Preslaughter stress and muscle energy largely determine pork quality at two commercial processing plants

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ABSTRACT: The objective of the present experiment was to study physiological changes elicited in response to stress in the immediate preslaughter period and to link them to pork quality characteristics. Crossbred, halothane-free pigs (n = 192) were processed in eight groups (24 pigs per group) on various days at one of two commercial processing plants operating different stunning systems (electrical and CO_2 stunning in Plants A and B, respectively). In each group, half the pigs were exposed to either minimal or high preslaughter stress. Blood samples were taken at exsanguination, and lactate, cortisol, and catecholamines, as well as blood pH and temperature, were assessed and linked to various longissimus muscle quality attributes. Additionally, muscle pH and temperature were measured 30 min postmortem, and muscle glycolytic potential was determined 22 h postmortem. At both processing plants, high preslaughter stress resulted in higher ($P < 0.05$) blood cortisol and lactate; however, the effects of preslaughter stress on catecholamines and blood pH were believed to be biased by the different stunning methods employed at the plants. High preslaughter stress increased ($P < 0.05$) blood temperature at Plant A but not at Plant B. At both plants, high stress increased ($P < 0.05$) 30-min muscle temperature and decreased ($P < 0.05$) 30-min muscle pH. Ultimate pH was increased ($P < 0.05$) and muscle glycolytic potential was decreased ($P < 0.05$) by high preslaughter stress. At both plants, high stress resulted in inferior pork quality attributes ($P < 0.05$), including reflectance, electrical conductivity, filter paper moisture, drip loss, and L* value. The effect of stress was greater on water-holding capacity than on pork color, with drip losses increased by 56%. Of all stress indicators measured at exsanguination, only blood lactate was strongly correlated with pork quality attributes. Regression analyses revealed that blood lactate and glycolytic potential accounted for 52 and 48% of the variation in drip loss and L* value, respectively. In combination with high preslaughter stress, high glycolytic potentials were related to increased drip losses. We conclude that high preslaughter stress leads to impaired pork quality, with high muscle energy levels aggravating the negative effects of preslaughter stress. Monitoring stress level by blood lactate measurement in combination with strategies to control muscle energy present at slaughter may help to improve meat quality.

Key Words: Glycogen, Lactate, Meat Quality, Pigs, Stress, Stunning

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Introduction

Pale, soft, and exudative (PSE) pork and red, soft, and exudative pork cause economical losses for the pork industry. It is widely accepted that stress immediately before slaughter plays a crucial role, even with stress-resistant breeds (Warriss et al., 1994; van der Wal et al., 1999; Channon et al., 2000). Stress may increase the temperature and rate of pH decline in the carcass early postmortem, resulting in characteristic PSE pork (Briskey, 1964; Offer and Knight, 1988). However, pH and temperature measured at 30 to 45 min postmortem do not sufficiently explain variation in meat quality (Kauffman et al., 1993; van der Wal et al., 1995b; Hambrecht et al., 2003).

Seldom a direct causal relationship has been established between the stress level of individual pigs and the resulting meat quality. Most experiments studying preslaughter stress have either not considered meat quality (Troeger, 1989; Weeding et al., 1993; Hartung et al., 1997) or have not measured variables directly related to stress (van der Wal et al., 1999; Channon et al., 2000). Warriss et al. (1998) found low, or no,

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correlations between selected blood-based stress indicators and meat quality in a survey under commercial circumstances. In that study, however, no further information on the handling history or on the background of the pigs was taken into account. Therefore, the aim of this study was to establish a link between pork quality and various physiological variables and to select the variables that show potential to serve as monitoring tools for controlling preslaughter stress levels.

Materials and Methods

The experimental protocol was approved by the Animal Care and Ethics Committee of the University of Nijmegen, The Netherlands.

