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Evaluation of the bacteriological consequences of the temperature regimes experienced by fresh chilled meat during retail display

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Temperature histories were recorded from the surfaces of chilled steaks in a commercial retail case. Steaks were placed at the rear, centre or front of the case, and at 17 or 13 cm below, or 4 cm above the load line. The coldest average temperatures (1·7–4·5°C) were recorded at the rear, and the warmest (6·1–10°C) at the centre of the case. Average temperatures increased with upward location of the steaks, from between 1·7 and 6·1°C at 17 cm below to between 4·5 and 10°C at 4 cm above the load line. The meat surface temperatures did not correlate with the air temperatures at the rack level. The average temperatures for steak surfaces and case air in the vicinity of steaks differed by up to 1°C, but the surface and deep temperatures of steaks were similar.

Calculated values for the proliferations of psychrotrophic pseudomonads and *Escherichia coli* correlated well with the average surface temperatures of the steaks. Apparently, *E. coli* growth would be negligible with average surface temperatures of ≤4°C. However, a survey of air temperatures in four commercial retail cases indicated that temperatures of ≤4°C cannot be maintained throughout existing retail cabinets. To assure food safety, some means of identifying the maximum average temperature experienced by a product in individual display cases is required, with a specification of the maximum residence time that can be tolerated at any maximum temperature.

Keywords: chilled meat, retail display, meat temperatures, air temperatures.

INTRODUCTION

Retail display is possibly the weakest link in the commercial cold chain (James & Bailey, 1990). As the contamination of raw meat with human pathogens is inevitable, there must be concern that they may proliferate to hazardous numbers during periods of temperature abuse in display cases (Luiten *et al.*, 1982; Grau, 1987). Moreover, the temperatures experienced during display will affect the product storage life (Greer, 1981). The economic significance of inadequate display temperature is substantial, as 55% of the total spoilage losses sustained by the meat industry apparently occur at the retail level (Breidenstein, 1986).

The need for good control of temperatures during the display of meat has been recognized in recommendations, by various regulatory and trade organizations, that the temperatures of displayed products be maintained at or below a specified maximum (Anon., 1978; James & Evans, 1990; Olsson, 1990). Unfortunately, such apparently simple recommendations are rendered ambiguous by a general failure to define which temperatures should be measured. The uncertainty is evident in the available published data on display case temperatures which variously report air or product temperatures, and variously consider instantaneous and/or average values for those temperatures (Pivnick *et al.*, 1976; Sumner *et al.*, 1981; Powell & Cain, 1987; Gormley, 1990).

For raw meat that has not been comminuted or rolled, bacteria are located only on the product surface (Gill, 1986). The temperatures of relevance to the safety and storage life of such product are, therefore, those at the product surface, rather than those of the sterile deep tissues (Greer &

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Jeremiah, 1980). Any recommended maximum temperature for displayed raw meat should, therefore, refer to the product surface temperatures, or to temperatures that correlate in a known fashion with the surface temperatures. Moreover, case air temperatures will inevitably fluctuate to relatively high values during defrosting cycles (Brolls, 1986), and air temperature fluctuations are likely to affect the surface temperatures of the products. Instantaneous surface temperatures obtained during defrosting will then be uncharacteristically high, and so misleading as to the hygienic adequacy of the case temperatures. Consequently, any recommendation of practical utility must likely refer to average rather than instantaneous surface temperatures.

With those requirements in mind, a study was undertaken to identify the relationships between the surface and deep temperatures of steaks and air temperatures in a chilled commercial display cabinet; to ascertain the bacteriological consequences of the temperatures experienced by steak surfaces; and to apply those findings to assess the hygienic adequacy of temperature control in other commercial meat display cases.

MATERIALS AND METHODS

Temperature measurements

Retail case and product temperatures were measured using MIRINZ-Delphi temperature data loggers (Tru-Test, Auckland, New Zealand). The loggers were set to record temperatures at 15-min intervals, with an accuracy of ±0·25°C and a resolution of 0·25°C (Gill & Jones, 1992). Retail case air temperature histories were obtained using data loggers fitted with internal temperature sensors. Entering air, meat surface and deep tissue temperatures were recorded using loggers fitted with an external thermistor probe encased in a teflon sheath. Temperatures were recorded for periods of 48 or 72 h. Such intervals were representative of the maximum times that raw meat is resident in chilled, commercial display cases.

