EARLY-POSTMORTEM COOLING RATE AND BEEF TENDERNESS

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SUMMARY

Four distinct early-postmortem cooling rates (as measured within the longissimus *muscle) were obtained by exposing one side of each of five fat and five lean steers to moving air at* $-2°$ *and the other to* $9°$ *static air. Loin steaks of the fastest cooling group were found to be the least tender and to have the shortest sarcomeres; the three remaining groups differed significantly from each other in tenderness but not in sarcomere length. For all twenty sides, regardless of treatment group, tenderness was highly dependent on, and almost linearly related to, the muscle temperature attained at 2 hours post mortem* $(27–40°)$, *the relationship deteriorating rapidly as longer time intervals and lower temperature ranges were considered. The results indicate that (1) except in very rapidly chilled lean carcasses, cold shortening is not a significant determinant of tenderness; (2) the enhanced tenderness of slowly chilled beef is not due primarily to the relatively prolonged avoidance of shortening-inducive temperatures but to the accompanying retardation of cooling during the first 2–4 hours post mortem, when muscle temperatures are still far above those associated with cold shortening and (3) the generally recognised superior tenderness of well-finished beef is largely (and perhaps entirely) a consequence of slower cooling during this very early-postmortem period.*

INTRODUCTION

The great effect of early-postmortem chilling rate on meat tenderness has been demonstrated in many laboratories. Stemming from the initial discoveries of Locker (1960) and Locker & Hagyard (1963), the investigations have established that cold

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shortening may be responsible for much of the considerable tenderness variation (and, sometimes, frank toughness) found in beef and lamb.

If a fairly precise relationship is to be developed between tenderness and cooling velocity—precise enough, that is, to allow comparisons and predictions over a wide range of conditions—then we must recognise that the chilling rate which really matters—that of the muscle itself—is the resultant of many variables, including the size, shape and fatness of the carcass and the temperature, relative humidity and flow pattern of the chiller air. Air temperature data, either alone or combined with air velocity measurements, permit the chilling rate to be inferred only in vague comparative terms; meaningful collation of results, even from one carcass or chiller to another within the same unit, is impossible.

For this reason, we have placed strong emphasis in the present study on the accurate and continuous monitoring of chilling rate *within the musculature*, and consequently have been able to demonstrate the dependence of tenderness on chilling rate in a single relationship, despite intentionally wide variations in carcass fatness and air cooling power. Of more practical significance, however, is the quite unexpected finding that the greatest influence of temperature on tenderness is that which is exerted during the first two or three hours post mortem, when there is no possibility at all of cold shortening.

EXPERIMENTAL

Ten half-sib Angus steers, all about 15 months of age and in similar condition, were divided into two equal groups. The first, of mean liveweight 387 kg, was designated 'fat' (F) because of the *ad libitum* diet of corn and corn silage the animals would receive during the next six months; the second, 'lean' (L), of mean weight 393 kg, would be fed alfalfa hay for the same period in sufficient quantity to permit limited growth while maintaining trimness. Mean daily gains during the six months were 1·00 kg (F) and 0·20 kg (L).

All animals were slaughtered after 170–190 days of this differential feeding. Carcass data (Table 1) indicate that major differences existed in all measured characteristics except maturity score. About 40 minutes post mortem, the unshrouded sides were moved to one of two coolers; all right sides were subjected to −2 °C air moving at 90 m/min ('rapid', R), and all left sides were exposed to 9 °C air without forced-air movement ('slow', S). A thermocouple, connected to a Honeywell–Brown recorder, was inserted into the middle of each *longissimus* muscle opposite the 12th thoracic vertebra to monitor temperature changes.

At 7·5 hours post mortem, each left side was transferred to the −2° cooler to prevent excessive microbial growth. (This transfer is responsible for the points of inflexion seen in two curves of Fig. 1: prominent in LS and just perceptible in FS.) At 24 hours post mortem, the thermocouples were removed and all sides were moved to

TABLE 1
DESCRIPTION OF CARCASSES

|	Lean group	Fat group
Liveweight (kg)	429 ± 13*	569 ± 34
Hot carcass weight (kg)	242 ± 13	367 ± 27
Fat thickness at 12th rib (cm)	0·5 ± 0·1	2·6 ± 0·7
Loin eye area at 12th rib (cm²)	67·2 ± 9·6	83·5 ± 10·6
Estimated kidney, heart and pelvic fat (%)	1·3 ± 0·4	3·7 ± 0·4
USDA yield grade	2·0 ± 0·3	4·7 ± 0·7
Maturity score	A	A Slightly
Marbling score	Small ± one degree	Abundant ± one degree
Extractable fat in longissimus (%)	4·6 ± 0·9	10·1 ± 4·0
pH of longissimus, 48 hours post mortem	5·53 ± 0·05	5·38 ± 0·06