Animals and Experimental Design. All pigs were commercial, halothane-free crossbreeds with an average hot carcass weight of 89.4 kg and a lean percentage of 55.5 measured by the Hennessey Grading Probe. Gilts and barrows were equally distributed across treatments and randomly assigned to either minimal or high preslaughter stress before transportation to one of two commercial pork processing plants (A or B). Four groups (24 pigs per group) were used, resulting in 48 pigs/treatment at each plant. Every slaughter group originated from a different commercial farm and was processed either Plant A or B.

Preslaughter and Slaughter. All farms were located near (<35 km) the respective processing plant. Depending on time of arrival, pigs were held in lairage for 3 to 8 h before slaughter at 0630. Experimental stressor treatments were begun approximately 5 min before slaughter. Pigs in the minimal stress group were guided to the stunning area without the use of electric goads and were handled as calmly as possible, whereas pigs in the high-stress group were forced, by yells and electric goads, to move four times back and forth in the corridor leading to the stunning area. At Plant A, pigs were electrically stunned in a fully automated, head-to-heart stunning system (MIDAS, Stork, The Netherlands), whereas at Plant B pigs were stunned by carbon dioxide (COMBI88, Butina, Denmark). Carcass dressing and fabrication processes were similar at both plants.

Sampling Procedures and Chemical Analyses. At exsanguination, from each pig two blood samples (2 × 9 mL) were collected in heparinized tubes (Monovette LH; Sarstedt, Nümbrecht, Germany) for cortisol and lactate determination, or collected in tubes containing EDTA (Monovette EDTA KE; Sarstedt) for catecholamine determination. Blood samples were immediately put on ice and centrifuged for 10 min at 1,300 × *g* within 1 h after sampling. Plasma (0.5 mL) was transferred to Eppendorf tubes, and stored at –80°C until analysis. Plasma cortisol concentrations were determined using a solid-phase RIA kit (Coat-a-Count Cortisol TKCO; Diagnostic Products Corporation, Apeldoorn, The Netherlands). Plasma lactate concentrations were determined using a blood analyzer (ABL 605; Radiometer Nederland BV, Zoetermeer, The Netherlands). Additional plasma samples were analyzed for epinephrine and norepinephrine by HPLC with electrochemical detection procedure described by Smedes et al. (1982).

For determination of the glycolytic potential, muscle samples were taken from the longissimus muscle at the fourth lumbar vertebra, rapidly put on dry ice, and stored at –80°C until analysis. According to Maribo et al. (1999), there is no difference in glycolytic potential irrespective of sampling immediately after exsanguination or 30 h postmortem. Sampling the day after slaughter is more practical and hygienic, and, therefore, it was chosen for the removal of muscle samples at 22 h postmortem. Muscle lactate, glucose, and glycogen were extracted by homogenizing the samples in 0.6 *M* perchloric acid. After centrifuging the suspension for 10 min at 1,500 × *g*, the supernatant was neutralized with 5 *M* KOH. The formed potassium perchlorate was removed by centrifugation for 10 min at 1,500 × *g*. Glucose and lactate concentrations were measured using commercially available kits (NR115 and NR826B for glucose and lactate, respectively; Sigma-Aldrich Chemie BV, Zwijndrecht, The Netherlands). Assays were adjusted for measurement in microtiter plates. Glycogen was enzymatically hydrolyzed to glucose with amyloglucosidase (A7420; Sigma-Aldrich Chemie BV) according to procedures outlined by Passoneau and Lowry (1993). The glycolytic potential was calculated as the sum of 2 × ([glycogen] + [glucose-6-phosphate] + [glucose]) + [lactate] (Monin and Sellier, 1985).

