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Effect of retail display illumination and headspace oxygen concentration on cured boiled sausages

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ARTICLE INFO

Article history:
Received 4 February 2014
Received in revised form
3 April 2014
Accepted 7 April 2014
Available online 24 April 2014

Keywords:
Cured sausage
Color
Residual oxygen
Shelf life
MAP

ABSTRACT

The objective of this study was to investigate the influence of various commercial lamps and residual oxygen on discoloration and oxidation of cured boiled sausage. The wavelength dependence of different spectral bands on sausage color and oxygen absorption was investigated. A model packaging system, simulating a gastight package was used to compare the influence of fluorescent tubes, metal halide lamps, color optimized fluorescent tubes and LEDs. Sausages exposed to daylight fluorescent tubes showed significantly ($p < 0.005$) higher rates of oxygen absorption and discoloration in comparison to metal halide lamps and color optimized fluorescent tubes for meat products after 24 h of storage time at 6 ± 1 °C. To investigate the effect of light and residual oxygen in the headspace of the packaging, oxygen concentrations of 0.0%, 0.5%, 1.0% and 2.0% were tested with daylight fluorescent tubes in regard of oxygen absorption and discoloration of the sausages. Higher residual oxygen concentrations showed higher discoloration and also higher rates of oxygen absorption of the sausage. Low initial oxygen contents in the headspace of packaged sausage in conjunction with optimized illumination can prolong the shelf life of cured sausages in retail shelves.

1. Introduction

Color appearance of sausages is the most important attribute for buying decision in retail stores (Eyiler & Oztan, 2011). The consumers use the color of meat and meat products as an indicator of freshness (Haile, Smet, Claeys, & Vossen, 2011; Nicolalde, Stetzer, Tucker, McKeith, & Brewer, 2006). Therefore, the meat and meat products in retail shelves are mainly offered in transparent packaging (Gibis & Rieblinger, 2011; McMillin, 2008). Residual oxygen in conjunction with the cabinet display light causes discoloration of the packed products (Andersen, Bertelsen, Boegh-Soerensen, Shek, & Skibsted, 1988). Economic losses of about 1 billion US$ are reported by the discoloration of fresh beef due to price reduced and discarded meat (Smith, Belk, Sofos, Tatum, & Williams, 2000).

Food packaging serves to protect products against deteriorative effects. In recent years the demand for packaged meat products increased as well as the application of modified atmosphere packaging (MAP) to meat products and sliced cured boiled sausages. The main reason of MAP is to prolong the shelf life of perishable foods (McMillin, 2008). Two forms of MAP can be distinguished. The atmosphere inside a given volume can either be removed completely, denoted by vacuum packaging, or be replaced by a defined mixture of selected gases (Church & Parsons, 1995; McMillin, 2008). Two gases are generally used for cured products. CO_2 effectively inhibits the growth of many microorganisms. Nitrogen is used as a filler gas to replace oxygen. For cured products a modified

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http://dx.doi.org/10.1016/j.fpsl.2014.04.003
2214-2894/

atmosphere of 80% nitrogen and 20% carbon dioxide is recommended (Church & Parsons, 1995). Despite the application of modified atmosphere, there is often a small amount of residual oxygen (up to 2%) present in the package. This little amount of oxygen can lead to color fading by oxidation of the color pigment nitrosomyoglobin which is formed from myoglobin (Gibis & Rieblinger, 2011).

In meat myoglobin, the red iron-containing pigment which is responsible for meat color mainly exists in different conformations. The denaturated nitrosomyoglobin (dMbNO) is formed when muscle myoglobin reacts with nitrite to nitrosomyoglobin and is heated up to 65 °C until the pigment is converted into the denaturated form (Fox, 1966; Andersen et al., 1988). The denaturated nitrosomyoglobin causes the characteristic pink color of cured boiled sausages and is also named nitrosylmyochrome (Andersen & Skibsted, 1992), nitrosylmyochromogen (Bak et al., 2013) or nitrosohemochromogen (Sun, Zhou, Xu, & Peng, 2009). The exposure of dMbNO to light and oxygen promotes oxidation to metmyoglobin (Møller, Jensen, Olsen, Skibsted, & Bertelsen, 2000). Metmyoglobin (MMb) appears as brownish color on the meat surface (Faustman & Cassens, 1990; Mancini & Hunt, 2005).

