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Extending the Storage Life of Raw Chilled Meats

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ABSTRACT

Preservative packagings for raw meats must both delay the deterioration of the appearance of the product and retard the onset of bacterial spoilage. Preserving the product appearance is largely a matter of slowing or preventing the formation of brown metmyoglobin at muscle surfaces. Browning is slowed in atmospheres which are rich in oxygen, and persistent browning is entirely prevented when meat is packaged under oxygen-depleted atmospheres. Bacterial spoilage is delayed by packaging under aerobic atmospheres rich in carbon dioxide, or by packaging under anaerobic conditions. However, the control of bacterial spoilage also requires that product temperatures be maintained close to the optimum for chilled storage, and attention to the hygienic condition of the product before it is packaged. Packaging techniques for conforming an extended storage life on most raw meats are available, and long term economic trends seem to require a general improvement of the storage life of raw meats. However, current commercial systems for distributing meat are largely geared to the handling of highly perishable product, and the potential economic advantages from trading in more stable product will not be fully realizable while such systems persist. Consequently, commercial progress towards greater storage stability for chilled meats is likely to be uneven and uncertain. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Raw, chilled meat has traditionally been regarded as a highly perishable product which must reach the consumer expeditiously if it is to be wholesome when it is prepared for consumption. Some sectors of the meat industry still seem to view meat in that way. However, other sectors, driven by the general tendencies towards the centralization of slaughtering in fewer, large packing plants and the expansion of international trading in meat, have adopted techniques which confer a long storage life on their products. There is then no uniform application of techniques for storage life extension within the meat industry. A general improvement in the storage life of raw meat, which seems to be needed given the current commercial trends, would therefore appear to require wider application of the large body of existing knowledge and know-how on raw meat preservation, rather than the identification of wholely novel techniques.

The principal factors that must be addressed in the preservation of chilled meat are the retention of an attractive, fresh appearance for the product which is displayed, and the retardation of bacterial spoilage. In addition, the minimizing of exudate losses is of

commercial concern, because such losses can effectively increase the cost of product which is often traded on narrow profit margins. Each of those matters requires separate consideration although, in practice, they have to be dealt with concurrently.

PRESERVATION OF MEAT COLOUR

When purchasing fresh meat, consumers judge the acceptability of the product largely on the appearance of the exposed muscle tissue (Allen, 1989). Fat tissue which is dull and/or discoloured, and darkened cut bone surfaces can detract from the overall appearance of a cut when the muscle tissue appears attractive, but good appearances of fat and bone cannot compensate for a degraded appearance of the muscle tissue.

The appearance of muscle tissue is determined by the state of the muscle pigment, myoglobin (MacDougall, 1977). In the absence of oxygen, the pigment is in the form of deoxymyoglobin which has a dull, purple colour. On exposure to air, the pigment is oxygenated to form oxymyoglobin, which imparts to muscle the bright, red colour which consumers find attractive (Jeremiah, 1982). Both deoxy- and oxymyoglobin also react with oxygen to form the oxidized form, metmyoglobin, which has a dull, brown colour that consumers associate with deterioration of quality (Hood & Riordan, 1973). However, the oxidation of deoxymyoglobin is more rapid than the oxidation of oxymyoglobin (Robach & Pierson, 1979). That results in the superficially anomalous, faster oxidation of myoglobin at low than at high concentrations of oxygen (O'Keeffe & Hood, 1982).