Meat and retail case air temperatures

The relationships between meat surface temperatures, deep tissue temperatures and case air temperatures were determined for a commercial meat display case.

The cabinet was of the single deck (81 cm W × 365 cm L), fan-assisted type where air is drawn over an evaporator coil and then blown from the rear of the cabinet across the displayed meat (Malton, 1976). Beef rib-eye steaks, 4 cm thick, were placed on styrofoam meat trays and wrapped in a polyvinyl chloride film that is used commercially for overwrapping meat (Vitafilm Choice Wrap, Goodyear Canada Inc., Toronto, ON). The steaks were placed at three locations on the support rack of the case, or at positions directly above those locations. The three locations were at the (1) rear, (2) centre, or (3) front, of the left side of the case. Thus, the steaks were located at distances of 8, 40 and 75 cm from the outlet for refrigerated air at the rear of the case, with their surfaces 17 or 13 cm below, 4 cm above, or at the load line limit specified by the manufacturer. On each occasion that temperatures were monitored, a steak was placed at each of the three locations, or at the same level above each location. The surfaces of the steaks were not covered by other products during the periods of monitoring.

For the recording of steak surface temperatures, a teflon probe was inserted through the polyvinyl wrapping and into each steak, so that the tip lay at the approximate centre and 1 mm below the meat surface. Deep tissue temperatures were similarly recorded from the approximate geometric centre of each steak.

Display case air temperature histories were collected from data loggers placed on the supporting rack and at locations immediately adjacent to the surface of each steak. All temperature histories were collected over a period of 48 h.

Integration of temperature history data with respect to bacterial growth

Each surface temperature history was integrated with respect to a model describing the dependency on temperature of the aerobic growth of *Escherichia coli*, and with respect to a second model describing the dependency on temperature of the growth of psychrotrophic pseudomonads.

The model for the aerobic growth of *E. coli* has previously been used for assessing the hygienic adequacy of various meat cooling processes (Gill & Jones, 1992). The triphasic model has the form:

$y = (0{\cdot}0513x - 0{\cdot}71)^2$ when x is between 7 and 30;
$y = (0{\cdot}027x + 0{\cdot}55)^2$ when x is between 30 and 40;
$y = 2{\cdot}66$ when x is between 40 and 47; and
$y = 0$ when x is <7 or >47;

where y is the growth rate expressed as generations h^{-1} and x is the temperature in °C.

The model for growth of pseudomonads was derived from published data describing the dependency on temperature of the growth rates of various *Pseudomonas* species proliferating on meat, in milk or in rich synthetic media (Gill & Newton, 1977, 1980; Ahmed, 1979; Pooni & Mead, 1984; Chandler & McMeekin, 1985; Fu *et al.*, 1991). The model describes the regression line fitting those combined data, for temperatures between 0 and 25°C, when they are plotted as the square root of the growth rate against temperature (Ratkowsky *et al.*, 1982). The regression line is extrapolated to −2°C. That extrapolation is supported by data on the relative rates of flesh spoilage at sub-zero temperatures (McMeekin *et al.*, 1988). The model is terminated at −2°C on the assumption that growth at lower temperatures would be prevented by the freezing of the meat surfaces. The varied deviations from the simple square root model of the growth of different strains of psychrotrophic pseudomonads at temperatures above 25°C (Ratkowsky *et al.*, 1983) is accommodated by assuming a uniform rate of growth for temperatures between 25 and 35°C. The biphasic model has the form:

$y = (0{\cdot}033x + 0{\cdot}27)^2$ when x is between −2 and 25;
$y = 1$ when x is between 25 and 35; and
$y = 0$ when $x < -2$ or > 35;

where y is the growth rate expressed as generations h^{-1} and x is the temperature in °C.

