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Original Scientific Paper

Application of infrared ocular thermography for welfare and meat quality assessment of slaughter pigs

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ABSTRACT

Infrared ocular thermography is a non-invasive tool used in the pork industry to quickly assess animal stress and its impact on meat quality. The aim of this study was to investigate the association between the infrared ocular temperature and blood indicators and meat quality traits in slaughter pigs. The study was conducted on 60 market-weight pigs (average live weight of about 110 kg and 6 months old) of the same genetics. Infrared ocular thermography images were obtained immediately after stunning. Blood samples were collected at exsanguination to determine glucose level and oxidative stress biomarkers, including advanced oxidation protein products (AOPP), ceruloplasmin, reduced glutathione (GSH), total antioxidant capacity (TAC), total oxidant status (TOS) and the oxidative stress index (OSI). Meat quality traits, including pH, temperature, colour (L^*, a^* and b^* values), water-holding capacity (drip, thawing and cooking loss) and pork quality classes, were measured. Pigs with infrared ocular temperatures above 32 ºC had higher plasma concentrations of GSH and TOS. Pork obtained from the same group of pigs had higher cooking loss and a^* value, along with tendency towards higher L^* and b^* values. Furthermore, pigs with infrared ocular temperatures above 32 ºC had higher tendency towards development of pale, firm and non-exudative meat. These results indicate that elevated ocular temperature is linked to oxidative stress and changes in meat quality, suggesting a connection between pre-slaughter stress and post-mortem meat characteristics. In conclusion, infrared ocular thermography has potential as rapid, non-invasive tool for assessing pig welfare and predicting pork quality.

1. Introduction

The meat industry and consumers are becoming increasingly critical regarding how food is produced, with key concerns related to economic, animal welfare and meat safety and quality (*Sanchez et al*., 2022, *Svoboda et al*., 2024). Traditional methods for assessing animal welfare (behaviour observation, biochemical stress indicators and resource-based indicators) and meat quality (sensory analysis, chemical composition and technological properties) are often invasive/destructive, costly, inaccurate, labor-intensive and time-consuming, making them unsuitable for industrial use (*Sanchez et al*., 2022; *Svoboda et al*., 2024). Therefore, there is a need for novel and advanced methods that are non-invasive/non-destructive, fast, accurate and adaptable to industry conditions (*Sanchez et al*., 2022, *Svoboda et al*., 2024).

Infrared thermography is a non-invasive technique that enables body temperature measurement

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without direct contact with the animal (*Weschenfelder et al*., 2013). Because skeletal muscle temperature is associated with early postmortem pH decline, thermography can detect elevated temperatures in pigs resulting from poor pre-slaughter handling, thereby providing a tool to predict variations in pork quality (*Bressan et al*., 1992; *Weschenfelder et al*., 2013). However, surface temperature measurements may be less accurate due to interference from dirt, hair or water (*Banhazi and Black*, 2009; *Weschenfelder*, 2013).

The brain, as the major source of metabolically produced heat and the central regulator of body temperature, represents the site of core temperature. Consequently, ocular temperature, due to its close proximity to the brain, serves as a reliable indicator of core temperature (*Tan et al.*, 2009; *Kessel et al*., 2010; *Johnson et al*., 2011, *Weschenfelder*, 2013). Because ocular blood flow is closely regulated by sympathetic activity, even mild stress responses can be detected through changes in ocular temperature (*Weschenfelder et al*., 2013). Accordingly, infrared ocular thermography is regarded as a promising non-invasive tool for assessing physiological responses and pork quality variations (*Weschenfelder et al*., 2013). However, available scientific literature lacks data on the physiological range of ocular temperature and threshold values that could indicate stress and, consequently, compromised welfare and deterioration in pork quality. Considering the aforementioned facts, the aim of this study was to investigate the association between the infrared ocular temperature and blood indicators and meat quality traits in slaughter pigs.

2. Materials and methods

2.1. Ethical approval

The experimental procedures used throughout this study were approved by the Local Ethics Committee on Animal Experimentation of the Faculty of Veterinary Medicine, University of Belgrade, Serbia (Approval No: 01-159 of 14 February 2025).