The oxygenation of myoglobin is rapid and reversible, and the fraction of the pigment in the oxygenated form increases with increasing oxygen concentration (Forrest *et al.*, 1975). In contrast, metmyoglobin is stable, and is reconverted to deoxymyoglobin only slowly, by enzyme mediated reactions termed metmyoglobin reduction activity (Ledward, 1985). Muscle tissue which is deficient in the enzymes that mediate metmyoglobin reduction, or in the reduced co-factors necessary for the reduction reaction will be unable to reconvert metmyoglobin, which will persist once it is formed. Muscles vary widely in metymyoglobin reduction activity (O'Keeffe & Hood, 1980–81). Those which tend to have a high activity, such as the *longissimus dorsi*, are relatively colour stable in air, their red colour persisting for 3 or 4 times as long as that of colour unstable muscles of low metmyoglobin reduction activity, such as the *psoas*. However, metmyoglobin reduction activity decays during the storage of muscle, so after lengthy periods of storage the colour stability of initially colour stable muscles is similar to that of those muscles which were initially of relatively poor colour stability (Moore & Gill, 1987).

Apart from maintaining the meat at as low a temperature as is possible without freezing it, to slow reactions associated with pigment oxidation and to increase the depth of the oxygenated surface layer (Renerre, 1990), there are two obvious means of preserving muscle tissue colour by modifying the atmosphere to which it is exposed. Those are, to increase the fraction of oxidation-resistant oxymyoglobin by exposing the meat to high concentrations of oxygen; or to largely, or preferably wholely, exclude oxygen from the meat. One or other of those approaches is employed in most preservative packagings.

High oxygen atmospheres are used mainly for retail-ready product, including poultry, for which high oxygen atmosphere may be inappropriate because of the meats' limited ability to bloom (Millar *et al.*, 1994). The product may be packaged in trays which contain the preservative atmosphere and which are sealed with a lidding film of low gas permeability. Alternatively, several trays of product which are typically overwrapped with a film of high gas permability are master packaged in a bag of low gas permeability (Taylor, 1985). The gas with which packs are filled usually has a composition of about 65% O_2, 25% CO_2 and 10% N_2 (Renerre, 1989). The CO_2 is required to retard the growth of

aerobic spoilage bacteria. Nitrogen has no preservative function for the meat and may be omitted, but it is often included to guard against the collapse of sealed trays, which may result from the dissolution of the highly soluble CO_2 in the meat (Gill, 1988). Nitrogen serves no purpose in the input gas for master packs, but it is not uncommon to find it used there as well.

A high oxygen atmosphere is dynamic, with CO_2 dissolving in the meat and being formed by tissue and bacterial respiration, with the consumption of O_2. Also, O_2 and CO_2 escape, and N_2 enters, through the barrier film at different rates (Brown, 1992). To buffer against those changes, the gas volume has to be about three times that of the meat (Holland, 1980). Then, the CO_2 concentration in the pack atmosphere can be relatively stable, but less than the concentration in the input gas, while the O_2 concentration will progressively decline and the N_2 concentration will progressively increase.

The need for a relatively large volume of atmosphere in sealed trays conflicts with display requirements, as a small piece of meat in a large pack reduces the amount of product that can be displayed in a given display area and gives the appearance of over-packaging. Thus, in practice, sealed trays are often formed with a headspace far less than that required for optimum preservation of the product.

The use of master packs overcomes the difficulty with atmosphere volume at the sacrifice of extended product stability during display (Scholtz *et al.*, 1992). However, the master pack atmosphere is often inadequate in composition. Master packs for high oxygen atmospheres are commonly formed using equipment which evacuates and fills the pouches with gas through a snorkel or snorkels inserted into the mouth of the pouch between pads which close off the pouch (Church, 1994). The snorkels are retracted from the pouch before it is sealed.

The pouch is exposed to the pressure of the atmosphere throughout the evacuation and gassing operations. Consequently, a volume of air sufficient to prevent the pouch collapsing around and crushing the retail packs must remain in the pouch at the end of the evacuation phase. That minimum volume varies widely for different types of product. Moreover, the extent to which individual pouches are filled with air can vary, while timed evacuation will remove an approximately constant volume of air from each pouch. The result is that the input gas can be greatly and variably diluted by the air present in pouches at the time of gassing. The matter can be remedied by evacuating the pouch within a hood which is also evacuated, for a time sufficient to remove the maximum volume of air likely to be present at the start of master packaging. That appropriate technique is used by some, but by no means all who master package meat in high oxygen atmospheres.