In conclusion the discolouration of cured meat products is predominantly caused by light and oxygen (Møller, Bertelsen, & Skibsted, 2002; Haile et al., 2011). The redness of cured meat products can be measured as a^*value. A decrease in a^*value can be explained by the chemical reaction of the light induced oxidation of the color pigment and is described by Andersen and Skibsted (1992) as:

$$\mathrm{MbNO} + h\upsilon \rightarrow \mathrm{MbNO}^* \quad \text{(i)}$$

$$\mathrm{MbNO}^* + {}^3\mathrm{O}_2 \rightarrow \mathrm{MMb} + \text{other products} \quad \text{(ii)}$$

The nitrosylmyoglobin (MbNO) is a light sensitive substance functioning as a photosensitizer like dMnNO and is promoted to an excited state upon absorption of light. The activated state of MbNO* reacts with triplet oxygen ($^3O_2$) and forms metmyoglobin (MMb) and other products. Metmyoglobin formation causes the gray brown color of illuminated cured sausages and therefore the decrease in a^*value (Andersen & Skibsted, 1992).

Møller et al. (2000) found that 0.5% oxygen in the headspace of a modified atmosphere packaging leads to a significant light induced discoloration of cured cooked ham when illuminated with fluorescent tubes in a chill cabinet with 1000 lx compared to products stored in the dark. The consumers' purchase decision is influenced by the light source; the desirability of salami illuminated with fluorescent (FL), incandescent (IC) and metal halide lamps (MH) was significantly higher with incandescent light (Barbut, 2004). Different light sources have several spectral properties. IC and MH have a high emission in the infrared range and produce heat which increases the surface temperature of meat and meat products and reduce the shelf life (Calkins, Goll, & Mandigo, 1986). FL has a higher emission in the UV-A range. UV-light reduced the retail shelf life of beef steaks significantly compared to steaks stored in the dark or with absence of UV radiation (Djenane, Sánchez-Escalante, Beltrán, & Roncalés, 2001). Barbut (2001) found that four of five retail stores use cool white fluorescent lamps for meat illumination because of cost saving. The product appearance was different because of a weak emission in the red range in comparison to daylight or incandescent light. Andersen et al. (1988) found that the color of sliced packaged ham displayed in chill cabinets was dependent on the combination of light in the visible range and oxygen in the headspace of the packaging. Unlike to fresh beef, cured (boiled) sausages showed no sensitivity to UV-light in case of discoloration (Djenane et al., 2001; Sáenz, Hernández, Beriain, & Lizaso, 2005). The discolouration or graying of cured boiled sausage depends on wavelength (Kampschmidt, 1955). Every lamp type has special spectral properties. Light sources vary widely and range from overhead fixtures to lights positioned inside the display case. Therefore, different illumination sources influence not only the product appearance, but also the product quality during storage in retail stores.

In the first trial of this study, the influence of daylight fluorescent tubes, color optimized fluorescent tubes for meat products, metal halide lamps and LEDs were investigated on color and oxidation of cured boiled sausages. These lamps represent commonly used lamps in retail stores for the illumination of meat counters and self-service shelfs (Barbut, 2001; Wieser, 2010). The tested parameters were oxygen absorption, color changes and rancidity (hexanal) of the sausages during storage. A standardized oxygen concentration in the headspace was used for analyses. In the second trial, the effect of different initial oxygen concentrations and daylight fluorescent tube light was investigated on discoloration and oxygen absorption of cured boiled sausage.

2. Material and methods

2.1. Sample preparation

''Lyoner'' type sausages were manufactured at Fraunhofer IVV in Freising, Germany with a standard recipe consisting of 3.5 kg lean pork meat category SII (lean pork meat without tendons with a maximum of 5% visible fat), 3.0 kg fat (50% jowls, 50% neck fat), 1.35 kg water (ice), 7.5 g ascorbic acid (Wiberg, Germany), 22.5 g diphosphate (Wiberg, Germany), 150 g sodium nitrite 0.65% (esco, Germany), 22.5 g sugar (Wiberg, Germany), 18.75 g pepper (Wiberg, Germany), 7.5 g ginger (Wiberg, Germany), 7.5 g cardamom (Wiberg, Germany) and 7.5 g nutmeg (Wiberg, Germany). Seven pigs were slaughtered in slaughterhouse Šentjur, Slovenia. The carcasses of the pigs were deboned and deep-frozen (−18 °C) directly after refrigeration. Two weeks after slaughtering the meat was defrosted for 24 h at 2 °C for sausage production. After grinding the meat through a plate with 6 mm openings, the lean meat was added to the chopping bowl (Typ 30 L 5000 Express, KILIA Fleischerei- u. Spezialmaschinenfabrik, Germany) and chopped for several minutes with sodium nitrite, diphosphate and one-third of the crushed ice until a temperature of 4 °C was reached. This was followed by the addition of fat and the spices with 0.45 kg crushed ice. The sausage meat was chopped up to 8 °C, then the bowl chopper was scraped out and the rest of the ice was added. The lid of

the bowl chopper was closed and the batter was chopped at a pressure of 150 mbar until a temperature of 13–14 °C was reached. The sausage meat was then filled by a vacuum-filler (Typ VF 608 plus, Handtmann Maschinenfabrik GmbH, Germany) into impermeable fibrous casings of 75 mm diameter (Wiberg, Germany). The sausages were boiled in a vessel (Kochmeister, Reich, Germany) at a water temperature of 72 °C until a core temperature of 68 °C was reached. After cooling in iced water, the sausages were stored at 2–4 °C for 4 days before slicing and packaging.

