 0.05$) at

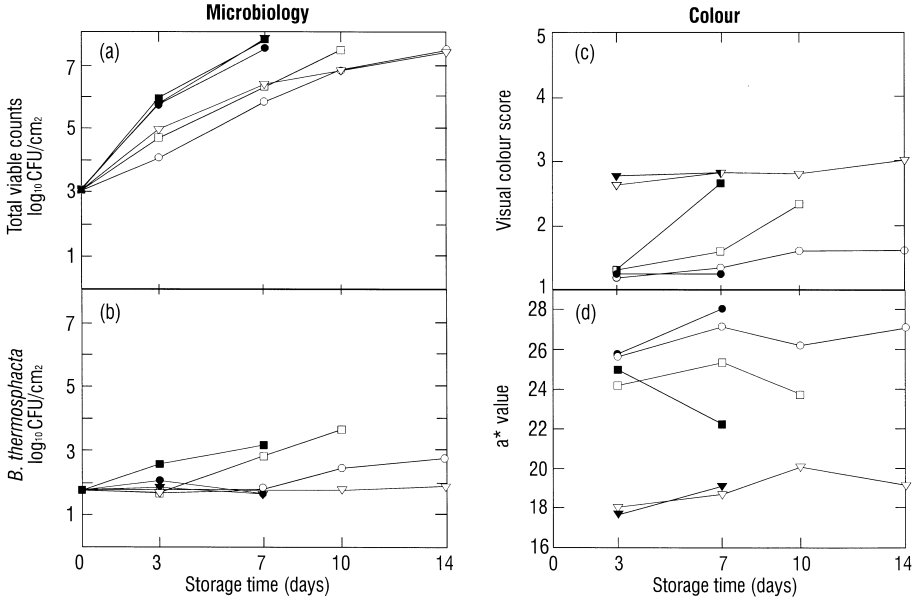

Fig. 2. Mean values ($n = 5$) for (a) total viable counts, (b) numbers of *Brochothrix thermosphacta*, (c) visual colour scores and (d) CIE a^* values for beef loin steaks stored in 0.4% CO/60% CO_2/40% N_2 at 4°C (○) or 8°C (●), in 70% O_2/30% CO_2 at 4°C (□) or 8°C (■), or in vacuum packs at 4°C (▽) or 8°C (▼). Colour was assessed on a scale where 1 = bright red and 5 = extremely discoloured.

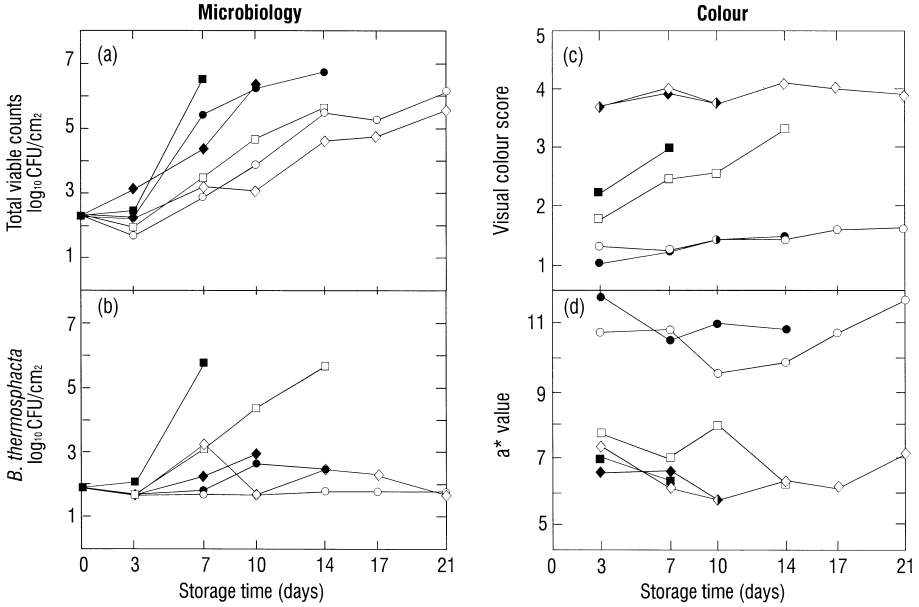

Fig. 3. Mean values ($n = 5$) for (a) total viable counts, (b) numbers of *Brochothrix thermosphacta*, (c) visual colour scores and (d) CIE a^* values for pork chops stored in 0.4% CO/60% CO_2/40% N_2 at 4°C (○) or 8° C (●), in 70% O_2/30% CO_2 at 4°C (□) or 8°C (■), or in 60% CO_2/40% N_2 with O_2 absorbers at 4°C (◇) or 8°C (◆). Colour was assessed on a scale where 1 = light bright red and 5 = extremely discoloured.