2.2. Experimental pigs and pre- and post-slaughter conditions

The study was conducted on 60 market-weight pigs (average live weight of about 110 kg and 6 months old) of the same genetics ([Yorkshire × Landrace] sows sired with Pietrain boars) across three groups (Group 1=11 pigs; Group 2=19 pigs; Group 3=30 pigs). Pigs originated from two commercial farms (Farm A – Group 1 and 2; Farm B – Group 3), where they were housed under similar conditions. All pigs were subjected to the same pre-slaughter procedures (loading, transport, unloading and lairage). Pig slaughter and carcasses processing were performed at the two commercial slaughterhouses in compliance with the standard industry-accepted practices.

2.3. Capture of infrared thermography images

Ocular images of each pig were captured immediately after stunning, while the animals were suspended by their hind legs and just prior to exsanguination, using a handheld infrared camera (Testo 875, Testo Ltd, United Kingdom) operated by the same trained technician. The images were captured from the right side of each pig at a distance of one meter, with focus on the eye. All thermography measurements were performed under controlled environmental conditions, with stable ambient temperature and relative humidity, to ensure accurate and consistent results. Thermograms were exported to a computer and processed using the appropriate software (IRSoft, Testo Ltd, United Kingdom) to obtain parameters of the recorded region. The examined region (eye) was outlined, and the maximum temperature of the marked area was calculated. The analysis and marking of the region of interest were performed by the same trained evaluator. A representative ocular thermographic image from taken on a pig in the present investigation is provided in Figure 1.

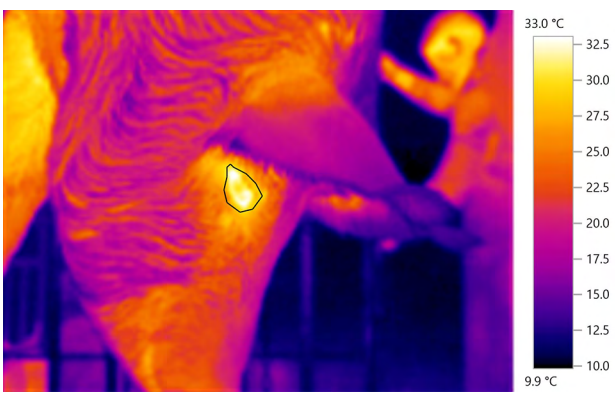

Figure 1. Determination of infrared ocular temperature in pigs after stunning

2.4. Determination of blood glucose concentration at exsanguination

Whole-blood glucose concentration was measured on the slaughter line within 60 seconds of exsanguination using a handheld device (Accu-Chek® Performa, Roche Diagnostics, Mannheim, Germany). To assess oxidative stress indicators, whole blood samples collected in 10 mL EDTA vacutainers during exsanguination were transported on ice packs (maintained at 3 ± 1 °C) inside a portable cooler box. Immediately upon arrival at the laboratory (180 minutes after sampling), whole blood samples were centrifuged at 3,000 rpm for 10 minutes. Plasma aliquots were then transferred into uniquely labelled tubes and immediately frozen at −80 °C pending analysis. Plasma ceruloplasmin concentration was determined based on its p-phenylenediamine (PPD) oxidase activity, according to the protocol of Hussein et al. (2019). Reduced glutathione (GSH) concentration in plasma was analyzed using a modified Ellman's method (*Jollow et al*., 1974), with 5,5'-dithio-bis-(2-nitrobezoic) acid (DTNB). Protein oxidation in plasma was evaluated by quantifying advanced oxidation protein products (AOPP), according to the method described by *Witko-Sarsat et al*. (1996). Total antioxidant capacity (TAC) in plasma was determined using the method of Erel (2004), with 2,2+-azinobis(3-ethylbenzothiazoline-6-sulfonic-acid) (ABTS). Total oxidative status (TOS) was determined according to *Erel* (2005), based on the oxidation of a ferrous ion-o-dianisidine complex to ferric ion by oxidants present in the sample. The oxidative stress index (OSI) was calculated as the ratio between TOS and TAC values.