Measurements. At exsanguination, pH and temperature were measured in blood with a portable pH meter (Portamess 911 pH; Knick Elektronische Messgeräte, Berlin, Germany) equipped with a probe-type glass electrode (LoT406; Mettler Toledo, Greifensee, Switzerland) and a portable thermometer (Hand Held Digital Thermometer; Stekon, Hoofddorp, The Netherlands). At 30 min postmortem, pH and temperature were measured in the LM at the level of the third lumbar vertebra, whereas ultimate pH was measured at the same site at 22 h postmortem. The day after slaughter (22 h postmortem), final meat quality measurements were collected in the same region of the LM, except for pork color. Objective color (L*, a*, and b*) was measured on a freshly cut surface at the height of the last lumbar vertebra after a 10-min blooming period with a Minolta Portable Chroma Meter (model CR 210; Minolta, Osaka, Japan) equipped with a 50-mm aperture and using illuminant D65. Internal light scattering was measured using the Fiber Optic Probe (TBL Fibres, Leeds, U.K.), and electrical conductivity was measured using the LF-Star (Ingenieurbüro Matthäus, Nobitz, Germany). Water-holding capacity of the LM was measured by two methods. A filter paper (45-mm diameter) was weighed, gently pressed on the caudal cut surface of the LM for 10 s, and subsequently reweighed to determine the absorbed moisture content. Additionally, a slice of the LM was placed with a cut surface facing down on a metal grid that was placed in a closed plastic

Table 1. The effect of preslaughter stress level on plasma concentrations of epinephrine, norepinephrine, cortisol and lactate at two processing plants

	Plant A				Plant B			
	Stress				Stress			
Item	Minimal	High	Pooled SE	*P*-value	Minimal	High	Pooled SE	*P*-value
No. of animals	47	45	—	—	49	48	—	—
Epinephrine, ng/mL	69.0	85.2	15.2	0.120	216.4	231.4	34.9	0.363
Norepinephrine, ng/mL	37.7	55.8	8.0	0.004	346.1	338.8	105.8	0.787
Cortisol, ng/mL	67.9	80.8	4.1	0.017	49.5	72.1	7.0	0.001
Lactate, mmol/L	15.6	27.7	1.0	0.001	11.9	21.3	2.0	0.001

container. Drip loss was determined as percentage of weight loss after 24 and 48 h of storage.

Statistical Analysis. Data were analyzed by the mixed-model procedure (PROC MIXED) of SAS (Version 8.02; SAS Inst., Inc., Cary, NC). Least squares means were generated by the LSMEANS statement. Tests of multiple comparisons of LSMEANS were adjusted according to the Tukey-Kramer method to ensure the overall significance level of $P = 0.05$. The model applied for plasma cortisol, lactate, and catecholamines included the fixed effects of stress level and the random effect of slaughter day. Blood hormones and metabolites were analyzed, separately, within plant because CO_2 stunning, as opposed to electrical stunning, caused an inevitable time lag between the onset of the stressor and the moment of blood sampling (3 min from entering stunning equipment until exsanguination). The model applied for temperature and pH measured in blood and the LM, as well as for all pork quality attributes measured in the LM, included the fixed effects of stress level and processing plant, as well as their interaction, and the random effect of slaughter day. After correction for plant effects, equations for prediction of drip loss and pork color (L* value) were developed using PROC STEPWISE with the maximum R^2 option (MAXR). Only equations with significant ($P < 0.05$) variables were used to determine the combination of variables leading to the highest R^2.

Results

Results of analyses of plasma catecholamines, cortisol, and lactate are shown in Table 1. At both plants, high preslaughter stress led to higher ($P < 0.001$) plasma cortisol and lactate concentrations, whereas norepinephrine was increased ($P < 0.01$) in highly stressed pigs when processed at Plant A but not ($P = 0.787$) at Plant B. Plasma epinephrine levels were unchanged ($P > 0.05$) by stressor treatment, regardless of where pigs were slaughtered. Interestingly, cortisol and lactate concentrations were of the same order at both plants, but epinephrine concentrations were two to three times higher, and norepinephrine levels six to nine times higher at Plant B than at Plant A.