2.2. Packaging and storage

The sample analysis was carried out for slices of cured boiled sausages with a thickness of 2 mm cut with a slicer (Euro 2500 Gastro, Gebr. Graef GmbH & Co. KG, Germany). Three slices of sausage (25–30 g) were stacked concentrically on top of each other in a Petri dish. The samples were put in special hermetic glass covered oxygen measuring cells in order to simulate a gastight, transparent package (Rieblinger, Ziegleder, Berghammer, & Sandmeier, 1995). Afterwards, the oxygen measuring cells were flushed with nitrogen and stored for 12 h at 6 ± 1 °C in the dark to remove the trapped and dissolved oxygen. Before starting the illumination with four different lamp types, the oxygen measuring cells were flushed with a gas mixture of 0.5% O_2/99.5% N_2 supplied by Linde AG, Germany to get standardized initial oxygen levels. The headspace volume of the oxygen measuring cells with product was 100 ± 10 ml. The storage time was set to 24 h. In order to investigate the influence of different oxygen concentrations in the headspace of the packaging in the second trial, the gastight cells were flushed with nitrogen and stored for 12 h as described herein above. Afterwards, the oxygen measuring cells were flushed with 0.0%, 0.5%, 1.0% and 2.0% oxygen in nitrogen before illumination with FL for 24 h. Storage tests with illumination were carried out at a temperature of 6 ± 1 °C for 24 h. References were stored at the same temperature in the dark. All trials were performed within 2 weeks after sausage production to ensure a comparable sausage quality.

2.3. Color measurement

The product color of the top slices was measured as $L^*a^*b^*$values by the non-contact digital color imaging system DigiEye (DigiEye V2.62, VeriVide, Leicester, England). Product pictures of the upper slice were taken without the oxygen measuring cell in the enclosed 'DigiEye Cube' eliminating all ambient light. The 'DigiEye Cube' is a controlled lighted cube with diffuse illumination of illuminant D65. A digital camera Nikon D90 was centrally positioned on top of the cube and captured the images from above. The observer angle was 0°. The images were displayed on a calibrated LCD monitor. The camera settings (aperture = 8 and shutter = 1/5) were fixed for each measurement and the system was calibrated with the DigiEye Digitizer Chart in order to characterize the camera response by relating its RGB signals to CIE (International Commission on Illumination) specifications under the fixed lighting conditions in the cabinet (Lau, Kan, Yuen, & Lau, 2011). The reflectance spectra of the top slices were also measured with the DigiEye system. The CIE a^*value was found to give the best correlation with visual color of cured ham (Larsen, Westad, Sørheim, & Nilsen, 2006). Therefore, a^*value was used to describe the color changes of cured boiled sausages.

2.4. Oxygen measurement

The oxygen concentration in the headspace of oxygen measuring cells and therefore the oxygen absorption of the sausages was measured by a non-destructive fluorescence measuring instrument Fibox 3 LCD trace (Fibox 3 LCD trace v7, PreSens-Precision Sensing GmbH, Regensburg, Germany). A sensor spot was fixed directly under the glass lid inside the measuring cell and a fiber optic cable was positioned on the outside. The luminescence lifetime of the oxygen-sensitive spot changed with the oxygen concentration and was therefore acting as the oxygen dependent parameter. At the beginning and end of the illuminated storage period, the oxygen concentration was measured.

2.5. Determination of lipid oxidation

The extent of rancidity was measured by hexanal concentration and quantified by headspace GC/MS following the method described by Ziegleder and Rieblinger (1999).

2.6. Light sources and spectral measurements

Lamp types used for this study were daylight fluorescent tubes (Lumilux Cool Daylight, 30 W/865, OSRAM, Munich, Germany) abbreviated "FL" in the following, color optimized fluorescent tubes for meat products (Basic Frischfarben-Leuchtstofflampe 30361, BÄRO, Leichlingen, Germany) abbreviated "FL–MP", metal halide lamps (MasterColour CDM-T Elite 35 W/930 Crisp white light, PHILIPS, Berlin, Germany) abbreviated "MH", and LEDs (Food LED, BÄRO, Leichlingen, Germany). Light intensity and spectral properties were measured from 300 to 1100 nm by a calibrated Compact Array Spectrometer (CAS 140 CT_156, Instrument Systems, Munich, Germany). The illuminating tests were performed at light intensities in the range between 2.6 and 2.8 W/m^2 for 24 h. The irradiance of the lamps varied in dependence of the distance and wattage of the lamps. To get comparable light intensities for the illumination of the samples, lamp to product distance was varied. A grid with a grid distance of 10 cm was placed under each lamp to measure the light intensities at each grid point to ensure, that each sample was exposed to the same irradiance.