The result of many high oxygen packaging systems being designed to take account of commercial factors without proper regard to the fundamental requirement for product preservation is that their preservative performances can be severely limited and highly variable. Consequently, central cutting operations often in practice depend for their success more on good temperature control and frequent delivery of product shortly after its preparation rather than on any supposed preservative packaging which they employ. Even when high oxygen packagings are properly formed for preservation, their ability to maintain the colour of colour unstable products is limited. With beef, for example, the colour of striploin steaks can be preserved for some 2 weeks (Nortjé & Shaw, 1989), but an acceptable colour for ground beef cannot be reliably retained for more than 6 days (Gill & Jones, 1994*a*). As about 50% of the beef sold is in the ground form, a central packing system based on high oxygen packaging must either be structured to accommodate the limited useful storage life of ground beef, or to not provide that basic, high volume product.

The alternative means of preserving meat colour is by packaging under vacuum or oxygen-depleted atmospheres. Such packagings are currently used mainly for packaging

primal cuts, but there has been limited use of vacuum packaging for retail-ready product, while oxygen-depleted packaging has as yet not been used for retail-ready product on any substantial scale.

Vacuum packaging can be considered as a special case of oxygen-depleted atmosphere packaging in which the volume of the pack atmosphere approximates zero. If a gas impermeable film is used for vacuum packaging, the meat is effectively removed from exposure to oxygen at the time of packaging. There can then be no formation of metmyoglobin during storage. Instead, metmyoglobin formed before packing will be reconverted to myoglobin as far as the capacity of the metmyoglobin reduction activity allows (Hood, 1980). Thus, vacuum packaged meat in a gas-impermeable film will indefinitely retain its ability to bloom to a fresh colour.

Oxygen impermeable films are available in the forms of aluminum foil laminates, metalized film laminates and, only recently, laminates of silica-sputtered films (Kelly, 1989). However, such films are not used commercially for vacuum packaging meat, in part because the former two are opaque while purchasers of meat are instinctively adverse to accepting product which they cannot see, and in part because films of low, but measurable, gas permeability are adequate for most commercial purposes.

With packs into which oxygen is permeating slowly, the muscle tissue acts as an oxygen scavenger, to maintain a very low oxygen tension at the meat surface. Discolouration of the muscle will not develop while the rate of metmyoglobin formation is less than the rate of metmyoglobin reduction. However, metmyoglobin reduction activity will decay and exhaust with time. After which, metmyoglobin will slowly accumulate to discolour muscle tissue surfaces. Before that, the pigment present in pockets of exudate, which tend to form in vacuum packs, can oxidize and precipitate onto meat surfaces to discolour them (Jeremiah *et al.*, 1992). The times before such events produce deterioration of the meat appearance will obviously vary with the oxygen transmission rate of the packaging film and the oxygen scavenging capabilities of the enclosed meat. However, with film of the type widely used for vacuum packaging, which has an oxygen transmission rate of about 40 cc/m^2/24/atm at 25° and 70% rh, and muscle of relatively high metmyoglobin reduction activity, such as beef striploin, deterioration of the meat appearance can be delayed for 12 weeks or more (Newton & Rigg, 1979).

Meat packaged under oxygen-depleted atmospheres will also be colour stable indefinitely when gas-impermeable material is used for the packaging, and subject to slowly developing, persistent discolouration if film of a measurable gas transmission is used instead (Gill, 1990). However, gas permeable films used with oxygen-depleted atmospheres must have very low oxygen transmission rates, of about 1 cc/m^2/24 atm at 25°C and 100% rh, because a substantial part of the metmyoglobin reduction capacity of the meat will be consumed in reducing the metmyoglobin formed when residual oxygen is scavenged from the atmosphere shortly after pack closure, which limits the metmyoglobin reduction capacity remaining to counter the effects of any ingressing oxygen.