The models were applied in a computer program that interrogates a logger, requests definition of the times that the product temperature history record began and ended, calculates from each model the respective proliferations of *E. coli* and pseudomonads during each record interval, and derives the total proliferations by the summation of each series of incremental proliferations (Gill *et al.*, 1988).

Rack-level air temperatures in retail cabinets

Air temperatures were recorded in the retail display case used in the measurement of meat temperatures (Case A) and in each of three other cases, each at a retail outlet operated by a different company. Temperatures were recorded for periods of 72 h. Each data logger was placed on a styrofoam meat tray and overwrapped with the polyvinyl chloride film. Wrapped loggers were secured to the support rack of each case at five locations. Those locations were at the three used when recording meat temperatures, and at (4) the centre, and (5) the centre right side of the case. Thus, temperature histories were obtained from locations distributed from the rear to the front, and along the length, of each case. During residence in a case, each temperature logger was exposed or covered with meat in an unpredictable sequence determined by commercial activities. The temperatures of the refrigerated air entering each case from the ducting at the case rear, and the temperatures of the ambient air in the vicinity of each case were also recorded.

RESULTS

Meat and retail case air temperatures

The surface temperatures were influenced by both the horizontal and vertical location of each item within the retail case (Table 1). The coldest average meat surface temperatures (1·7–4·5°C) were recorded at the rear of the case, while the warmest average surface temperatures (6·1–10·0°C) occurred in the mid-section of the case. Irrespective of location within the retail case, the meat surface temperatures progressively increased as the vertical

Table 1. The effect of position in a retail display case on the surface temperatures of steaks[a]

Location in case[b]	Distance from load line (cm)[c]	Steak surface temperature (°C)[d]		
		Max.	Min.	Mean
1	−17	5·3	0	1·7
	−13	7·5	1·0	2·7
	0	8·0	1·3	3·3
	+4	8·3	2·8	4·5
2	−17	8·0	4·3	6·1
	−13	10·0	4·3	6·9
	0	10·0	4·0	6·7
	+4	11·8	7·5	10·0
3	−17	7·3	4·0	5·6
	−13	9·0	1·3	6·8
	0	9·5	5·8	7·2
	+4	10·3	6·0	8·3

[a] Temperatures were recorded over a 48-h period.
[b] Rib-eye steaks were located at distances of (1) 8 cm, (2) 40 cm, and (3) 75 cm from the rear of the case.
[c] Distances (cm) below (−) or above (+) the load line to the surface of each steak.
[d] Thermistor inserted 1 mm below meat surface.

Table 2. Air temperatures at the load line of retail case A, and the surface and deep tissue temperatures of steaks placed in the case with their upper surfaces at the load line. The data are from records of temperatures at 15-min intervals for 72 h

Location in case[a]	Temperature (°C)								
	Case air[b]			Steak surface[c]			Deep tissue[d]		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
1	10·8	2·0	4·1	7·3	2·3	4·2	7·0	2·3	4·1
2	11·3	3·5	5·7	9·3	4·8	6·8	8·8	4·3	6·4
3	11·8	4·3	6·6	8·0	4·0	6·0	7·8	3·5	5·7

[a] Rib-eye steaks were located at distances of (1) 8 cm, (2) 40 cm, and (3) 75 cm from the rear of the case.
[b] Retail case air temperatures were those at the load line at locations immediately adjacent to those of each steak.
[c] Thermistor inserted 1 mm below meat surface.
[d] Thermistor inserted into the geometric centre of the steak, i.e. 2 cm below the steak surface. Both surface and deep tissue temperatures were measured for each steak.

placement of the meat increased from well below (−17 cm) the load line (1·7–6·1°C) to above (+4 cm) the load line (4·5–10·0°C).

The average meat surface temperature, for all locations, was about 6°C. Simple linear regression analysis showed that meat surface temperature was only poorly correlated with retail case air temperature at the rack level ($r^2 = 0{\cdot}18$, $P > 0{\cdot}1$).