2.7. Absorption spectra of nitrosomyoglobin

Equine myoglobin 90% (Sigma–Aldrich, Germany), sodium nitrite (Merk, Germany) and ascorbic acid (Roth, Germany) were dissolved in deionized water resulting in concentrations of 40 μM Mb, 80 μM $NaNO_2$ and 80 μM ascorbic acid. The solution was protected from light and was deoxygenated by passing N_2 gas through the solution for 1.5 h. After 24 h at room temperature, the absorption was measured in 1 cm quartz glass cuvettes with a spectrophotometer (UVIKON XL, BioTek Instruments, Neufahrn, Germany) from 300 to 800 nm.

The absorption spectra confirmed that most of the Mb was converted to MbNO.

2.8. Statistical analysis

For each treatment, measurements were carried out in triplicate. Values are shown as mean with standard deviation. A two-way ANOVA with Holm–Sidak Test for pairwise multiple comparison with significance at a probability of $P < 0.05$ was used to analyze the influence of storage time and light source as well as storage time and oxygen content. Furthermore the test was used to reveal interactions between these factors. Linear regression analysis was used to examine linear dependence between oxygen concentrations in the headspace and oxygen absorption of the sausage. Both statistical analyses were carried out with SigmaPlot 12.5.

3. Results and discussion

3.1. Illumination

Different light sources produce a unique distribution of wavelengths. FL and MH (Fig. 1a) differed considerably in their spectral properties. FL had a higher proportion in the blue range between 410 and 505 nm whereas the MH had a higher emission in the range between 580 and 680 nm, which corresponded to red and orange. Between 815 and 830 nm, the infrared peak of the MH was visible and might led to heat generation on the product surface (Schmidt, 2004). The differences between the fluorescent tube with a higher proportion in the red range (FL-MP) and the LED were clearly visible (Fig. 1b). The spectra of a LED consisted of 3 peaks in the blue, green and red range, whereas the spectra of the FL-MP consisted of three primary colors blue, green and red with additional peaks in the dark red range and infrared range. The FL and FL-MP differed in their emission spectra between 410 and 500 nm, where FL showed a higher electromagnetic radiation and between 625 and 700 nm, where the FL-MP showed a higher radiation.

3.2. Oxygen absorption

In tests prior to this study, the headspace oxygen concentration increased during dark chilled storage. Møller et al. (2000) also observed an increase in oxygen concentration after packaging fresh cooked cured ham. The increase in oxygen level might be explained by oxygen trapped under and

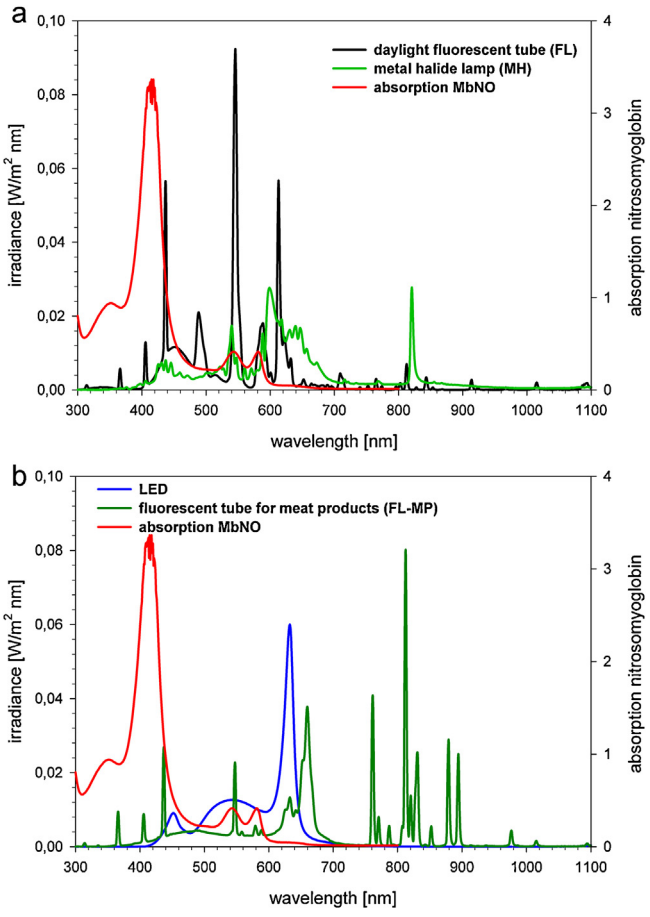

Fig. 1 – Emission spectra of (a) the daylight fluorescent tube (FL), the metal halide lamp (MH) in the range between 300 und 1100 nm and absorption spectra of nitrosomyoglobin between 300 and 800 nm and (b) the LED and the fluorescent tube for meat products (FL-MP) in the range between 300 and 1100 nm and absorption spectra of nitrosomyoglobin between 300 and 800 nm.