Blood and muscle temperature, pH values, and LM glycolytic potential are presented in Table 2. There were stress × plant interactions for blood and muscle temperature ($P = 0.057$ and 0.072, respectively), as well as for blood pH ($P < 0.001$). At Plant A, high preslaughter stress led to a higher blood temperature at exsanguination; however, blood temperature was similar for both stress levels at Plant B. Moreover, temperatures were lower ($P = 0.084$) at Plant B than Plant A. A similar stress × plant interaction ($P < 0.001$) was found for blood pH, with pigs subjected to the high preslaughter stress having lower blood pH values at Plant A, whereas stressor treatments did not alter blood pH at Plant B. Muscle temperatures, on the other hand, were increased ($P < 0.001$) at 30 min postmortem by high preslaughter stress at both plants, but differences between minimal and high preslaughter stress were greater at Plant A than Plant B. At both plants, muscle pH values were lower ($P < 0.001$) at 30 min postmortem in pigs subjected to high preslaughter stress; however, ultimate (22 h) pH values were higher ($P < 0.05$) for pigs of the high-stressor treatment. Even though glycolytic potential values were different ($P < 0.05$) between stress levels, minimally stressed pigs had higher ($P < 0.05$) glycolytic potentials than highly stressed pigs only at Plant A.

Pork quality attributes are displayed in Table 3. Except for redness (a*; $P < 0.01$), no ($P > 0.05$) interactions were observed between plant and stressor level for any pork quality trait. High, compared with minimal, preslaughter stress increased ($P < 0.05$) internal reflectance, L* values, electrical conductivity, filter paper moisture, and both 24- and 48-h drip loss percents. Yellowness (b*) did not ($P > 0.05$) differ between stress levels or plants; however, a* values were lower at Plant B than A ($P < 0.01$) and, additionally, were increased ($P < 0.01$) by high preslaughter stress only at Plant B. Water-holding capacity, as measured by filter paper moisture, was more favorable ($P < 0.01$) at Plant B than A, but both 24- and 48-h drip loss percents and electrical conductivity were similar ($P > 0.05$), regardless of where pigs were slaughtered.

Regression analysis revealed that both lactate and glycolytic potential explained a considerable portion of

Table 2. The effect of plant (P) and preslaughter stress level (S) on temperature and pH of blood (at exsanguination) and in the LM, as well as glycolytic potential of the LM

		Plant							
		A		B			*P*-value		
Item	Stress:	Minimal	High	Minimal	High	Pooled SE	S	P	S × P
No. of carcasses[a]		47	45	49	48	—	—	—	—
Temperature, °C									
Blood		39.6^{x}	40.0^{y}	39.1^{x}	39.2^{x}	0.233	0.004	0.084	0.057
30-min LM		39.7^{xy}	40.9^{z}	39.2^{x}	40.0^{yz}	0.278	0.001	0.121	0.072
pH									
Blood		7.17^{y}	7.03^{x}	6.96^{x}	6.97^{x}	0.072	0.001	0.231	0.001
30-min LM		6.56	6.28	6.62	6.39	0.076	0.001	0.413	0.562
22-h LM (ultimate)		5.55	5.62	5.60	5.64	0.049	0.012	0.555	0.441
Glycolytic potential, μmol/g		137.2	131.0	130.6	128.2	11.49	0.010	0.184	0.261

[a]For 30-min LM pH, n = 38, 43, 47, and 46 per treatment, respectively.
[x,y,z]Within a row, least squares means that do not have a common superscript letter differ ($P < 0.05$).

the variation in drip loss and L*. The equation accounting for the greatest amount of variation in drip loss (R^2 = 0.58) included blood lactate and temperature, glycolytic potential, and LM pH and temperature measured 30 min postmortem (Table 4). For L* value, glycolytic potential alone explained about 32% of the variation, whereas including the variables of blood lactate and LM pH measured 30 min postmortem in the model with glycolytic potential accounted for 50% of the variation in L* values.