2.5. Determination of pork quality traits

Sampling and determination of pork quality traits were performed on the carcass left side. Meat pH and temperature measurements were conducted in the chilling room 45 minutes and 24 hours postmortem using a portable pH meter (Testo 205, Testo AG, Lenzkirch, Germany) with an accuracy of ± 0.01, by insertion into *musculus longissimus lumborum* (at the level of the 3rd to 5th lumbar vertebrae) and *musculus semimembranosus* (central region).

Samples used for determination of colour and water-holding capacity traits were collected 24 hours postmortem by excising a portion of the musculature between the 3rd and 5th lumbar vertebrae, approximately 2.5 cm thick. Pork colour was subjectively assessed by three experienced technicians using the reference standards established by the *National Pork Producers Council* (2000), with scores ranging from 1 (pale) to 6 (dark). Objective evaluation of pork colour traits (*L*a*b**; CIELab, 1996) was performed using a portable colorimeter (NR110, 3NH Technology Co., Ltd, Shenzhen, China) equipped with a 4-mm aperture, 2° viewing angle, and D65 illuminant. Measurements were taken at nine randomly selected points on the lateral and medial surfaces of the longissimus lumborum muscle chops to obtain a representative average value (*Hunt et al*., 1991). Three methods (drip loss, thawing loss and cooking loss) were used for determination of water-holding capacity traits, as described in *Honikel* (1998) and *Klauke et al.* (2013).

Pork quality classes were defined based on pH_{24h}, drip loss variations and *L** (lightness) values, according to the criteria of *Correa et al.* (2007): (i) pale, soft, and exudative (PSE) meat; (ii) moderately pale, soft, and exudative (moderate PSE) meat; (iii) pale, firm, and non-exudative (PFN) meat; (iv) red, soft, and exudative (RSE) meat; (v) red, firm, and non-exudative (RFN) meat; (vi) moderately dark, firm, and dry (moderate DFD) meat; and (vii) dark, firm, and dry (DFD) meat.

2.6. Statistical analysis

Statistical analysis was performed using GraphPad Prism software (version 9.5.1, GraphPad Software, San Diego, CA, USA). In relation to infrared ocular temperature, pigs were divided into two groups: (1) lower temperature – pigs with an infrared ocular temperature ≤32 °C (n=25); (2) higher temperature – pigs with an infrared ocular temperature >32 °C (n=35). The 32 °C threshold was established based on preliminary data, which showed that ocular temperatures above this value were consistently associated with increased stress indicators and changes in meat quality. The student's t-test was performed to detect significant differences in blood indicators and meat quality traits between two groups. The data were presented as means along with standard deviations. Pearson correlations (r_p) were used to evaluate the associations between infrared ocular temperature and blood indicators and meat quality traits. Correlation coefficients were interpreted according to *Taylor* (1990) as weak ($|r_p| < 0.35$), moderate ($0.36 \leq |r_p| < 0.67$) and strong ($|r_p| \geq 0.68$). Statistical significance was set at $P < 0.05$, while $0.05 < P < 0.10$ was considered indicative of a tendency.

Table 1. The effect of infrared ocular temperature on oxidative stress parameters in pigs (n=60)

Infrared ocular temperature	Lower (≤32 °C)	Higher (>32 °C)	P - value	Significance
Number of pigs	25	35		
Glucose (mmol/L)	7.25 ± 1.37	7.64 ± 2.58	0.489	ns
AOPP (µM/L)	93.02 ± 13.61	92.30 ± 11.65	0.827	ns
Ceruloplasmin (mg/dL)	30.87 ± 11.41	29.31 ± 11.84	0.611	ns
GSH (µmol/L)	0.82 ±0.35	0.53 ± 0.32	0.050	*
TAC (mmol/L)	0.60 ± 0.29	0.68 ± 0.42	0.420	ns
TOS (µmol/L)	90.42 ± 34.48	110.30 ± 70.45	0.039	*
Oxidative stress index	0.25 ± 0.26	0.33 ± 0.35	0.380	ns

* Statistical significance at $P<0.05$; t: tendency ($0.05 < P < 0.10$); ns: not statistically significant ($P>0.05$)

Table 2. The effect of infrared ocular temperature on pork meat quality (n=60)