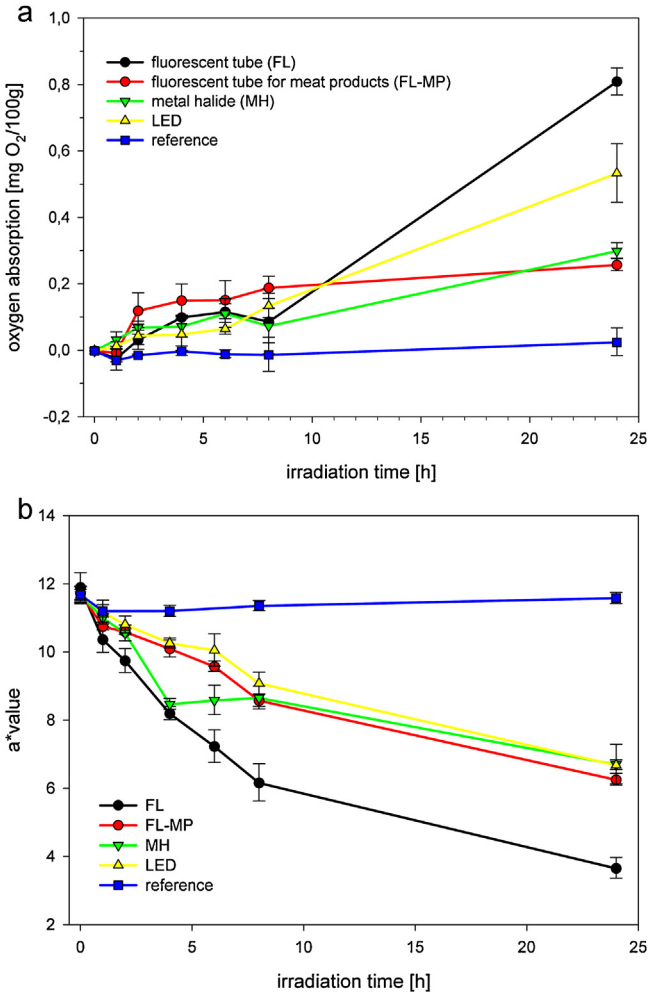

Fig. 2 – (a) Oxygen absorption and (b) changes in redness (a^* value) of "Lyoner" type sausages exposed to daylight fluorescent tube, fluorescent tube for meat products, metal halide lamp and LED for 24 h and dark stored references with an initial oxygen concentration of 0.5% in the headspace ($n = 3$).

between the sausage slices and also by diffusion from dissolved oxygen into the headspace. According to Møller et al. (2000) storage of cured meat products in the dark with oxygen concentrations up to 0.5% had no influence on product color. The oxygen measuring cells were therefore flushed with nitrogen and stored for 12 h in the dark to remove the residual oxygen before flushing with the experimental gas mixture.

In Fig. 2a the oxygen absorption of cured boiled sausages illuminated with different lamps is illustrated. The oxygen absorption of all illuminated samples increased slightly during 24 h of illumination. The samples illuminated with FL absorbed 0.80 mg O_2/100 g of sausage in 24 h. This was three times as much as the samples illuminated with the MH (0.30 mg O_2/100 g) and the FL-MP (0.26 mg O_2/100 g) for 24 h. The samples illuminated with LED (0.53 mg O_2/100 g) had a lower oxygen absorption compared to FL but a higher compared to MH and FL-MP after 24 h illuminated storage. The dark stored references showed non-significant ($p > 0.05$) changes in headspace oxygen concentration during 24 h storage. The oxygen absorption was affected by the light sources and exposure time ($p < 0.001$). The Holm–Sidak test showed a significant ($p < 0.05$) difference between FL samples and other light sources and between the samples stored in dark and the illuminated samples. This is in agreement with results from Møller et al. (2000) who measured a decrease in headspace oxygen of illuminated samples with 0.5% initial oxygen content, whereas the dark stored references showed no significant changes.

3.3. *Color changes*

The changes in a^*value indicate the changes of the red product color, are illustrated in Fig. 2b. The illuminated samples showed a decrease in a^*value.