Discussion

Effect of Stress on Pork Quality and Blood and Muscle pH and Temperature

Results of this experiment confirm the detrimental effect of stress on meat quality (van der Wal et al., 1999; Channon et al., 2000). The tenet that high temperatures, in combination with low-pH values, in postmortem muscle are responsible for meat quality defects is

Table 3. The effect of plant (P) and preslaughter stress level (S) on pork quality attributes of the LM

		Plant						
		A		B			*P*-value	
Item	Stress:	Minimal	High	Minimal	High	Pooled SE	S	P
No. of carcasses[a]		47	45	47	48			
FOP[b]		34	40	39	43	4.7	0.005	0.592
L* [c]		50.9	52.4	51.2	51.6	0.96	0.040	0.834
a* [cd]		17.9^{z}	17.7^{z}	15.4^{x}	16.1^{y}	0.33	0.100	0.006
b* [c]		6.4	6.3	5.8	5.9	0.22	0.867	0.143
EC, mS[e]		5.9	9.2	6.6	9.0	0.52	0.001	0.685
FPM, mg[f]		89	130	59	100	6.6	0.001	0.006
Drip loss, %[g]								
24 h		1.36	1.90	1.08	1.91	0.292	0.001	0.738
48 h		2.27	2.97	1.90	2.76	1.261	0.001	0.598

[a]For meat color measurements (L*, a*, b*), n = 36, 33, 47, and 48 per treatment, respectively.
[b]FOP = fiber-optic-measured light scattering (higher value is indicative of greater light scattering and paler color).
[c]L* = a measure of darkness/lightness (higher value indicates a lighter color); a* = a measure of redness (higher value indicates a redder color); and b* = a measure of yellowness (higher value indicates a more yellow color).
[d]Stress × plant interaction ($P = 0.007$).
[e]EC = electrical conductivity (a higher value indicates a lower water-holding capacity).
[f]FPM = filter-paper-measured moisture content.
[g]Drip loss percents were calculated after storage at 4°C for either 24 or 48 h.
[x,y,z]Within a row, least squares means that do not have a common superscript letter differ ($P < 0.05$).

Table 4. Single- and multiple-variable prediction equations for drip loss percents after 24 h of storage and lightness (L*) values

		Drip loss, %				Lightness (L*) value		
Item	Equation:	1	2	3	4	1	2	3
R^2		0.32	0.52	0.56	0.58	0.32	0.48	0.50
Intercept[a]		–0.032	–0.048	–0.063	–0.071	–0.201	–0.279	–0.311
Variables[b]								
Blood lactate		0.076	0.076	0.056	0.044	—	0.156	0.120
Blood temperature		—	—	—	–0.213	—	—	—
Glycolytic potential		—	0.041	0.037	0.039	0.156	0.164	0.148
30-min LM pH		—	—	–0.914	–0.976	—	—	–1.969
30-min LM temperature		—	—	—	0.244	—	—	—

[a]The intercept was not different from zero ($P > 0.05$) in any equation.
[b]Variables were corrected for plant effects, and all variables included in each model were significant ($P < 0.05$).

widely accepted (Wismer-Pedersen and Briskey, 1961; Briskey, 1964; Offer, 1991). In agreement, the inferior pork quality observed for the high-preslaughter-stress pigs was associated with an increased temperature and a lower pH at 30 min postmortem. The differences in temperature and pH between high and minimal preslaughter stress could already be measured in blood at exsanguination at Plant A after electrical stunning, but not at Plant B after CO_2 stunning. It is unclear why the high-stressor treatment increased blood temperature and decreased blood pH at Plant A, but not at Plant B, because there is sufficient evidence that numerous different stressors elevate body temperature (Geers et al., 1994; Veum et al., 1979; Judge et al., 1973) and decrease blood pH (Kallweit, 1982; Veum et al., 1979; Judge et al., 1973). However, the lower blood pH level for the minimally stressed pigs at Plant B, compared with Plant A, may be explained by the differing methods of stunning. Forslid and Augustinsson (1988) and Overstreet et al. (1975) showed that inhalation of CO_2 lowers blood pH by the formation of HCO_3^-, which leads to a systematically lower blood pH after CO_2 stunning compared with electrical stunning.