The need to use films of very low, preferably zero, oxygen transmission rate when packaging meat under oxygen depleted atmospheres is a result of the practical impossibility of establishing an atmosphere completely free of oxygen at the time of pack sealing. Oxygen contamination is inevitable both because of traces of O_2 in the input gas and because of traces of air remaining in the evacuated pouch. In practice, an initial oxygen concentration of about 100 ppm is the lowest concentration that can be reliably achieved with available commercial equipment designed for oxygen-depleted packaging.

At such low concentrations, the oxygen is rapidly stripped from the atmosphere by the formation of metmyoglobin at the meat surface. Generally, that will cause discolouration of the meat. The only exception is when muscle of high colour stability and of a temperature a little below 0°C is packaged (Gill & McGinnis, 1995*a*). That appears to occur

because the rate of metmyoglobin formation declines sharply at some temperature close to 0°C, while metmyoglobin reduction activity is not so effected. Whatever the reason, beef striploins can tolerate residual oxygen concentrations of about 400 ppm or more without discolouration when they are at a temperature of −1°C, when packaged, but discolour at all achievable initial oxygen concentrations when they are at a temperature of 2°C.

The rate of discolouration is related to the oxygen concentration, but the extent of the discolouration depends also on the total amount of oxygen which must be scavenged from the headspace gas. If nitrogen is used for the atmosphere, the gas volume can be kept to the minimum required to prevent any crushing of the contained product (Gill & Jones, 1994*b*). If, as is more usual, CO_2 is used, to enhance the microbiological stability of the product, then sufficient gas must be added to both prevent crushing and to allow for the absorption of about 1 litre of gas per kilogram of meat. Thus, discolouration is likely to be greater with a CO_2 then with an N_2 atmosphere.

That initial discolouration presents no practical problem for meat which must be stored for periods longer than a few days, because, provided the amount of residual O_2 was not excessive, the discolouration will resolve in 2 to 4 days. The transient discolouration is a possible problem only when some of the meat may have to be displayed within a short time of packaging, as might be convenient or, indeed, necessary if oxygen-depleted packaging is used for retail-ready product.

It is an obvious consideration that both transient discolouration following pack closure and discolouration associated with the use of films which are not wholely gas impermeable might be ameliorated, or prevented, by including packettes of oxygen-scavenging chemicals in the pack. Such materials are commercially available, and are widely used in some countries to prevent the oxidative deterioration of packaged food products. If scavengers are to prevent discolouration of meat in oxygen-depleted atmospheres, they must remove the oxygen at a considerably faster rate than can the meat itself. Unfortunately, the rate of oxygen uptake by commercial scavengers declines exponentially with decreasing oxygen concentrations below 1% (Gill & McGinnis, 1995*b*). Consequently, when oxygen is at concentrations of about 100 ppm their rates of oxygen uptake are low. Transient discolouration can indeed be prevented by oxygen scavengers, but only if they are present in packs in numbers sufficient to reduce the residual oxygen concentration below 10 ppm within an hour or so. The large scavenging capacity required to achieve such rates suggests that it would probably be uneconomical to prevent transient discolouration by use of currently available, commercial oxygen scavengers. However, that does not preclude the possibility of future developments in that area.

When meat in vacuum or oxygen-depleted atmosphere packages is stored for very long periods, deterioration of the appearance of fat tissue and cut bone surfaces may become of practical importance. With prolonged storage, fat tissue is infiltrated with muscle pigment, which imparts initially bright pink tones to the tissue on exposure to air after the rigorous exclusion of oxygen, but which will dull and discolour the tissue after relatively short times in air or in packs into which oxygen infiltrates (Bell *et al.*, 1996).

As for cut bone, haemoglobin released from disrupted red blood cells in the marrow will accumulate at the surface and become dark brown and finally black when the bone is exposed to air. Discolouration of fat and bone blackening after short periods of display of long stored meat are undesirable consequences of prolonged storage for which there is no apparent means of control.