After 1 h there was a significant difference ($p < 0.05$) between FL illuminated samples and the dark stored references (Fig. 2b). After 2 h, a^*values of the samples stored under the FL were significantly different ($p < 0.05$) to those stored under different light sources and the references. After 24 h of light exposure, the decrease in a^*value of FL illuminated samples ($a^* = 3.6$) was twice as high as compared to other illuminated samples. The MH, FL-MP and LED illuminated

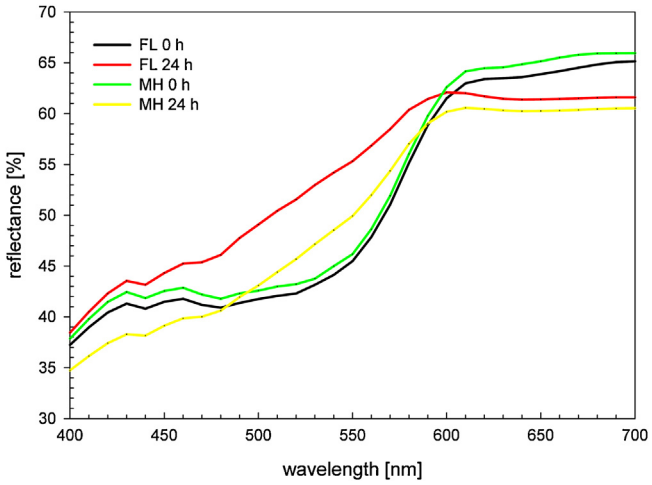

Fig. 3 – Reflection curves between 400 and 700 nm of "Lyoner" type sausage before and after illumination for 24 h with daylight fluorescent tube (FL) and metal halide lamp (MH).

samples had a^*value between 6.2 and 6.7 after an exposure time of 24 h. The color of the dark stored references did not change significantly during 24 h. The various lamps and the exposure time showed a significant effect ($p < 0.05$) on the graying of the cured boiled sausages. Howe, Gullett, & Usborne (1982) found that the color parameter hue (h°) expressed as $\tan^{-1}$ a^*/b^* is a good parameter to monitor color changes during storage. High values indicate less red and therefore more MMb (Howe et al., 1982). The results of a^* measurements were confirmed by the h°value, where higher values indicate a less red pigment content and therefore a stronger fading of color. The h°value of the FL samples, which is significantly higher after 24 h ($h^\circ = 1.29$) compared to the illuminated samples with the other light sources ($h^\circ = 1.14 \pm 0.02$) and the dark stored references ($h^\circ = 0.71$) indicates a higher rate of discoloration.

Fig. 3 shows the displacement of the reflection curves of FL and MH samples after illumination of 24 h. In American Meat Science Association (2012) a method to determine the cured color intensity and the fading, using the reflectance ratio 650 nm/570 nm of cured products is described by Kropf and Hunt. Low values of the reflectance ratio indicate product fading. High values indicate good cured color (American Meat Science Association, 2012). The samples illuminated with FL showed significantly ($p < 0.05$) lower values for the reflectance ratio (1.054 ± 0.006) compared to the other light sources (1.108–1.117), this agrees with the results from a^*value measurement (Fig. 2b) as well as h°value measurement (Table 1).

Table 1 – h°values and reflectance ratio: 650 nm/570 nm of "Lyoner" type sausages before and after exposure to daylight fluorescent tube, fluorescent tube for meat products, metal halide lamp and LED for 24 h and dark stored references with an initial oxygen concentration of 0.5% in the headspace.

Parameter	Color index (h°)	Wavelength ratio (650/570 nm)
Initial value	0.68	1.253 ± 0.008
Reference	0.71	1.289 ± 0.003
FL	1.29^a	1.054 ± 0.006^a
MH	1.12^b	1.117 ± 0.010^b
LED	1.14^b	1.114 ± 0.004^b
FL-MP	1.15^b	1.108 ± 0.004^b

Mean values in the same column and relating to each attribute are significantly different when accompanied by different superscripts ($p < 0.05$).

3.4. *Influence of absorption and emission spectra*

The emission spectra of the four lamps can be grouped into short (300–550 nm), medium (551–800 nm) and long (801–1100 nm) wavelength range (Table 2) to explain the differences in discoloration and oxygen absorption during illuminated storage. The FL showed an irradiance of 1.69 W/m^2 in the short range, which is two times higher than the MH, FL-MP and the LED. However, the FL had a small radiation in the medium and long range. The highest radiation in the medium range is from the LED (1.81 W/m^2) and the MH (1.61 W/m^2).