Effect of Stress on Cortisol, Lactate, and Catecholamines

High preslaughter stress, commencing only 5 min before slaughter resulted in higher blood cortisol levels at both plants, which is consistent with other experiments (Becker et al., 1985; Jensen-Waern and Nyberg, 1993). Both physical exercise (Jensen-Waern and Nyberg, 1993; Steinhardt and Lowe, 1985) and psychological stress (Neubert et al., 1996; Fernandez et al., 1994) may increase lactate concentrations. Accordingly, results of the present experiment are consistent with other studies reporting higher blood lactate values as a result of preslaughter stress (Warris et al., 1994; Hartung et al., 1997; Brown et al., 1998). At both plants, a similar stress response could be observed for cortisol and lactate, although effects of the different stunning methods cannot be completely ruled out. Norepinephrine, by contrast, was increased in highly stressed pigs slaughtered at Plant A, but not at Plant B. Moreover, both norepinephrine and epinephrine levels were much higher at Plant B, suggesting a higher stress level in the immediate preslaughter period. This was, however, not confirmed by blood lactate and cortisol levels or by pork quality traits, which were more favorable at Plant B. Results of Althen et al. (1977) and Troeger and Woltersdorf (1991) also suggest that the extremely high catecholamine levels after stunning, particularly after CO_2 stunning, are independent of the stressful events that pigs experience before slaughter, but are the consequence of the act of stunning.

Effect of Stress on Glycolytic Potential

Stress, as applied in the present experiment, was related to physical activity and therefore energy consumption. As a consequence, glycolytic potential (a good approximation of muscle glycogen at slaughter) was reduced by high preslaughter stress. This is in agreement with D'Souza et al. (1998), who observed a decrease in muscle glycogen after application of electric shocks before slaughter.

Relationship Between Stress Indicators and Meat Quality

Blood pH, epinephrine, and norepinephrine were not considered in the regression analysis because they appeared to be influenced more by the stunning system than by the stress experienced before stunning. Although clearly increased by preslaughter stress, cortisol did not contribute to the explanation of variation in either drip loss or pork color. This may be due to the fact that cortisol is raised by long-term stress (e.g., transport and fighting) leading to DFD meat (Warriss and Brown, 1985; Fernandez and Tornberg, 1991), as well as by short-term stress, which is more related to PSE meat. Results of the present experiment are in agreement with studies of Shaw et al. (1995) and Warris

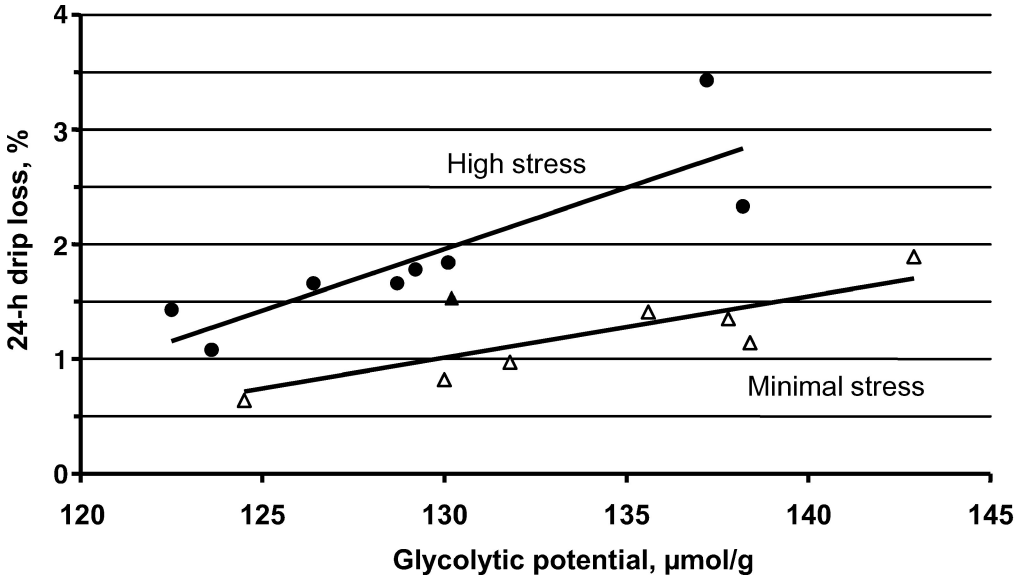

Figure 1. Relationship between glycolytic potential and 24-h drip loss. Each point represents the mean of 12 pigs of the same preslaughter stress level (black circles = high stress and triangles = minimal stress) processed on the same day.

et al. (1998), who could not establish a relationship between cortisol levels and the occurrence of PSE meat.