As deterioration of the appearance of meat can be similarly prevented by packaging under vacuum or oxygen-depleted atmospheres, the need for the latter type of packaging may not be readily apparent. The need for packaging under oxygen-depleted atmospheres arises from the limited range of products to which vacuum packaging can be applied. Vacuum packaging is ineffective for whole carcass or cuts of shapes which prevent the

packaging film being closely applied to all surfaces. Moreover, bone-in cuts generally cannot be vacuum packaged without bone puncture of some fraction of the packs. In packaging under oxygen-depleted atmospheres, the problem of vacuities does not arise, because the packaging is not forced onto the meat surface by the packaging process and wrappings or other items of packaging can be included with the meat to prevent contact between bones and the pouch. Vacuum packaging is also of very limited use for retail-ready product. Trial sales of conventionally vacuum packaged retail-ready cuts have been undertaken on numerous occasions, but the dull purple colours of anoxic meat and the inevitable pockets of exudate in packs are apparently viewed with disfavour by consumers who have at hand similar cuts in conventional display packagings (Young *et al.*, 1988). To overcome the problem with colour, some have resorted to vacuum-skin packaging in film from which the outer gas barrier layer can be stripped to expose a gas permeable layer and permit blooming of the meat. Such packaging is apparently acceptable to consumers. However, vacuum-skin packaging can be applied to a limited range of products only, as the technology will not accommodate cuts thicker than 2 or 3 cm. Moreover, the packs are prone to puncture by bone-in product, and cannot present ground meat attractively. In contrast, retail-ready product in any form can be master packaged under oxygen-depleted atmospheres, and will bloom to the colour of freshly cut meat when it is removed from the master pack for display.

BACTERIAL SPOILAGE

Delaying the bacterial spoilage of raw meat requires that proper attention be paid to the hygienic condition of the product and the control of product temperatures as well as the use of preservative packagings.

Techniques for improving processing hygiene and for decontaminating carcasses and other forms of raw meat are currently being intensively investigated by the meat packing industry. The proper application of such techniques, to achieve initially low loads of spoilage bacteria on product, does have large effects on the storage stability of meat. However, examination of those matters would require lengthy discussion, so only the effects of differences in the initial bacterial load on product is considered here.

It is obvious that decreasing the initial numbers of the bacteria which grow during storage to form the spoilage flora will extend the time required before they reach numbers sufficient to cause spoilage and, as growth is exponential, that exponential decreases are required for incremental increases in the storage life. Less obviously, decreasing the initial load of spoilage bacteria can also extend the storage life by altering the composition of the spoilage flora.

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 (Gill, 1986).

Under aerobic conditions, the dominant spoilage organisms are the strictly aerobic pseudomonads. Those organisms are nutritionally versatile, but display strong repression of other catabolic pathways when glucose is available as a substrate (Gill, 1982). Glucose is relatively abundant in most muscle tissue, allowing the growth of pseudomonads to numbers of about $10^8/cm^2$ before that substrate becomes growth limiting at the muscle surface. As the supply of glucose fails, the pseudomonads switch to amino acids as substrates for growth. While consuming glucose the bacteria do not produce offensive byproducts, but in breaking down amino acids produce a variety of byproducts which are detected organoleptically as putrid odours and flavours. With bacterial numbers of $10^8/cm^2$, the offensive byproducts accumulate rapidly, so spoilage onset is an abrupt phenomenon.

In some muscle with DFD characteristics and all fat tissue which is not bathed in exudate, the available glucose can support only far smaller populations. On such tissues the pseudomonads commence utilizing amino acids when their numbers are low. Spoilage then becomes evident as their numbers approach about $10^6/cm^2$, when the biomass is sufficient for the offensive byproducts to be generated in organoleptically detectable quantities within relatively short times.