The data in Table 2 show retail case air, steak surface and deep tissue temperatures for steaks at the load line limit. The retail case air temperature was found to increase with distance from the entering air and to fluctuate from minima as low as 2°C to maxima as high as 12°C. The corresponding variation in steak temperatures was slightly smaller (2–9°C). Temperatures measured at the steaks' surface and within the deep tissue were similar.

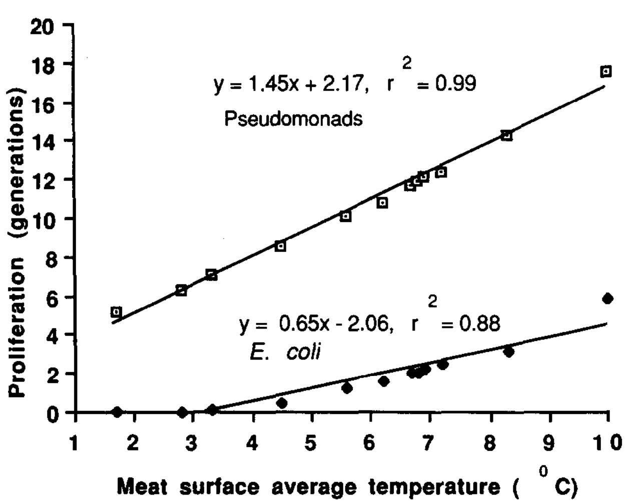

Fig. 1. The relationships between average temperatures and the proliferations of pseudomonads and *E. coli* estimated from the temperature histories of steak surfaces recorded over a period of 48 h.

Estimation of bacterial growth at meat surfaces

Integration of steak surface temperature histories with respect to models relating bacterial growth rate to temperature indicated that pseudomonads would grow on all the steaks, while *E. coli* would grow only on steaks experiencing average surface temperatures >3°C. The estimated proliferations of pseudomonads correlated very closely ($r^2 = 0{\cdot}99$, $P \leq 0{\cdot}001$) with the average surface temperatures. There was good correlation ($r^2 = 0{\cdot}88$, $P \leq 0{\cdot}001$) between average surface temperatures and the estimated proliferations of *E. coli* (Fig. 1).

Rack-level air temperatures in retail cases

The average temperatures of the refrigerated air entering the four retail cases ranged from −3·3–1·8°C (Table 3). However, the temperatures fluctuated by about 30°C (e.g. −4·3–28°C) during each 12-h defrosting cycle. In contrast, the ambient air temperatures, which averaged between 20 and 24°C, varied by no more than ±3°C.

The average air temperatures at the rack level in all four cases varied from −0·6–7·5°C at the various locations within the retail cases. The lowest average temperatures and temperature fluctuations (−8–15°C) were recorded from case A, while the highest temperatures and largest fluctuations occurred in case C (Table 3). In each case, the coldest area was at the rear (position 1), and the warmest average temperature was recorded for a position along the long axis of the case in the midsection (positions 2, 4 and 5). Temperatures varied throughout the length of the retail cases in no consistent pattern (positions 2, 4 and 5) and differences between locations could be as much as 4°C.

Table 3. Rack-level air temperatures in four commercial retail cabinets[a]

Location[b]	Temperature (°C)											
	Case A			Case B			Case C			Case D		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
Entering air	28·0	−4·3	−2·3	16·8	−9·3	−1·6	27·8	−1·3	1·8	16·8	−6·0	−3·3
1	4·8	−2·3	−0·2	11·0	0·5	4·0	14·8	−2·0	2·8	7·0	−7·8	−0·6
2	9·0	−1·0	1·4	10·5	1·3	4·2	15·0	−2·3	4·6	9·3	−8·0	3·2
3	5·0	−0·5	1·1	8·8	1·3	3·7	12·3	−1·0	3·8	6·8	−6·5	2·1
4	7·8	0·3	2·2	8·5	−3·8	0·8	15·3	1·3	5·7	10·3	1·0	3·5
5	8·5	0·8	2·6	13·5	−1·3	1·9	14·5	−0·3	4·5	13·0	2·5	7·5

[a] All cabinets were single tier forced air types. Case air temperatures were measured at the rack level and entering air temperatures at the rear of the case where the refrigerated air left the ducting.
[b] Temperature loggers were placed at 5 positions within each case. The positions were left hand side, (1) 8 cm, (2) 40 cm, or (3) 75 cm from the rear; (4) case centre; and (5) 40 cm from the rear on the right hand side. Records were collected at 15-min intervals over a period of 72 h.