Previous studies with nitrosylmyoglobin showed absorption maxima at 421, 545–548 and 575–579 nm (Møller & Skibsted, 2004; Sørheim et al., 2006). Andersen and Skibsted (1992) showed that an absorption curve of nitrosylmyoglobin is displaced slightly from the absorption curve of denaturated nitrosylmyoglobin. The overlapping of emission- and absorption spectra (Fig. 1a and b) in the short wavelength range leads to the assumption that the photooxidation of denaturated nitrosylmyoglobin is also dependent on the wavelengths of irradiation. Andersen and Skibsted (1992) found that reaction quantum yield for photooxidation of nitrosylmyoglobin is moderately dependent on the wavelengths of irradiation and ranges from 254 to 546 nm in aqueous air-saturated solution at 5 °C. The wavelength dependence for photooxidation of nitrosylmyoglobin was confirmed by a study of Iversen (1984) who found tenfold decrease in the degradation reactions (color degradation and fat oxidation) when excluding light of wavelengths lower than 600 nm (Grini, Sørheim, & Nissen, 1992). The FL showed the highest irradiance in the

Table 2 – Irradiance (W/m²) of daylight fluorescent tube, fluorescent tube for meat products, metal halide lamp and LED grouped into short (300–550 nm), medium (551–800 nm) and long (801–1100 nm) wavelength ranges.

Wavelength range	FL	LED	FL-MP	MH
Short (300–550 nm)	1.69	0.87	0.65	0.70
Medium (551–800 nm)	0.91	1.81	1.30	1.61
Long (801–1100 nm)	0.11	0.01	0.78	0.42

short wavelength range which is congruent with the absorption maxima of the denaturated nitrosomyoglobin. Therefore a higher decrease in redness and higher oxygen absorption could be measured on samples illuminated with FL.

3.5. *Influence of residual headspace oxygen*

The effect of residual oxygen in the headspace of sausage packaging was tested with four different gas mixtures containing 0.0% O_2, 0.5% O_2, 1.0% O_2 and 2.0% O_2 in nitrogen. The influence of different initial oxygen concentrations on oxygen absorption of cured boiled sausages is shown in Fig. 4a. After 4 h of illumination with FL, the oxygen uptake of tested groups was significantly different ($p < 0.05$). The sausages with 2.0% O_2 in the headspace had the highest oxygen consumption of 0.63 mg O_2/100 g sausage compared to 0.45 mg/100 g with 1.0% O_2 in the headspace and 0.32 mg/100 g with 0.5% O_2 in the headspace. The samples flushed with pure nitrogen showed no changes in headspace oxygen concentration. This leads to the assumption that during the storage with nitrogen for 12 h all dissolved and trapped oxygen was eliminated. After 24 h of illumination, the differences in oxygen uptakes of the sausage packaged with different oxygen contents were increasing. More oxygen in the headspace of the packaging leads to a higher oxygen absorption of the sausages. After 24 h, the samples with 2.0% O_2 in the headspace absorbed 2.02 mg O_2/100 g sausage. This is twice as high as the samples stored with 1.0% O_2 in the headspace and four times higher than the samples stored with 0.5% oxygen. The oxygen absorption was affected by the initial oxygen concentration and exposure time ($p < 0.001$), with a significant interaction between these factors.

The discolouration, measured as a^*value is shown in Fig. 4b. After 2 h of illumination with FL, a^*-value was significantly higher for pure nitrogen (0% oxygen) as compared to other initial oxygen contents. Until 6 h of illumination, no