Variation in glycolytic potential accounted for a considerable portion of the variation in pork quality. Rosenvold et al. (2001b), Schäfer et al. (2002), and Henckel et al. (2002) indicated that the level of glycogen was related to meat quality only if extremely low and/or extremely high levels were found in muscle. Low glycolytic potentials may be caused by energy depletion in response to exhaustive events preslaughter (Fernandez and Tornberg, 1991), whereas extremely high levels are related to the rendement napole (*RN*) gene (Monin and Sellier, 1985; van Laack and Kauffman, 1999). In the present experiment, however, none of the experimental pigs exceeded the value of 180 to 200 µmol/g wet tissue, used to identify *RN* carriers (Fernandez et al., 1992; van Laack and Kauffman, 1999; Miller et al., 2000). Moreover, ultimate LM pH was well below the frequently used limit of 6.0, indicating that muscle energy had not been depleted before slaughter. Although within a normal range of glycolytic potential values, muscle energy had a clear impact on drip loss and on meat color, with low muscle energy levels being associated with lower drip losses and darker pork color. Figure 1 presents the relationship between glycolytic potential and drip loss for the high- and minimal-stress groups. The relationship was clearly distinct for the two stress levels but, nevertheless, followed a similar linear pattern over the range of glycolytic potentials. The differences in results between the aforementioned (Rosenvold et al., 2001b; Schäfer et al., 2002; Henckel et al., 2002) and present studies may be attributed to different experimental conditions. In the present study there was variation in genotype, feed withdrawal, and lairage times between groups of pigs, which possibly influenced muscle energy level at slaughter differently than in experiments with greater control over experimental treatments/conditions designed to reduce animal-to-animal and/or treatment variation (Rosenvold et al. 2001b; Schäfer et al., 2002; Henckel et al., 2002).

The introduction of 30-min LM pH into both the drip loss and L* prediction equations, as well as the introduction of 30-min LM temperature into the drip loss prediction equation, increased R^2 only slightly and changed the regression coefficient of blood lactate. Indeed, blood lactate and 30-min LM pH, and blood lactate and 30-min LM temperature were highly correlated (r = –0.60 and 0.65, respectively; results not shown), indicating that they explain, to some extent, the variation in drip loss and pork color by a similar mechanism (an increase in both antemortem and postmortem metabolism). A major advantage of monitoring stress by blood lactate levels, as opposed to muscle pH and temperature measurements, could be the time of sampling. Blood lactate would not be influenced by poststunning handling, such as shackling, scalding, and singeing; poststunning handling of carcasses can affect muscle pH and temperature commonly measured at 30 or 45 min postmortem (Aalhus et al., 1991; van der Wal et al., 1995a; Maribo et al., 1998).

In contrast to the regression analysis for drip loss, muscle energy accounted for a greater portion of the variation in LM L* values than did either blood lactate or 30-min LM pH. The effect of glycolytic potential on both pork color and drip loss was probably, at least partly, mediated by its relation with ultimate pH (r = –0.71; results not shown). Consequently, the effect of glycolytic potential on pork color can be explained by altered absorption characteristics of myoglobin and reduced light scatter of the meat surface associated with