The principal microbiological objective of preservative packagings is the partial or total inhibition of the rapidly growing pseudomonads. Then slower growing organisms, notably lactic acid bacteria, psychrotrophic enterobacteria and *Brochothrix thermosphacta*, can become dominant or major fractions of the spoilage flora. Ideally, a preservative packaging should allow dominance of the flora by lactic acid bacteria, which have a low spoilage potential, while the spoilage potentials of the other organisms are high.

In high oxygen + CO_2 atmospheres, the growth of pseudomonads is inhibited by the high concentration of CO_2. With CO_2 at a concentration of about 20%, the growth rate of the pseudomonads is approximately halved (Gill & Tan, 1979). Increasing the CO_2 concentration further produces little additional inhibition, but the degree of inhibition does increase with decreasing temperature. The other spoilage organisms are little or not inhibited by that concentration of CO_2, and grow at rates roughly comparable to those of the inhibited pseudomonads. Consequently, the composition of the spoilage flora which develops, and the course of the spoilage process, is greatly affected by the relative numbers of the various spoilage types in the initial flora.

If lactic acid bacteria are predominant over other spoilage types in the initial flora, they can dominate the spoilage flora and, as they approach their maximum numbers, inhibit some competing organisms by the production of bacteriocins. In such circumstances, the lactic organisms will tend to dominate the spoilage process even when the product is displayed in air after storage in a high oxygen + CO_2 atmosphere (Gill & Jones, 1994*a*). However, an obviously mixed flora is more likely to develop, with one or all of the other spoilage types persisting as substantial fractions of the flora at all times (Gill & Jones, 1996). With pseudomonads or enterobacteria persisting as substantial fractions of the flora, exhaustion of glucose as the flora approaches its maximum numbers will result in the removal of catabolite repression, with consequent breakdown of amino acids and the evolution of putrid odours and flavours. The time for the putrid byproducts to accumulate to organoleptically detectable levels will depend upon the absolute numbers on the meat of the bacteria which produce them. Even so, putrid odours can finally become evident with the bacteria which produce them at numbers of 10^4 in a flora of maximum numbers of $10^7/cm^2$ (Gill & Harrison, 1989). If product stored under a high oxygen + CO_2 atmosphere is displayed in air, the growth of pseudomonads will not be further inhibited, and their numbers in the flora will increase to accelerate putrid spoilage.

If *B. thermosphata* persists as a substantial fraction of the flora, the offensive byproducts which it produces throughout its growth, irrespective of the availability of glucose, will accumulate to impart to the product odours that are usually described as being redolent of sweaty socks (Grau, 1983).

Thus, high oxygen + CO_2 atmospheres may little delay the onset of spoilage in product which is initially relatively heavily contaminated with potent spoilage organisms other than pseudomonads. Product of very good hygiene is then required if spoilage is to be reliably and substantially delayed by high oxygen + CO_2 atmospheres.

Under vacuum and oxygen-depleted atmospheres of N_2 or CO_2, the anaerobic conditions prevent all growth of the pseudomonads. On muscle and in exudate of pH $\leq$5.8, anaerobic growth of the facultatively anaerobic enterobacteria and *B. thermosphacta* are totally inhibited (Grau, 1980Grau, 1981). Then, flora composed only of lactobacilli develop in anoxic packs. However, many products include fat, muscle or other tissues of

pH > 5.8. On those, the facultative anaerobes can grow under anaerobic conditions. Despite that, lactics can still dominate the flora if the initial numbers of spoilage bacteria are small, because they have a growth rate advantage over the facultatively anaerobic species which is manifest by a progressive increase in their relative numbers as growth of the flora progresses. However, relatively heavy initial contamination of higher pH tissues with either of the facultative anaerobes can allow their numbers to increase to levels where they precipitate spoilage of the packaged product even in the presence of a predominately lactic flora. Even if spoilage does not occur within the pack, product on which the faucultative anaerobes have grown can spoil rapidly on display because of their uninhibited, enhanced rates of growth in air.