Infrared ocular temperature	Lower (≤32 °C)	Higher (>32 °C)	P - value	Significance
Number of pigs	25	35		
Physiciochemical parameters				
Musculus longissimus lumborum				
pH_{45min}	6.44 ± 0.25	6.38 ± 0.23	0.348	ns
T_{45min} (°C)	34.44 ± 1.78	33.76 ± 1.25	0.089	t
pH_{24h}	5.67 ± 0.26	5.64 ± 0.21	0.533	ns
T_{24h} (°C)	5.99 ± 1.03	5.08 ± 1.13	0.003	*
Musculus semimembranosus				
pH_{45min}	6.56 ± 0.19	6.56 ± 0.23	0.967	ns
T_{45min} (°C)	34.17 ± 2.38	33.26 ± 2.47	0.159	ns
pH_{24h}	5.52 ± 0.15	5.57 ± 0.22	0.313	ns
T_{24h} (°C)	6.24 ± 1.00	5.49 ± 1.10	0.008	*
Water-holding capacity indicators (%)				
Drip loss	1.96 ± 1.08	1.92 ± 0.80	0.867	ns
Thawing loss	2.26 ± 1.17	3.30 ± 3.76	0.187	ns
Cooking loss	17.87 ± 4.71	20.56 ± 5.23	0.049	*
Meat color indicators				
*L** value	47.69 ± 2.98	48.95 ± 2.80	0.099	t
*a** value	5.41 ± 2.33	4.26 ± 1.50	0.022	*
*b** value	6.03 ± 0.90	6.63 ± 1.53	0.062	t
Sensory color score	2.40 ± 0.69	2.27 ±0.58	0.437	ns
Meat quality classes				
Moderately PSE meat	4.00	8.57	0.484	ns
RFN	60.00	68.57	0.493	ns
PFN	16.00	31.43	0.074	t
Moderately DFD	20.00	11.43	0.359	ns

* Statistical significance at $P<0.05$; t: tendency ($0.05 < P < 0.10$); ns: not statistically significant ($P>0.05$)

Table 3. Relationships between infrared ocular temperature and blood indicators and meat quality traits in slaughter pigs (n=60)

	Infrared ocular temperature (°C)		
	r_p	*P* - value	Strength
Blood indicators			
Glucose (mmol/L)	0.057	0.663	-
AOPP (µM/L)	0.143	0.274	-
Cerulopasmin (mg/dL)	-0.174	0.184	-
GSH (µmol/L)	-0.062	0.637	-
TAC (mmol/L)	0.009	0.942	-
TOS (µmol/L)	0.084	0.521	-
Oxidative stress index	0.116	0.379	-
Physicochemical parameters			
Musculus longissimus lumborum			
pH_{45min}	-0.251*	0.050	weak
T_{45min} (°C)	-0.439*	0.001	moderate
pH_{24h}	0.069	0.599	-
T_{24h} (°C)	-0.472*	0.001	moderate
Musculus semimembranosus			
pH_{45min}	0.109	0.409	-
T_{45min} (°C)	-0.311*	0.016	weak
pH_{24h}	0.246	0.058	-
T_{24h} (°C)	-0.418	0.001	moderate
Water-holding capacity trait (%)			
Drip loss	0.131	0.326	-
Thawing loss	0.030	0.817	-
Cooking loss	0.347*	0.007	weak
Meat colour traits			
*L** value	0.248*	0.050	weak
*a** value	-0.572*	0.001	moderate
*b** value	0.539*	0.001	moderate
Sensory color score	-0.150	0.253	-

Level of significance: * $P < 0.05$.

3. Results

3.1. Effects of the infrared ocular temperature on blood indicators and meat quality traits of slaughter pigs

Effects of the infrared ocular temperature on blood indicators and meat quality traits are shown in Tables 1 and 2. Infrared ocular temperature significantly affected plasma concentrations of GSH (*P*=0.050) and TOS (*P*=0.039).

Infrared ocular temperature significantly affected cooking loss (*P*=0.049) and the *a** value (*P*=0.022). Additionally, pigs with higher infrared ocular temperature (>32 ºC) exhibited an increased tendency towards higher *L** (*P*=0.099) and *b** (*P*=0.062) values and towards a higher occurrence of PFN meat (*P*=0.074).