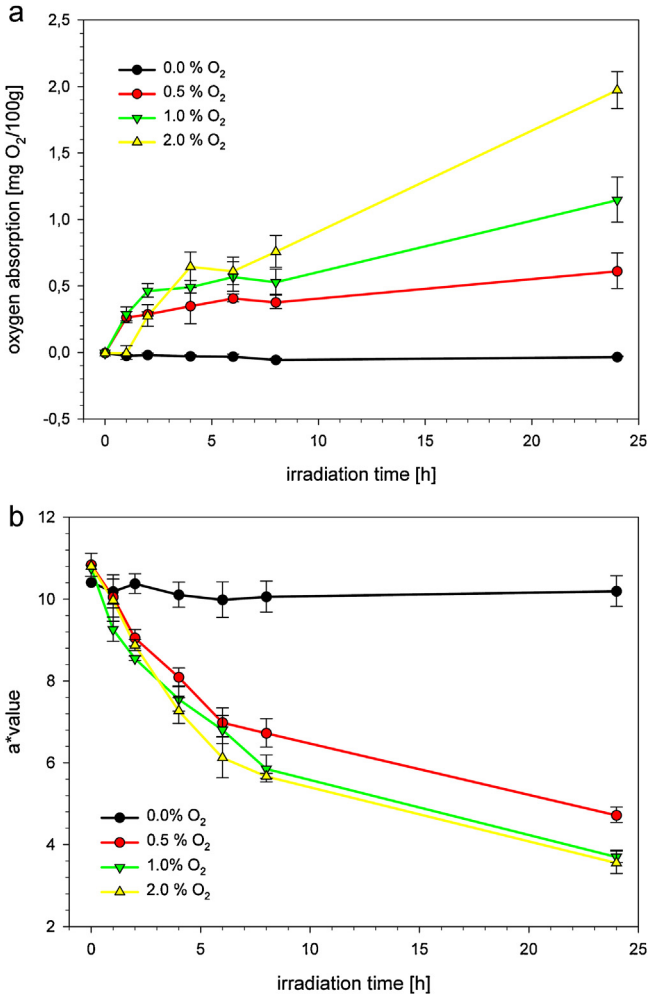

Fig. 4 – (a) Oxygen absorption and (b) changes in redness (a^*-value) of "Lyoner" type sausages exposed to daylight fluorescent tubes for 24 h with an initial oxygen concentration of 0.0%. 0.5%, 1.0% and 2.0% in the headspace ($n = 3$).

significant difference was observed between the samples with 0.5%, 1.0% and 2% initial headspace O_2. After 8 h, the sausages with 0.5 % headspace oxygen showed a significantly ($p < 0.001$) higher a^*value than samples with 1.0 and 2.0% initial oxygen. At the end of the illuminated storage, a^*value decreased to 3.6 for the samples with 2.0% initial O_2, whereas the sausages with 0.5% headspace O_2 decreased marginally to 4.7. The samples with 0% oxygen showed no significant changes ($p > 0.05$) during 24 h. The initial oxygen contents showed a significant effect ($p < 0.001$) on discolouration. The time of irradiation also showed a significant effect ($p < 0.001$) as well as the interaction between these factors. These results confirm that higher oxygen concentrations in the headspace of cured boiled sausages appear to have negative effects on discoloration, which concurs with studies by Grini et al. (1992) and Larsen et al. (2006). After 24 h the oxygen absorption was linearly dependent on the initial oxygen content ($r^2 = 0.968$). This agrees with Møller et al. (2002) who stated, that the light induced oxidation of nitrosylmyoglobin depends linearly on the oxygen concentration in the headspace of packaging.

3.6. *Lipid oxidation*

Rancid aroma is related to the presence of some volatile compounds derived from lipid oxidation, which exhibit rancid notes, especially these originating from the oxidation of linoleic acid, such as hexanal (Andrés, Cava, Ventanas, Thovar, & Ruiz, 2004). Therefore hexanal is used to measure lipid oxidation (Larick, Turner, Schoenherr, Coffey, & Pilkington, 1992). During a short lightning time of 24 h with FL no changes in hexanal content could be detected. Also during a longer storage period of 23 days no significant changes in hexanal concentration were detectable. The detection limit for hexanal of the used method was at 0.05 ppm. This agrees with findings of Parra et al. (2012) who found that an illuminance of 600 lx did not show a significant oxidation effect of dry cured Iberian ham after 1 and 30 days of storage. Cross and Ziegler (1965) found that hexanal was present in volatiles of uncured ham, but were barely detectable in volatiles of cured products. Carballo, Cavestany, & Jiménez-Colmenero (1991) found that photooxidation did not appear to be a determining factor in lipid oxidation. For cured boiled sausages the measurement of hexanal as an indicator for lipid oxidation is not expedient, especially if the storage period is very short.

4. Conclusion

Color changes of irradiated cured boiled sausages occur because of the oxidation of nitrosylmyoglobin to metmyoglobin. The residual oxygen content and the type of lamp have a strong influence on the degree of graying or color changes in meat. Higher initial oxygen concentration in the headspace of sausage packaging and FL showed negative influences on sausage color and oxygen absorption. Therefore, the best packaging for cured boiled sausages should be protected from light or without oxygen. As both of these factors are unconvertible, because of dissolved or trapped oxygen and the consumers' demand for a transparent packaging the use of lamps with a reduced radiation in the short wavelength range is recommended. Lamps with higher ratio in the shorter wavelengths like the most frequently used daylight fluorescent lamps showed a higher discoloration and oxygen absorption. Lamps with a higher radiation in the medium and long wavelength range of the visible spectra could reduce the discoloration of cured sausages. With the new LED technology the spectra can be varied by altering these parameters to create an illumination with less negative influence on color of cured boiled sausages and without thermal effect. The reduction of oxygen during the slicing and packaging process also leads to a prolonged shelf life with regard to discoloration of cured boiled sausages. Further research on new lighting technologies and on the effect of single wavelength bands in the visible spectrum is necessary to reduce the deterioration in quality of MA-packaged cured sausages.

Acknowledgements

This project was implemented under the CORNET initiative. The authors would like to thank the German Federation of Industrial Research Associations (AiF) for its financial support of the research project CureColour 49 EN/1. This project was carried out under the auspices of AiF and financed within the budged of the Federal Ministry of Economics and Technology (BMWi) through the program to promote collective industrial research (IGF).

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