8 than at 4°C. Approximately 75% of the chops in high O_2 had black back bones at the time of sampling. Chops in the mixture with O_2 absorbers were moderately discoloured from day 3 to the end of storage. These chops had a^* values similar to those of chops in high O_2.

4. Discussion

4.1. Off-odour and microflora

The shelf life of the meat, as determined by the time to develop off-odours, was influenced by the packaging method, the storage temperature and the initial microbiological load on the meat. Storage of meat in the CO mixture, in vacuum packs or in chub packs gave the longest shelf lives. Meat stored in high O_2 generally developed off-odours 2–7 days earlier at 4 or 8°C than meat packaged in the other gas mixtures or by the other methods.

The differences in the rates of development of off-odours, as affected by the packaging method, were seldom related to any differences in numbers of total viable counts. However, the development of off-odours from the three meat types, especially ground beef and pork chops in high O_2, coincided with the attainment of high numbers of *B. thermosphacta*. For ground beef, storage in the CO mixture retarded growth of *B. thermosphacta* even more than storage in chub packs. At chill temperatures above 1°C, *B. thermosphacta* often causes spoilage of meat stored in high O_2 atmospheres (Dainty & Mackey, 1992). High concentrations of CO_2, removal of O_2 and low storage temperature inhibit the growth of *B. thermosphacta* (Gill, 1996; Nissen, Sørheim, & Dainty, 1996). Pseudomonads probably contributed to the off-odours of ground beef. Meat in high O_2 is often spoiled by *Pseudomonas* spp., but the growth of pseudomonads is retarded under anaerobic conditions (Dainty & Mackey, 1992; Gill, 1996). A shift in the metabolism of lactic acid bacteria under aerobic conditions can also produce off-odours (Nissen et al., 1996). In the present experiments, the numbers of coliforms or *E. coli* did not exceed $\log_{10}$ 3 CFU/g or cm^2 in any samples. Therefore, those organisms probably did not contribute to off-odours.

For pork chops, the effect of CO on the microflora can be evaluated because the gas compositions of the CO mixture and of the mixture with O_2 absorber were identical, except for the inclusion of 0.4% CO in the former. Although a 4 day increase in the time to develop off-odours was observed with the CO mixture, there was no significant reduction in the microbiological counts. Luño et al. (1998) used 1% CO in high O_2 atmospheres and noted a delay in the onset of off-odours without any reduction in the numbers of psychrotrophic bacteria. However, Clark et al. (1976) found that the addition of 0.5-10% CO to N_2 atmospheres reduced the number of psychrotrophic bacteria and increased the odour shelf life of beef. For example, 1.0% CO in 99% N_2 increased the time to develop off-odours at 5°C from 18 to 24 days. The lack of such an effect of CO on bacteria in our experiments may be due to the use of 60% CO_2 overshadowing any effect of CO.

The use of CO makes it possible to dispense with O_2 and so to increase the CO_2 concentration in a MA to about 60%. Our data suggest that 0.4% CO probably has little or no direct effect on the growth of bacteria. Other studies have shown that increasing the CO_2 concentration from 20 to 100% increases the bacteriostatic effect of the gas, but the efficiency is highly dependent on low storage temperatures (Gill & Molin, 1991; Nissen et al., 1996). The high CO_2 concentration and absence of O_2 in the CO mixture will favour the growth of lactic acid bacteria, which usually cause a mild form of spoilage only late in the development of the spoilage flora (Gill, 1996).

The present experiments were performed at acceptable and abusive storage temperatures to assess the effects of temperatures commonly encountered in the distribution and sale of retail-ready meat. The storage temperature strongly affected the rates of growth of microflora and the time to develop off-odours. Consequently, independently of the packaging method, the shelf life of meat can be considerably extended by maintaining low temperatures in the chill chain (Gill & Molin, 1991; Nissen et al., 1996).

4.2. Colour

The CO mixture gave a stable bright or light bright red colour with consistent high a^* values for all three products, irrespective of the storage temperature. The initial level of residual O_2, up to 0.5%, did not adversely affect the visual scores and instrumental values for the colour of meat stored in the CO mixture.