* Mean ± standard deviation.
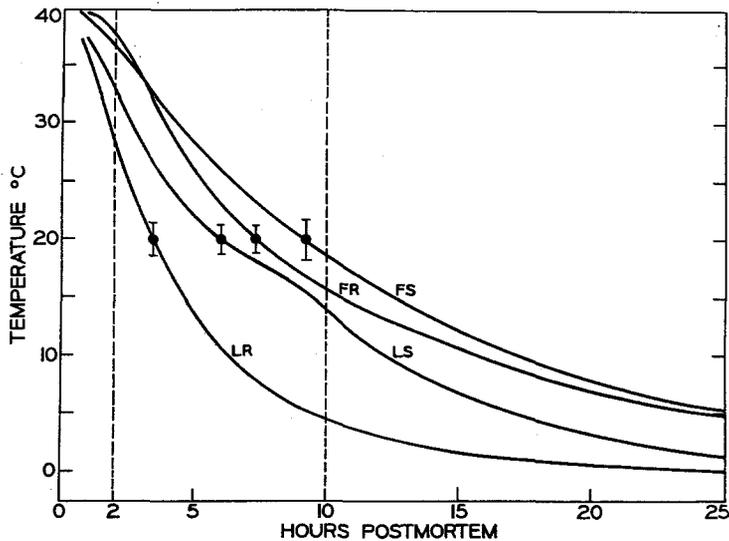
Fig. 1. Cooling curves of *longissimus* muscles during chilling of beef. F and L: sides of fat and lean carcasses, respectively. R and S: rapid- and slow-chilling conditions, respectively. Vertical bars: standard deviations when mean group temperatures attained 20° (*n* = 5 for each group). See text for further details.

a 3° cooler, where they were ribbed and evaluated for USDA quality and yield grades. At 48 hours post mortem, small samples were taken from each *longissimus* muscle for later determination of sarcomere length and pH. A larger (25 cm) section of the cranial end of the short loin was also cut from each side, wrapped and left at 3° for an additional 48 h before being frozen and stored at −20° until required for taste panel evaluation, shear testing and fat estimation.

Sarcomere lengths were measured on the small sample, using $20 \mu m$ frozen sections stained with Harris haematoxylin. Twenty-five randomly selected myofibrils from each *longissimus* muscle of every side were measured by eyepiece micrometer. Five grammes of each muscle from every right side were blended in 25 ml of distilled water for determination of 48-h pH, to verify that differential feeding had not drastically altered glycogen reserves.

For taste panel evaluation, nine steaks, 2·5 cm thick, were cut from each short loin. After bone and subcutaneous fat removal from the most cranial steak (corresponding to the 13th thoracic vertebra), the *longissimus* muscle was homogenised and analysed for total intramuscular ether-extractable lipid (AOAC, 1965). The remaining steaks were thawed at 3° and oven-broiled to an internal temperature of 70° (thermocouple). The second and ninth steaks were cooled to room temperature and cores of 2·5 cm diameter were removed from medial, central and lateral sites for shearing in a Warner–Bratzler apparatus. From each remaining cooked steak, still hot, five 2·5-cm cores were removed for subjective evaluation; tenderness, juiciness, flavour intensity and overall desirability were assessed by a thirty-member semi-trained taste panel. Each judge at every session evaluated paired samples (i.e. from left and right sides) of each of two carcasses. All parameters were evaluated on a ratio-scaling seven-point ballot.

Statistical treatment followed the procedures of Steel & Torrie (1960).