DISCUSSION

The results from a single retail case indicate that with an average entering air temperature of −2°C, the average temperature of the rack level air and the steak surfaces were 2 and 6°C, respectively. A similar relationship was discerned by Powell & Cain (1987) who found that with supply air temperatures ranging from −8 to −2°C, retail case air temperatures ranged from 2–7°C and product temperatures from 5–8°C. James & Evans (1990) also concluded that air must enter a cabinet at −2°C to maintain maximum meat temperatures of 5°C.

The present study did not demonstrate any substantial differences between steak surface temperature and deep tissue temperature, at least at the level of the load line. Although it would be expected that deep tissue average temperatures would be less variable and perhaps somewhat lower than those of the surface (Malton, 1980), such an effect was not evident with retail steaks. It might occur, however, with larger pieces of meat.

Previous studies have shown that actual increases in the numbers of specified bacteria on meat can be accurately calculated by temperature function integration techniques (Pooni & Mead, 1984; Reichel *et al.*, 1991). From such calculations it appears that the growth of pseudomonads correlates closely and directly with the average surface temperature of steaks during retail display, within the range 2–10°C. Under experimental conditions similar close relationships have been observed between the average temperature of the entering air and the measured growth of psychrotrophic bacteria or the time to spoilage of displayed steaks (Greer, 1981; Greer & Jeremiah, 1981).

Similarly, good correlations between the average steak surface temperature and the growth of *E. coli* appear to exist for temperatures between 4 and 8°C, although for higher and lower average temperatures a direct correlation is probably not maintained.

It has been common practice to define storage temperatures for chilled meat from consideration of the temperatures required to control the growth of *E. coli*, as that organism is widely regarded as an appropriate indicator of the risk to consumers from mesophilic pathogens (Gill & Phillips, 1990). It appears that the growth of *E. coli* on displayed meat is likely to be negligible when the average surface temperature is ≤4°C. Thus, that guideline temperature, which is recommended in Canada, would seem to be appropriate with respect to public health concerns when it refers to the average surface temperature of product. If a one generation increase in *E. coli* numbers were considered tolerable, then the guideline temperature could be raised to 5°C which is recommended in the UK (James & Evans, 1990). It becomes more difficult, however, to justify the proposed official Swedish temperature limit of 6°C, let alone that country's current limit of 8°C (Olsson, 1990). Further study will be necessary to properly confirm a general, simple relationship between the average surface temperatures of displayed meat and the growth of bacteria of public health concern.

Unfortunately, routine determination of average product temperatures, whether surface or deep, would be difficult in commercial circumstances. It would then be of great practical convenience if recommended temperatures could refer to the average temperature of the entering, rack-level or other case air.

The four commercial display cases monitored in the present survey were operated with entering air average temperatures that ranged from about −3–2°C. The simple expectation would be that the average air temperatures within cases, at least at the level of the support rack, would generally correlate with the temperatures of the incoming air. However, that will not be so if there is unequal distribution of air within the case (James & Evans, 1990). Air temperatures at two of the five locations at which temperatures were monitored were highest in retail cases with low incoming air temperatures. Indeed, the highest rack level air temperature was recorded from the front of the case with the lowest temperature entering air. Similar, if less pronounced, unequal distributions of air were also evident in two of the other cases. Thus, the refrigerative performances of the commercial cases could not be predicted from the temperature of the entering refrigerated air. However, the results indicate that even equally distributed entering air must be at a sub-zero average temperature if average air temperatures at the rack level are not to exceed 4°C at some locations.