3.2. Pearson correlations between infrared ocular temperature and blood indicators and meat quality traits in slaughter pigs

Pearson correlations between infrared ocular temperature and blood indicators and meat quality traits in slaughter pigs are shown in Table 3. Infrared ocular temperature was weakly negatively correlated with pH_{45min} in *musculus longissimus lumborum* (P=0.050) and T_{45min} in *musculus semimembranosus* (P=0.016). Furthermore, a weak negative correlation was found between infrared ocular temperature and cooking loss (P=0.007) and L^* value (P=0.050). In addition, infrared ocular temperature moderately negatively correlated with T_{45min} (P=0.001) and T_{24h} (P=0.001) in *musculus longissimus lumborum*. A moderate negative correlation was found between infrared ocular temperature and a^* value (P=0.001), but moderate positive correlation between infrared ocular temperature and b^* value (P=0.001).

4. Discussion

Infrared ocular temperature is a non-invasive method for assessing body temperature in pigs, offering an alternative to rectal measurements (*Weschfelder et al*., 2013; *Yanmaz*, 2020; *Ferreira et al*., 2024). In this study, pigs with ocular temperatures above 32 ºC had lower plasma concentration of GSH and a higher plasma concentration of TOS (Table 1), indicating exposure to stressful conditions prior to slaughter (*Bernatoniene and Kopustinskiene*, 2018). As GSH serves as a major cellular antioxidant that neutralizes free radicals (*Bernatoniene and Kopustinskiene*, 2018), these results indicate activation of oxidative stress.

In the present investigation, meat obtained from pigs with ocular temperatures above 32 ºC had lower water-holding capacity (higher cooking loss) and paler colour (lower a^* value) (Table 2). Furthermore, the same group of pigs had higher tendency towards increased L^* and b^* values and development of PFN meat. Nevertheless, with L^* values ranging from 42 to 50, the meat remained within the RFN class, which is considered acceptable to consumers (*Correa et al*., 2007). Accordingly, the findings of this study indicate that pigs with higher infrared ocular temperatures (>32 °C) experienced only mild stress, resulting in slower postmortem metabolism, partial protein denaturation and an increased risk of PFN meat (*Čobanović et al*., 2021). As supporting evidence of these findings, no associations were observed between infrared ocular temperature and the plasma concentrations of glucose, AOPP, ceruloplasmin, GSH, TOS, TAC or OSI; nevertheless, weak to moderate correlations were established between infrared ocular temperatures and meat physicochemical (pH and temperature 45 minutes postmortem) and colour traits (a^* value) (Table 3).

The negative correlation with the a^* value indicates a more yellowish and less reddish meat colour, potentially associated with a faster pH decline and activation of oxidative stress, leading to reduced pigment stability in pork (*Ereke*, 2022). Consistent with the present study, *Weschfelder et al.* (2013) reported that higher infrared ocular temperatures were associated with lower meat pH 60 minutes postmortem in the *musculus longissimus dorsi* and *musculus semimembranosus*, as well as with higher meat temperatures 60 minutes postmortem and increased drip loss in the longissimus dorsi muscle. Although correlation coefficients were low, this was attributed to the limited variability in meat quality within the study. The obtained results suggest that elevated infrared ocular and skeletal muscle temperatures at the time of slaughter can influence the extent and rate of pork acidification, potentially contributing to meat quality defects (*Weschefelder et al*., 2013). Furthermore, *Gariepy et al.* (1989) reported that higher infrared skin temperatures were associated with the occurrence of defects and variations in pork quality.

5. Conclusion

The results of this study showed that the use of infrared ocular temperature has potential to serve as a tool for rapid, non-invasive tool for pig welfare assessment and prediction of pork quality variations. However, although a degree of association between infrared ocular temperature and certain blood indicators and meat quality traits was established, the correlation coefficients were relatively low. This may be attributed either to the limited variability in pork quality or to the insufficient accuracy of the infrared thermography equipment used. Therefore, to more reliably validate the use of infrared ocular temperature for monitoring pig welfare and variations in pork quality, further research should be conducted under diverse pre-slaughter conditions, with larger sample sizes and including pigs of various genotypes.

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