<div align="center">RESULTS</div>

Chilling rate

The rates of temperature decline in the four treatment groups are summarised in Fig. 1. To indicate the quite small variations within the groups, standard deviations have been included in the figure, each calculated for the time at which the mean temperature of the group ($n = 5$) attained 20°; unavoidable slight differences among carcasses and minor imprecisions in the siting of thermocouples were presumably responsible for the spread of values. By contrast, imposed differences in carcass characteristics (L versus F) and in air chilling power (R versus S) clearly produced major effects on chilling rates among the four groups. At 30°, for instance, the LR sides were cooling at almost twice the rate of their LS counterparts and at appreciably more than twice the rate of the FR sides. While the ranking of these rates could perhaps have been predicted in general terms (although probably with some

confusion of the two intermediate rates), the direct and quantitative 2×2 comparison of this study reveals the true magnitude of the rate differences. It also stresses the great influence of carcass size or fatness on cooling rate—large enough, in fact, to more than overcome the considerable disparity in air cooling power that existed between the two chillers used in the study. The same influence is well illustrated by the comparative effects of transferring the two groups of slowly chilled sides to a fast chiller at seven-and-a-half hours post mortem; the temperature response to this sharper cooling rate is very prominent in the LS curve, but is barely detectable in the FS curve because of the enhanced temperature-buffering capacity of the larger and fatter sides. Carcass characteristics are thus at least as important in determining muscle cooling rate as the temperature and velocity of the chiller air.

A small and not entirely consistent anomaly is to be noted in the early stages of chilling the fat sides. It would be expected that the FR temperature would be lower than that of the FS sides throughout the chilling process, but this was found in only one of the five comparisons, the net result being a mean 2-h temperature difference (FR–FS) of almost $+1°$ instead of a more probable negative difference. This discrepancy may be due to the asymmetrical placement on the carcass of kidney and pelvic fat, which is looser and tends to hang lower on one side than on the other. Although the effect is small, it is to be noted that it occurs in the high temperature range, where the temperature coefficient of glycolysis is high (Marsh, 1954); thus a difference of only a degree or two in the region of $37°$ or higher might exert a quite profound effect on the progress of rigor onset.

Sarcomere length

Table 2 shows that the *longissimus* muscles of the fastest cooling sides, LR, had significantly shorter sarcomere lengths at 48 hours post mortem than those of the other three groups. This is in line with the earlier observations (Fig. 1) that the LR sides reached the potentially cold shortening temperature region much more quickly than those of the other groups. If $10°$ is assumed to be the practical upper limit of detectable cold shortening, then groups LR, LS, FR and FS entered the possibly hazardous zone at about 6, 12, 16 and 17 hours post mortem, respectively. Applying

TABLE 2
SARCOMERE LENGTHS OF *longissimus* MUSCLES FROM THE
FOUR TREATMENT GROUPS

Group	Sarcomere length*
Lean, rapid chill (LR)	1.72 ± 0.08^a
Lean, slow chill (LS)	1.98 ± 0.08^b
Fat, rapid chill (FR)	1.85 ± 0.14^b
Fat, slow chill (FS)	1.94 ± 0.10^b

* Mean $\pm$ standard deviation.
[ab] Values with different superscripts differ significantly ($p < 0.05$).

the temperature coefficient data of Marsh (1954) to the cooling curves, we find (assuming an initial pH of 7·0) that only the LR group could have attained 10° while it was still sufficiently pre-rigor to respond by shortening (calculated pH 6.2 or higher at 6 hours post mortem). Even the next fastest (LS) group would have virtually reached its ultimate pH by the end of the 12-h period needed to attain this temperature and the two F groups would have been fully in rigor within 5–7 hours post mortem, long before their temperatures were low enough to induce shortening. So far as early-postmortem length changes are concerned, therefore, our observations conform with the results of earlier work on cold shortening and its dependence on both temperature and time post mortem (Locker & Hagyard, 1963; Marsh & Leet, 1966).

Quality evaluation

The results of organoleptic and shear value testing of steaks from all twenty sides are shown in Table 3. The correlation between panel tenderness and shear value was −0·74. Subjective and objective tenderness data supported each other completely; by both assessment methods the order of improving tenderness was LR, LS, FS and FR. The panel also demonstrated smaller but still significant improvements in juiciness in the order LR, LS and FS = FR, and in flavour (LS < LR < FS = FR), while in overall desirability the lean groups were considerably inferior to the fat groups, regardless of chiller treatment.