Average steak temperatures at the rack and load line levels differed by up to 1·5°C, or up to 4°C for product above the load line, and the average surface temperatures of steaks could exceed those of the surrounding air by as much as 1°C. Consequently, in-case air temperatures could be used for defining adequate control of product temperatures only if highly conservative assumptions are made about the relationships between measured air temperatures and the temperatures of the product.

The findings of this study indicate that, in the 15 years since the last major survey in Canada, and recommendation of a 4°C maximum temperature for the product (Anon., 1978), there has been no improvement in the control of the temperature of displayed meat. It is also apparent that products cannot in practice be reliably held at or below the recommended maximum temperature in existing display cases. The continued advocation of an appropriate, but practically unattainable maximum average temperature for displayed meat cannot then be expected to enhance food safety. Instead, means for the routine monitoring of display cases that will allow identification of the maximum average temperature experienced by any product item are required. The safety of food could then be sought by specifying the maximum residence time that can be tolerated in a case by reference to the maximum average product temperature that is consistently achieved.

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REFERENCES

Ahmed, M. A. (1979). Aspects of the microbiology of the spoilage of meat with special reference to Gram-negative facultative anaerobic rods of the family *Enterobacteriaceae*. PhD thesis, The Queen's University, Belfast. Data quoted in Pooni & Mead (1984).

Anon. (1978). Canadian industries take stand on bacteriological standards. *Nat. Provis.*, **178**, 8–24.

Breidenstein, B. B. (1986). Economic impact of meat spoilage organisms. *Proc. 39th Ann. Recip. Meat Conf. (Vol. 39)*, pp. 1–4.

Brolls, E. K. (1986). Factors affecting retail display cases. In *Recent Advances and Developments in the Refrigeration of Meat by Chilling*. International Institute of Refrigeration, Commission C2, UK, pp. 405–13.

Chandler, R. E. & McMeekin, T. A. (1985). Temperature function integration and its relationship to the spoilage of pasteurized, homogenized milk. *Austral. J. Dairy Technol.*, **40**, 37–41.

Fu, B., Taoukis, P. S. & Labuza, T. P. (1991). Predictive microbiology for monitoring spoilage of dairy products with time–temperature integrators. *J. Food Sci.*, **56**, 1209–15.

Gill, C. O. (1986). The control of microbial spoilage in fresh meats. In *Advances in Meat Research, Vol. 2. Meat and Poultry Microbiology*, ed. A. M. Pearson & T. R. Dutson. AVI Publishing Company, Westport, CT, pp. 49–88.

Gill, C. O. & Jones, T. (1992). Assessment of the hygienic efficiencies of two commercial processes for cooling pig carcasses. *Food Microbiol.*, **9**, 335–43.

Gill, C. O. & Newton, K. G. (1977). The development of aerobic spoilage flora on meat stored at chill temperatures. *J. Appl. Bacteriol.*, **43**, 189–95.

Gill, C. O. & Newton, K. G. (1980). Growth of bacteria on meat at room temperatures. *J. Appl. Bacteriol.*, **49**, 315–23.

Gill, C. O. & Phillips, D. M. (1990). Hygienically appropriate time/temperature parameters for raw meat processing. *Proc. 36th Int. Cong. Meat Sci. Technol.*, Havana, Cuba, pp. 458–70.

Gill, C. O., Phillips, D. M., Loeffen, M. P. F. & Bishop, C. (1988). A computer program for evaluating the hygienic efficiency of meat processing procedures from product temperature history data. *Proc. 34th Int. Cong. Meat Sci. and Technol.*, Brisbane, Australia, pp. 531–2.

Gormley, T. R. (1990). Temperature measurements in chilled retail cabinets and household refrigerators. In *Processing and Quality of Foods, Vol. 3. Chilled Foods: The Revolution in Freshness*, ed. P. Zeuthen, J. C. Cheftel, C. Eriksson, T. R. Gormley, P. Linko & K. Paulus. Elsevier Science Publishers, London, pp. 3.295–3.304.