If an oxygen-depleted atmosphere of CO_2 is used with product, the growth of the facultative anaerobes is further restricted. Growth of the enterobacteria on high-pH tissue is prevented, as is the growth of *B. thermosphacta* at temperatures of 0°C or below (Gill & Harrison, 1989). Thus, with storage of product at sub-zero temperatures, the growth of a flora of lactobacilli on all types of meat can be assured. Meat displayed after such storage will be spoiled relatively slowly by the relatively innocuous byproducts of the lactic acid bacteria, rather than relatively rapidly by the grossly offensive byproducts of the other spoilage organisms.

Oxygen-depleted CO_2 atmospheres can then substantially prolong the storage life of high-pH, heavily contaminated product provided that the initial flora contains few lactic acid bacteria. That is exemplified by the 10 week storage life attainable with chicken stored under oxygen-depleted CO_2, whereas 7 or 8 days is the most that can be expected for chicken stored under any other atmosphere (Gill *et al.*, 1990). In contrast, oxygen-depleted CO_2 atmospheres extend the storage life of fat-free pork loins only moderately beyond that attainable with vacuum packaging, because lactic acid bacteria dominate the flora and ultimately cause deterioration of the flavour in either packaging (Jeremiah & Gibson, 1996).

With regard to storage temperatures, apart from the specific effects of low temperatures on the inhibition of pseudomonads and *B. thermosphacta* by CO_2, the general effect of lower temperatures is slower growth of all spoilage bacteria. If follows that the optimum storage temperature for chilled meat is the minimum which can be maintained indefinitely without overt freezing of the product. That optimum storage temperature for packaged meat is -1.5 ± 0.5°C (Gill *et al.*, 1988*a*).

There are large losses of storage life for small increases above the optimum temperature irrespective of the packaging used for meat. At temperatures of 0, 2 or 5°C, the storage life is respectively about 70, 50 or 30% of the storage life obtained at the optimum temperature (Gill *et al.*, 1988*b*). Obviously, maintenance of product temperature close to the optimum is a primary requirement if product is to have a prolonged storage life.

The need for good control of product temperature in the surface shipment of product to distant, overseas markets has been widely recognized. However, the optimal management of product temperatures has not generally extended to storage and distribution in more local markets. In those, temperatures between 2 and 4°C still seem to be considered suitable by many involved in the trading of meat (Gill *et al.*, 1995*a*). And, at the retail display level, control over product temperatures is largely lost, because most display cases in current use are incapable even of maintaining the average temperatures of all product below 10°C (Greer *et al.*, 1994). The wastage of product arising from such disregard of a major factor affecting the storage stability of meat must be substantial.

The fundamentals for good control of product temperatures during storage and transport are well known. Most transport and storage facilities are designed to maintain product temperatures, and cannot be expected to rapidly cool product which is loaded into them while still above their operating temperatures (Scrine, 1985). Consequently,

product must be cooled to near the optimum temperature soon after it is prepared, in chilling facilities designed for that purpose. Thereafter, the product temperature can be maintained if transport and storage facilities are operated at the optimum temperature, and product is well managed at change over points to assure that it does not experience non-refrigerated environments for any lengthy times.

Proper management of product is greatly assisted by the routine collection of temperature histories from randomly selected product units moving through a process (Gill & Jones, 1992). The temperature histories can be analyzed by integrating each with respect to a suitable model describing the dependency on temperature of the growth of an appropriate spoilage bacterium. The variations in the durations of such processes for individual items can be accommodated by calculating a storage efficiency factor for each storage temperature history. The storage efficiency factor is the percent ratio of the bacterial growth calculated from the temperature history to the bacterial growth calculated to occur if the optimum storage temperature had been maintained throughout the process.