TABLE 3
PANEL EVALUATION AND OBJECTIVE ASSESSMENT OF BROILED STEAKS

Treatment group[1]	Tenderness[2,3]	Juiciness[2,3]	Flavour intensity[2,3]	Overall desirability[2,3]	Shear value[4]
LR	2·59[a]	3·49[a]	3·97[a]	3·75[a]	8·8 ± 1·7[a]
LS	2·95[b]	3·70[b]	3·74[b]	3·60[a]	7·4 ± 1·9[b]
FR	4·08[c]	4·19[c]	4·15[ac]	4·53[b]	6·2 ± 1·5[c]
FS	3·81[d]	4·03[c]	4·24[c]	4·61[b]	6·7 + 2·0[c]
LSD[5]	0·25	0·20	0·20	0·22	

[1] Five sides per group.
[2] Thirty panelists per side.
[3] Scale: 1 = very tough, dry, bland, undesirable; 7 = very tender, juicy, pronounced, desirable.
[4] Warner–Bratzler, kg/cm², 2·54 cm cores, Mean ± standard deviation; 3 cores per steak, 2 steaks per side.
[5] Least significant difference (5%).
[abcd] Within each column, values with no common superscript differ significantly.

When attempts are made to relate these tenderness results to the sarcomere length measurements already presented, a quite serious descrepancy arises. If shortening (as indicated by partly contracted sarcomeres) were the sole or principal determinant of tenderness, we might expect from Table 2 that the LR group would be relatively tough and the other three reasonably tender; instead, the LS group is much closer in tenderness to the LR group than to the other two. A direct plot of

mean group sarcomere length against mean group panel tenderness or shear value, indeed, indicates that, if tenderness is determined by shortening, it should be maximal at intermediate lengths, say 1·8–1·9 μm, falling off steeply on each side of this value (Fig. 2). Such a suggestion receives no support at all from previous studies of the tenderness/shortening relationship. At least for the *longissimus* muscle during its normal cooling *in situ*, therefore, we are forced to question the supposition that the extent of cold shortening is a major determinant of beef tenderness.
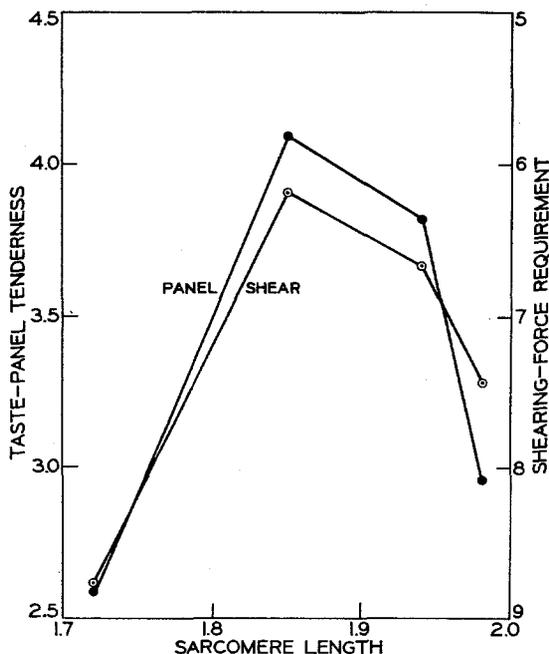

Fig. 2.   Apparent influence of sarcomere length on panel tenderness and shearing force requirement. See Tables 2 and 3 for further details and statistical treatment.

The discrepancy is demonstrated more clearly when attempts are made to relate tenderness results directly to observed chilling rates. An appropriate inverse measure of the latter variable is the temperature attained within the muscle at a particular time post mortem, and we have selected 10 h as a suitable time for two reasons: three of the treatment groups are obviously at much higher temperatures after 10 h than the fourth (Fig. 1), and (as mentioned earlier) a potentially critical temperature of 10° lies between the two clusters. Thus, if cold shortening is a significant factor in determining beef tenderness under practical conditions, we might anticipate that tenderness would correlate highly with 10-h temperature, a linear or simple curvilinear relationship extending from the tougher meat of the LR sides to the much more tender meat of the sides of the other three treatment groups.