Grau, F. H. (1987). Prevention of microbial contamination in the export beef abattoir. In *Elimination of Pathogenic Organisms from Meat and Poultry*, ed. F. M. Smulders. Elsevier Applied Science Publishers, Amsterdam, pp. 221–33.

Greer, G. G. (1981). Improved acceptance of retail beef through proper temperature control. *Dairy Food Sanit.*, **1**, 460–2.

Greer, G. G. & Jeremiah, L. E. (1980). Influence of retail display temperature on psychrotrophic bacterial growth and beef case-life. *J. Food Prot.*, **43**, 542–6.

Greer, G. G. & Jeremiah, L. E. (1981). Proper control of retail case temperature improves beef shelf life. *J. Food Prot.*, **44**, 297–9.

James, S. J. & Bailey, C. (1990). Chilling systems for foods. In *Chilled Foods: The State of the Art*, ed. T. R. Gormley. Elsevier Applied Science, London, pp. 1–35.

James, S. J. & Evans, J. (1990). Temperatures in the retail and domestic chill chain. In *Processing and Quality of Foods, Vol. 3, Chilled Foods: The Revolution in Freshness*, ed. P. Zeuthen, J. C. Cheftel, C. Eriksson, T. R. Gormley, P. Linko & K. Paulus. Elsevier Applied Science, London, pp. 3.273–3.278.

Luiten, L. S., Marchello, J. A. & Dryden, F. D. (1982). Growth of *Salmonella typhimurium* and mesophilic organisms on beef steaks as influenced by type of packaging. *J. Food Prot.*, **45**, 263–7.

Malton, R. (1976). Refrigerated retail display for fresh meat. *Inst. Meat Bull. (UK)*, **91**, 17–19.

Malton, R. (1980). Displaying wrapped meat in refrigerated cabinets: the problems. *Meat (UK)*, **53**, 37–43.

McMeekin, T. A., Olley, J. & Ratkowsky, D. A. (1988). Temperature effects of bacterial growth rates. In *Physiological Models in Microbiology, Vol. 1*, ed. M. J. Bazin & J. I. Prosser. CRC Press, Boca Raton, FL, pp. 75–89.

Olsson, P. (1990). Chill cabinet surveys. In *Processing and Quality of Foods, Vol. 3. Chilled Foods: The Revolution in Freshness*, ed. P. Zeuthen, J. C. Cheftel, C. Eriksson, T. R. Gormley, P. Linko & K. Paulus. Elsevier Applied Science, London, pp. 3.279–3.288.

Pivnick, H., Erdman, I. E., Collins-Thompson, D., Roberts, G., Johnston, M. A., Conley, D. R., Lockapelle, G., Parvic, V. T., Foster, R. & Milling, M. (1976). Proposed microbiological standards for ground beef based on a Canadian survey. *J. Milk Food Technol.*, **39**, 408–12.

Pooni, G. S. & Mead, G. C. (1984). Prospective use of temperature function integration for predicting the shelf-life of non-frozen poultry-meat products. *Food Microbiol.*, **1**, 67–87.

Powell, V. H. & Cain, B. P. (1987). The shelf life of meat during retail display. *Food Technol. Austral.*, **39**, 129–33.

Ratkowsky, D. A., Olley, J., McMeekin, T. A. & Ball, A. (1982). Relationship between temperature and growth rate of bacterial cultures. *J. Bacteriol.*, **149**, 1–5.

Ratkowsky, D. A., Lowry, R. K., McMeekin, T. A., Stokes, A. N. & Chandler, R. E. (1983). Model for bacterial culture growth rate throughout the entire biokinetic temperature range. *J. Bacteriol.*, **154**, 1222–66.

Reichel, M. P., Phillips, D. M., Jones, R. & Gill, C. O. (1991). Assessment of the hygienic adequacy of a commercial hot boning process for beef by a temperature function integration technique. *Int. J. Food Microbiol.*, **14**, 27–42.

Sumner, J. L., Gorczyca, E. & Lim, K. B. (1981). The hygienic status of minced meat purchased in Melbourne. *Food Technol. Austral.*, **33**, 416–8.