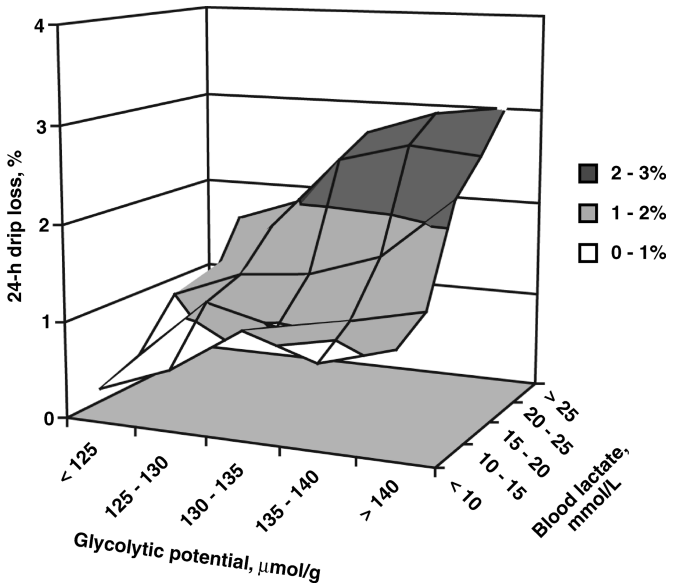

Figure 2. Relationship of the combination of blood lactate and glycolytic potential with drip loss after 24 h of storage. Individual data for lactate and glycolytic potential were grouped into classes. Drip loss values represent the average of all pigs with the respective lactate and glycolytic potential class (n = 3 to 14 pigs per class).

increasing ultimate pH values (Lawrie, 1998). In agreement with the results from the present study, Rosenvold and Andersen (2003) failed to find a relationship between early postmortem pH decline and pork color.

The increase in drip loss with increasing glycolytic potential was more pronounced in the high-stress group (Figure 1). Obviously, preslaughter stress had a greater effect on meat quality when muscle energy was high, which is visualized in Figure 2 for drip losses. Individual pigs were, independently from preslaughter stress level and processing plant, classified according to their blood lactate level and glycolytic potential. High glycolytic potentials alone caused only a moderate increase in drip losses; however, when in the presence of high muscle energy, the effect of preslaughter stress on drip loss was exacerbated. The reason why high muscle energy levels appear to be a risk factor when coinciding with high preslaughter stress is probably associated with its relation to ultimate pH. According to Offer and Knight (1988), water is held by the internal structure of myofibrils. Preslaughter stress causes a more rapid pH decline and higher muscle temperatures, which results in myofibrillar protein denaturation (Offer and Knight, 1988; Offer, 1991). As a consequence, water is less firmly held by that internal structure (Offer and Knight, 1988). Then, this loosely held water may be actually lost as muscle pH approaches the isoelectric point of muscle proteins (pH 5.0; Hamm, 1960). Thus, in the present study, low glycolytic potentials may have led to a higher ultimate pH, partly preventing water from being expelled from the meat. The proposed mechanism by which muscle energy influenced drip losses and pork color in the present study is different but not in contradiction to Rosenvold et al. (2003), who suggested that pork quality was affected by an alteration of glycometabolism rather than changes in ultimate pH.

The importance of both the rate and the extent of postmortem glycolysis in drip formation and pork color has been long recognized (e.g., Wismer-Pedersen and Briskey, 1961; Briskey, 1964; Offer and Knight, 1988). However, the present results provide additional evidence that this is true in pig populations free of both the halothane and the *RN* genes. Moreover, in contrast to other studies (Rosenvold et al., 2001b; Henckel et al., 2002; Schäfer et al., 2002), the importance of muscle energy level at slaughter in relation to drip losses and pork color is emphasized.

Implications

Stress immediately before slaughter has severe, negative consequences on pork quality attributes, such as drip loss and pork color, both after electrical and CO_2 stunning. The negative effects of stress may be aggravated by high muscle energy levels present at slaughter. Strategies are needed to monitor and decrease preslaughter stress, on the one hand, and to control muscle energy, on the other. Blood lactate seems to be a promising indicator of both the physical and psychological stress associated with the handling of pigs immediately before slaughter.

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