At first sight, these two variables do indeed appear to be highly related; the correlation coefficient of 0·66 (n = twenty sides) suggests a strong dependence of tenderness on cold shortening impetus. Closer examination, however, reveals that the coefficient is spuriously high because it is based on two rather widely separated families of points (Fig. 3); the five LR values on the one hand lie within the 10-h temperature range of 2·8–6·6°, whereas the fifteen values of the remaining three groups are all in the range 13·1–20·3°. Within each of these quite narrow but very
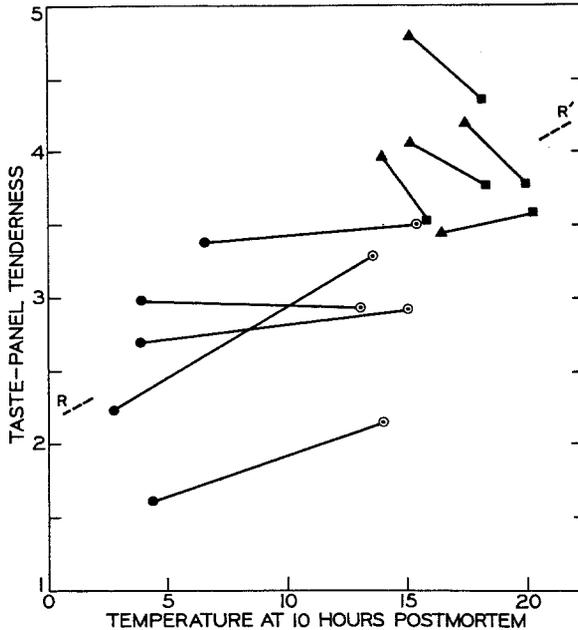

Fig. 3.   Panel tenderness in relation to 10-h *longissimus* temperature. Lines connect values for paired sides. R———R′: line of regression of tenderness on temperature. ● LR; ⊙ LS; ▲ FR; ■ FS.

distinct families, taste panel scores cover a wide range: almost 1·8 units in the former and more than 2·6 units in the latter. That the correlation is, in fact, a very poor one is emphasised by the lines connecting the values obtained on paired sides. There is a very appreciable 10-h temperature difference between the two groups of lean sides (LR mean 4·3°, LS mean 14·2°), the temperature at this time lying on opposite sides of, and well removed from, the 10° mark; yet the mean tenderness difference between the groups is small (LR 2·6, LS 3·0). In sharp contrast, the very small difference in 10-h temperature between the unpaired LS (14·2°) and FR (15·6°) groups is associated with a large difference between group tenderness scores (respectively 3·0 and 4·1) that clearly has nothing to do with cold shortening. Finally, the moderate 10-h temperature difference between the paired sides of the fat

carcasses (FR 15·2°, FS 18·5°) is apparently responsible for a tenderness difference *in the opposite direction* (FR 4·1, FS 3·8). Except perhaps for the small tenderness difference (and accompanying difference in sarcomere length) between the LR and LS sides, the results presented to this point offer no evidence at all to support the concept that chilling rate or cold shortening exerts a significant influence on the tenderness of beef as prepared in a normal commercial operation. Indeed, if the analysis of our data could be taken no further, we would be forced to conclude that the very considerable and well recognised tenderness difference between lean and fat cattle is totally unrelated to chilling rate.

Initial chilling rate

Because temperature monitoring was continuous, it has proved possible to seek relationships between tenderness and chilling rate over a wide range of time intervals. This extended analysis has revealed a quite unexpected and potentially important effect. As progressively shorter postmortem periods are considered, the correlation between panel tenderness and muscle temperature improves appreciably: $r = 0·66$ at 10 and 8 h, 0·72 at 6 h, 0·76 at 4 h and 0·78 at 2 h. Still closer to the time of slaughter, the correlation declines ($r = 0·67$ at 1 h). In contrast to the 10-h relationship (Fig. 3), in which r was falsely elevated by a polarisation of points into two distinct groups, a plot of tenderness against 2-h temperature (Fig. 4) results in a
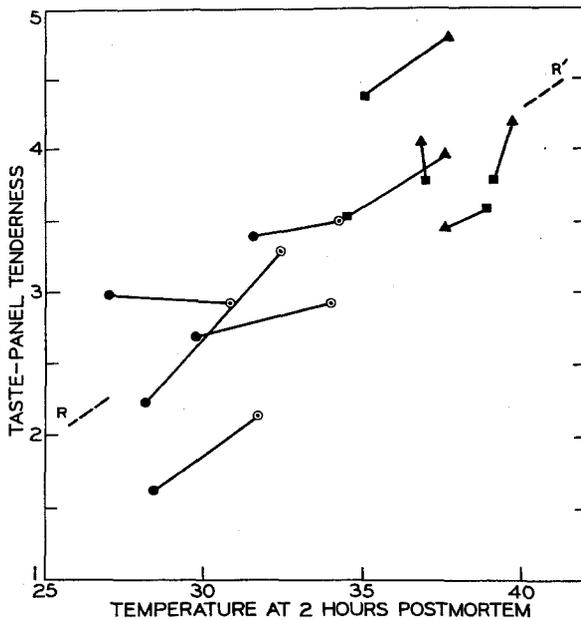