The values for bacterial growth and storage efficiencies can be used as input data for Quality Management purposes (Gill *et al.*, 1995*b*). In addition, if temperature histories are logged in real, dated time, those responsible for the product at any times of loss of temperature control can be unambiguously identified, and the causes of loss of temperature control ascertained and corrected. Such techniques have been applied in practice to improve product temperature control.

Similar techniques could be applied to retail display cases. Although there is little likelihood that the refrigerative performances of current display cases could be much improved, product passing through them could certainly be better managed, to avoid overloading and undesirable perturbation of refrigerated air flows, and to minimize the maximum time that any item occupies a display case.

EXUDATE

The loss of exudate from muscle tissue is unavoidable. Exudate losses are exacerbated by cutting of meat to smaller portions, temperature fluctuations and pressure on the product (Offer & Knight, 1988). Most of the exudate is lost from primal cuts within the first two weeks of their preparation (Zarate & Zaritzky, 1985). Even if the effects of all those factors are minimized prior to the preparation of retail-ready product, exudate losses of the order of 5% of the primal cut weight at the packing plant must be expected.

At present, losses arising from exudation must be accommodated, by adjusting the retail price for shrinkage, by those who purchase primal cuts. The only apparent way of avoiding the economic uncertainties arising from such shrinkage would be to prepare retail-ready meat at the packing or a closely associated plant, so that the exudate is largely included in the packed weight of the retail-ready product.

Although such a practice is rare it would seem to be both technically and economically feasible. Studies of the distribution and storage of meat until display at the retail level indicate that a maximum storage life of about 3 weeks is required for the convenient movement of meat through overland distribution systems. That allows for delays occasioned by weekends and statutory holidays, and for the stockpiling which is required to accommodate unpredictable fluctuations in consumer demand (Gill & McGinnis, 1993). Master packaging under oxygen depleted atmospheres can obtain such a storage life for colour unstable and microbiologically fragile product even under existing commercial temperature regimes (Gill *et al.*, 1994). If temperatures during storage and overland transport were reduced to near the optimum, the storage life for the most perishable products would substantially exceed that required for convenient distribution

and consumer use of the product. Oxygen depleted atmosphere master packaging at the packing plant level could be economically feasible despite the possible relatively high cost of the required packaging system, because of savings occasioned by the abandonment of the intermediate packaging of primal cuts. The low packing density of retail-ready product as compared with boxed, vacuum packaged primal cuts would not incur higher costs for transportation by road, because loading limits for road trailers prevent their being loaded to their full volume capacity with boxes that are wholely filled with meat. However, a low packing density would incur substantially higher costs for containerized sea freightage, because sea containers can be filled with meat, and the cost of shipping a container is the same irrespective of the amount of meat it contains. So, overseas shipment of retail-ready product is unlikely to be economical, although it would be technically possible with the more microbiologically stable types of product.

CONCLUSIONS

The storage life of all raw meats, in forms ranging from whole carcasses to retail-ready cuts, can be extended to many weeks by proper control of the hygienic condition of product and product temperatures, and by the appropriate selection and use of preservative packagings. Techniques for achieving superior performance in each of those areas are known for most types of meat, or are currently emerging. There are then apparently, no intractable technical barriers to the centralization of the preparation of retail-ready meats and the expansion of global trading in the chilled product. Constraints on those commercial developments are more likely to arise from difficulties in adapting existing preparation and distribution systems, which are predicated on the highly perishable nature of the commodities being handled, to the handling of substantially stable, possibly branded consumer items. Commercial difficulties with changing current systems must be expected, because piecemeal introduction of stable product into systems geared to and continuing with the handling of rapidly perishable product will not allow realization of the full economic benefits which should arise in systems designed for the handling of stable product only. The availability of effective technologies and the long-term economic realities must ultimately ensure that chilled meat will generally become a far more stable commercial item than it is at present. However, progress towards generally enhanced stability is likely to be punctuated rather than smooth, so major changes in the near future cannot be anticipated with any confidence.

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