CO binds to myoglobin and forms cherry red carboxymyoglobin (El-Badawi et al., 1964). This pigment is spectrally similar to the bright red oxymyoglobin which normally develops at the surface of fresh meat in air. Carboxymyoglobin is less readily oxidized to brown metmyoglobin than is oxymyoglobin, because of the strong binding of CO to the iron-porphyrin site on the myoglobin molecule (Lanier, Carpenter, Toledo, & Reagan, 1978; Wolfe, 1980). Consequently, CO in concentrations of 0.5–2.0% enhances and stabilizes a bright red colour of meat (Kropf, 1980; Sørheim et al., 1997a). In a recent study, 1% CO in combination with 24 or 70% O_2 stabilized the colour of beef by reduced formation of metmyoglobin after storage at 1°C for up to 29 days (Luño et al., 1998). However, in a study of beef stored in a MA of 2% CO/78% CO_2/20% N_2, the colour of the meat was characterized as "too artificial" by

a sensory panel (Renerre & Labadie, 1993). From our studies and experience from the Norwegian meat industry, 0.4% CO seems sufficient to produce a stable, attractive, bright red colour of meat.

All three meat types stored in high O_2 were bright red to red with high a^* values early in the storage periods, approaching the colour of meat in the CO mixture. As the microbiological counts of meat in high O_2 increased, the colour deteriorated, faster at 8 than at 4°C. Meat stored in a MA of high O_2 develops a thicker layer of oxymyoglobin than meat stored in air (Renerre & Labadie, 1993). However, the oxymyoglobin gradually oxidizes to metmyoglobin, and the oxidation is faster at higher temperatures.

For cut bone, haemoglobin released from disrupted red blood cells in the marrow will accumulate at the surface and ultimately become black after the bone has been exposed to air or O_2 (Gill, 1996). Although bone blackening was not considered in the present visual colour evaluation, it can negatively affect the saleability of bone-in meat at retail display. The cut bones of pork chops stored in high O_2 blackened during storage, but this discoloration was not observed on bones in the CO mixture and the mixture with O_2 absorbers.

Beef loin steaks stored in vacuum packs were slightly discoloured with low a^* values at both 4 and 8°C. In these packs, meat juices were observed between the upper and lower films, but that did not influence the colour evaluations.

O_2 absorbers in packs with high CO_2 facilitate the removal of residual O_2 and maintain atmospheres free of O_2 during storage (Smith, Abe, & Hoshino, 1995). Low levels of residual O_2, above 0.01–0.15% for beef and 0.5–1.0% for pork, will inevitably discolour the meat (Penney & Bell, 1993; Gill, 1996; Sørheim et al., 1997b). When no CO is present in an O_2 depleted MA, it is essential to remove the residual O_2 as fast and completely as possible to avoid formation of metmyoglobin. In these experiments, pork chops stored in the gas mixture with O_2 absorbers were moderately discoloured during the whole storage period at 4 or 8°C. Despite the obvious visible differences, these chops had similar a^* values to the chops in high O_2. The discoloured surface made the chops unfit for sale, even in the early stage of storage. The present findings contrast with previous results, where the colour of porcine *m. longissimus thoracis et lumborum* was significantly improved by using O_2 absorbers in MAs of CO_2 with residual O_2 (Sørheim et al., 1997b). The present discoloration could be caused by incomplete use or function of the absorbers (Gill, 1996).

4.3. Benefits and disadvantages of a MA with low CO/high CO_2

An objection raised against using CO as a small component of a MA for retail-ready meat is the possibility that the colour stability can exceed the microbiological shelf life, with the risk of masking spoilage of the meat (Kropf, 1980). Therefore, the consumer must evaluate the microbiological condition of meat in a CO mixture by off-odours. When a MA with CO is applied commercially, it is important to have a proper control of the hygienic condition of the meat raw materials and the chill chain temperatures.

CO used in concentrations below 1.0% does not present any hazard to the consumer, because consumption of meat packaged in such concentrations of CO will result in only negligible levels of carboxyhaemoglobin in the blood of consumers (Sørheim et al., 1997a). By delivering CO in a 1% mixture with 99% N_2, which is the practice of Norwegian gas suppliers, CO is considered safe for use in the working environment. Other MAs with high levels of O_2, up to 70%, must be regarded as explosive gas mixtures, which must be used with appropriate precautions for safety (Luño et al., 1998).

The suitability of gas mixtures and packaging methods for red meats for retail display depends on their ability to both reduce spoilage and stabilize colour. Gas mixtures with low concentrations of CO and high concentrations of CO_2 provide a combination of a long microbiological shelf life and a stable, bright red colour of meat. Meat packaged in a MA with high O_2 can achieve an initial bright red colour, but the microbiological shelf life and the colour stability are both considerably lower than those of meat in the CO mixture. Using CO eliminates the need to have O_2 as a component of the MA. Other MAs and packaging methods, like high CO_2 with O_2 absorbers, chub packs and vacuum packs may give a shelf life comparable to that of the CO mixture, but with a less acceptable colour or appearance of the meat. Thus, there appears at present to be no fully satisfactory alternative to the CO mixture used in packaging of retail-ready red meats in Norway.

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