Fig. 4.   Panel tenderness in relation to 2-h *longissimus* temperature. Symbols as in Fig. 3.

fairly even distribution of values throughout the entire range of observed temperatures (27·0–39·8°). Furthermore, the overall picture of a steadily rising panel score with increasing 2-h temperature is seen to apply also to individual pairs of sides; in eight of the ten carcasses, the same general relationship holds true and the two minor exceptions are within the possible experimental error of the panel estimate. A measure of the extent to which the individual pairs conform to the overall trend is obtained when a score for one side of each pair is calculated from that of the other side, using the regression line slope of Fig. 4 (R-R', 0·155 panel unit per °C) and the 2-h temperature difference between the sides. The mean difference (±SD, $n = 10$) between the calculated and the observed scores was $0·10 \pm 0·32$, a value clearly not differing significantly from zero. Thus, although the tenderness ranges of the lean and fat sides do not overlap, the fact that the overall trend is a composite of individual trends provides strong evidence that tenderness score is very highly related to (and perhaps determined by) the 2-h temperature. In sharp contrast, the same procedure applied to the 10-h temperatures, using the regression line slope of 0·093 (R-R', Fig. 3), leads to a mean difference of $0·55 \pm 0·29$, which is very significantly different from zero; the overall trend in this case is certainly not a reflection of the trends seen in separate pairs of sides. The relationships between tenderness score and both 2-h and 10-h temperature are shown in Fig. 5, using treatment group means for both variables to simplify interpretation and to emphasise the great difference in linearity between the two sets of data.

The slope of the regression line, 0·155, should be a measure of the tenderness difference between sides that differ by one degree in their 2-h temperatures. Two of the carcasses, the most tender and the most tough, lie somewhat away from the line
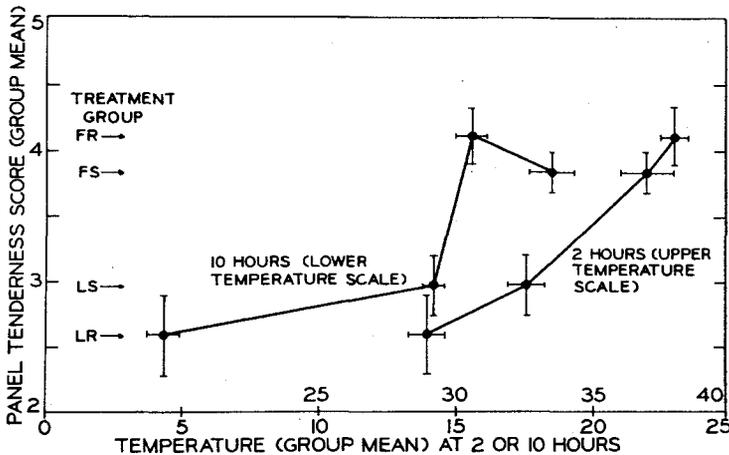

Fig. 5. Panel tenderness in relation to both 2-h and 10-h temperature, using mean values to emphasise the difference in linearity between the two correlations. Vertical and horizontal bars: standard errors ($n = 5$).

of best fit and may be exerting a disproportionate influence on the gradient; omission of these values leads to a possibly more realistic slope of 0·11 panel units per degree. Even this reduced value is remarkably large, particularly when it is noted that a 2-h temperature difference of almost 13° was observed between the slowest cooling fat side and the fastest cooling lean one, both of them exposed to the same rapid (R) chill. It seems not at all unreasonable to expect 2-h temperature differences of at least this magnitude (and perhaps much greater) in normal commercial operations, where carcasses may differ greatly in size and fat cover and wide variations in efficiency are found among chillers.

DISCUSSION

To prevent spoilage and meet regulatory requirements, the severity of chilling in commercial operations must be geared to the needs of the biggest and fattest animal likely to be encountered. A cooling rate that is adequate for heavy and well insulated carcasses will obviously be more than adequate for those that are smaller and/or leaner, the extent of this 'overchill' increasing markedly with decreasing carcass size and finish. Thus the question arises (Marsh, 1974): could the generally recognised greater tenderness of well finished cattle be due largely to slower carcass cooling, rather than to some unspecified inherent quality of intramuscular or subcutaneous fat? The hypothesis carries the implication that toughness due to lack of finish might be at least partly counteracted by appropriate manipulation of cooling conditions during the early-postmortem period, and was the principal reason for initiating the present investigation.

Many studies have shown that a less rigorous early chilling usually results in significant tenderness improvement, but they were not designed to address the specific question posed above. A more quantitative answer is needed if the practical value of this concept is to be assessed. It is not enough merely to demonstrate that a less severe chilling of lighter or less well finished carcasses enhances tenderness; it is also necessary to ascertain the extent of this enhancement *relative to that produced by regular chilling of fatter carcasses.*

Surprisingly few studies have been undertaken to examine the intermediary role that muscle cooling rate may play in accounting for the fatness:tenderness relationship. In a quite elegant investigation of the effects of subcutaneous fat thickness on lamb tenderness, Smith et al. (1976) showed that tenderness increased significantly with increasing fat cover and the slower cooling rate that this greater insulation caused. The experimental results of Merkel & Pearson (1975), although not revealed in their paper, suggested to its authors that 'the major differences in tenderness between "fat" higher-grading and "thin" lower-grading beef are due to the effects that fat, including marbling, has on slowing down the rate of heat dissipation during carcass chilling'. On the other hand, Bowling et al. (1977) detected only a

small and non-significant improvement in subjective tenderness when forage-finished beef was subjected to a high-temperature chilling routine in place of the more orthodox early-postmortem treatment, the meat remaining distinctly inferior to that of conventionally chilled, grain-finished animals.

In the present study, the lean carcass chilling rate was not retarded to that of either of the fat groups, so the tenderness of the lean carcasses could not be expected (on the tenderness/temperature hypothesis) to attain that of the fatter animals. Nevertheless, the high correlation observed between the two parameters and the near linearity of the relationship (Figs. 4 and 5) strongly suggest that retardation of temperature decline is a major reason for the greater tenderness of the better insulated carcasses. The closeness of the relationship is all the more remarkable when the wide variability among the animals is considered: carcass weight 227–397 kg, fat cover 0·4–3·3 cm, marbling slight to abundant, muscle fat content 4·1–15·2 % and yield grade 1·6–5·5. The results justify a definite and positive answer to our earlier question; the greater tenderness of well finished cattle could indeed be due to slower carcass cooling, and (in our view) almost certainly is. Fatness is then seen to influence tenderness primarily (and perhaps only) because its extent largely determines the time–temperature profile during the first few postmortem hours; it is the temperature in this period that is of major significance.

In recent years, the term 'early-postmortem' has been used as a synonym for 'pre-rigor' or 'before rigor completion', connoting the first 10–24 h following death. Clearly, we are not referring to such a wide time interval in the present work, for our results indicate that it is the first two to four hours after slaughter that are of overriding significance in relation to the temperature influence on tenderness. We therefore propose the term 'very early-postmortem' (VEP) to refer to this brief period immediately following death.

For two reasons, our results give a clear indication that the considerable tenderness improvement caused by VEP chilling retardation is not due primarily to cold shortening prevention. First, significantly greater shortening was detected in the LR group than in the paired LS group, yet the mean tenderness difference between the two was small; by contrast, the very appreciable difference in tenderness between the LS and FR groups was not accompanied by any difference at all in shortening. Secondly, the great superiority of the correlation and linearity of the tenderness/temperature relationship at two hours over that at ten hours is very strong evidence that cold shortening is, at most, of minor importance, for the temperatures encountered at two hours post mortem (roughly 27–40°) were far removed from the cold shortening region.

The procedures used in this study did not differ significantly from those of normal commercial practice, with the sole exception of thermocouple insertion. No unusual treatments were applied, either before or after slaughter; even the temptation to remove small samples of muscle for ATP or pH determination was resisted, lest cutting should provoke accelerated glycolysis or greater shortening. The ranges of

carcass size and fatness and of imposed cooling rates, although wide, did not exceed those often observed in meatworks chillers. There seems no reason, therefore, to limit our findings to laboratory scale operations, and it is justifiable to rephrase them in terms that are more obviously relevant to the meat industry: the tenderness superiority of well finished over poorly finished beef is due largely to differences in cooling rate, but only rarely is it due to differences in cold shortening.

This conclusion does not call into question the great toughening effect of cold shortening in certain rather special situations. It does not deny, for instance, that excised muscles, free to shorten during early-postmortem cooling, are much tougher than those that are restrained either at their initial lengths (Marsh & Leet, 1966) or in a stretched state (Herring et al., 1965). Nor does it rule out the possibility of some degree of shortening-induced toughening in very lightweight, lean beef that is exposed to rapid and early-postmortem chilling. It does, however, relegate shortening to a quite minor role as a toughening mechanism in beef of reasonable size and finish under normal commercial conditions. It also indicates that the mere imposition of a slower cooling rate on poorly finished carcasses will eliminate shortening but will not greatly improve tenderness (compare treatments LR and LS) unless a near-physiological temperature is maintained in the musculature during the VEP period.

The results of Herring et al. (1965) are relevant to this discussion. Using longitudinally halved bovine *semitendinosus* muscles that were rapidly chilled after early-postmortem excision, the authors noted that muscles permitted to cold shorten were much tougher (by an average of 1·8 panel units) than those held in a stretched condition. The effect of cold shortening on tenderness was thus clearly demonstrated under conditions of rapid temperature decline. However, comparison of their Tables I and III reveals important additional information; the excised stretched muscles, in turn, were much tougher (by 1·7 units) than the contralateral muscles that had been left on the carcass until 48 hours postmortem, despite their somewhat greater sarcomere length. This result (for which no explanation could be offered at the time) is entirely consistent with our present studies and in fact adds strong support to them, for the muscles that remained *in situ* during chilling obviously cooled much more slowly than those that were excised. The early postmortem temperature influence on tenderness, uncomplicated by shortening into the potentially toughening region, was thus very appreciable and highly significant.

There have been other indications in recent years that toughness and shortening are not tightly coupled in all circumstances. Locker & Daines (1976) showed that bovine *sternomandibularis* muscles, cold shortened for 24 h at 2° and then exposed to 37° for 3 h, were only about half as tough as control muscles held continuously at 2°, despite almost identical length changes in the two treatments. Culler et al. (1978) found that sarcomere length of myofibrils from loin steaks of conventionally handled carcasses was not significantly related to tenderness. Parrish et al. (1979) reported significant tenderness differences between loin steaks differing appreciably

in fat thickness (and hence in early-postmortem cooling rate) but not in sarcomere length. Dutson *et al.* (1975) found that a 12-h 'elevated-temperature' treatment (unspecified) resulted in improved tenderness that could be only partly explained by cold shortening suppression. Moeller *et al.* (1976) showed that 22° conditioning for four hours, followed by 12° treatment for eight hours, enhances the disruption of the lysosomal membrane, liberating cathepsin-C and β-glucuronidase. Dutson *et al.* (1977) summarised further evidence supporting the view that lysosomal enzyme release, as well as cold shortening reduction, may be responsible for the tenderness improvement noted when higher temperatures prevail during rigor onset. Our results take this assessment a step further, eliminating cold shortening as a really significant cause of beef toughness except perhaps in the most extreme cases of exceptionally rapid chilling applied almost immediately post mortem.

Viewed in this light, the frequently reported improvement brought about by higher chiller temperatures is seen to be due, not to the maintenance of temperatures above the cold shortening range for the first 10–12 hours post mortem, but rather to the retarded decline of temperature during the first 2–4 h. This is by no means a merely pedantic differentiation of effects, for 2-h and 10-h temperatures, in general, are not tightly coupled. In the present study, for instance (Fig. 1), the mean difference in temperature between the LR and LS groups increased from 3·8° at 2 h to 9·9° at 10 h, whereas that between the LS and FR groups *decreased* from 5·0° at 2 h to only 1·4° at 10 h.

It is of interest that the tenderising effect of early postmortem heat treatment was claimed over 30 years ago. Roschen *et al.* (1950) patented a process in which the freshly killed and dressed beef carcass was 'held at a temperature of approximately 98·6 °F ... for approximately 4 to 5 hours' before commencement of normal chilling.

The present recognition (or rediscovery) of the great influence of VEP temperature on tenderness and of the virtual insignificance of later temperature takes us nearer to a complete understanding of the greater tenderness of fatter carcasses. It is now clear that the superior eating quality of the fatter animal is caused, not by the prevention of cold shortening, but by an as-yet unidentified mechanism that is promoted by the maintenance of near physiological temperatures during the first 2–4 h after slaughter. Logical extension of this conclusion leads quite simply to the prediction that the tenderness of lean beef should be enhanced appreciably by application of a high-temperature, short-time heat treatment, thereby simulating the VEP 'natural' slow initial cooling of larger and fatter sides. Preliminary results of studies to test this hypothesis fully justify this prognosis.

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