Impact of raw ham quality and tumbling time on the technological properties of polyphosphate-free cooked ham

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ARTICLE INFO

Keywords: 
Water holding capacity 
Gelling properties 
Exudate 
Cooked ham 
Texture 
Technological yields

ABSTRACT

The effect of tumbling time (5 h30, 19 h and 26 h) and raw ham quality (superior, inferior or mixed quality) on the quality of polyphosphate-free cooked ham was investigated. The water holding capacity and total yield of the polyphosphate-free tumbled hams were dependent on both tumbling time and ham quality. Higher values of both parameters were obtained with an increase in tumbling time from 5 h30 to 19 h and with superior hams. The exudate after 19 h and 26 h tumbling showed a higher gel forming ability compared to 5 h30, which, in case of polyphosphate-free cooked hams produced with mixed and inferior meat quality, resulted in a better slice-ability (less holes). However, tumbling time did not affect hardness, which was only influenced by ham quality, resulting in a softer polyphosphate-free cooked ham produced with inferior ham quality compared to the other quality classes.

1. Introduction

Cooked ham is a very popular processed meat product in Europe. Regarding economic benefits and the sensorial quality, the retention of the brine is an important quality attribute of cooked ham (Offer & Knight, 1988). In addition, in the nowadays trend of pre-packed sliced cooked ham, the integrity of the ham slices is the principal determining factor in the consumers buying behaviour since the visual presence of pores, ruptures or pale and destructured zones are not appreciated (Hullberg & Ballerini, 2003), (Hugenschmidt et al., 2010). To meet both requirements, auxiliary additives are generally added during the production process of cooked ham. For example, polyphosphates are added to enhance the extraction and solubilization of the myofibrillar protein complex during tumbling (Hullberg & Lundstrom, 2004). However, due to the trend towards clean label, more natural and healthy food products, the production of high quality cooked hams becomes more important. In these products, the use of such kind of additives is strictly limited. For instance, in Flanders, cooked hams prepared with the quality label ‘Meesterlyck’ may not contain added polyphosphates or non-meat proteins (VLAM, 2019). As a consequence, the technological properties such as water holding capacity (WHC), meat binding and other texture features must be achieved by proper selection of raw ham and suitable production processes.

The most investigated cause of quality defects in cooked ham, is the inferior raw pork meat quality. Several studies have investigated the technological problems related to pale, soft and exudative (PSE) meat, characterized by a lower pH, resulting in an increased drip loss and a lighter colour as a result of denatured muscle proteins. The loss of functionality of the proteins is mainly caused by a too rapid pH-decline directly after slaughtering (Fernandez, Forslid, & Tornberg, 1994; Schafer, Rosenvold, Purslow, Andersen, & Henckel, 2002; Vanlaack, Faustman, & Sebranek, 1993). The production of cooked ham with PSE meat or low pH meat therefore results in quality deficiencies such as pores and holes (Hugenschmidt et al., 2010; Muller, 1991; Van de Perre, Ceustermans, Leyten, & Geers, 2010), colour deficiencies (McKeith & Pringle, 2013; Oliver et al., 2006) and poorer organoleptic quality (Honkavaara, 1988). The combined effect of higher cooking losses and poor sliceability when low pH meat is used for the production of cooked ham is a major economic issue (O’Neill, Lynch, Troy, Buckley, & Kerry, 2003).

Tumbling is one of the most crucial steps in the production process of cooked ham and is applied to increase the diffusion of the injected brine. The mechanical action also disrupts the muscle fibers (Katsaras & Budras, 1993), facilitating extraction and solubilization of the functional myofibrillar proteins, which ensures the water holding capacity.
of the end product (Sharedeh et al., 2012). During tumbling, the solubilized myofibrillar proteins at the surface of the ham parts form a protein exudate, which ensures the binding of the meat pieces upon pasteurization (Pancrazio et al., 2015; Pioselli, Paredi, & Mozarelli, 2011). As for the impact of the tumbling process on the quality characteristics of cooked ham, specifically, only a few studies are available. Lachowicz, Sobczak, Gajowiecki, and Zych (2003) showed that de hardness of cooked ham decreased while the viscosity of the exudate increased with tumbling time. This was in contrast to Pancrazio et al. (2015) who observed that a longer tumbling time resulted in a harder product. This could be attributed to an increased solubilization of the myofibrillar proteins, leading to a better binding of the meat pieces. Li et al. (2011) showed that cooking losses decreased with a longer tumbling time.

The objective of this study is to investigate the effect of tumbling time (5 h30, 19 h and 26 h) on the quality of cooked ham. The applied tumbling conditions are in accordance with industrial practice, as they were chosen based on a survey regarding tumbling conditions applied by Belgian producers of high quality polysphosphate-free cooked ham. While the vast majority of the above described studies was conducted on cooked hams produced with polysphosphate, this study hence focuses on high-quality polysphosphate-free cooked hams. In contrast to the above mentioned studies, the effect of tumbling time is investigated for different raw ham qualities, since the effect of tumbling time on cooked ham characteristics may depend on the raw ham quality. In this regard, a superior and inferior ham quality class was chosen as well as a quality class containing a mixture of both qualities. This mixed quality class reflects a situation where no raw ham selection occurs. This will allow to adapt the tumbling process according to the used raw ham quality for the production of high quality cooked ham. This tailored processing will enable the manufacturers of cooked ham to produce cooked ham with a constant high end quality, irrespective of the used raw ham quality. Considering the increased consumer demand for more natural and healthy food products with a restricted amount of E-numbers, the combined effect of tumbling time and raw ham quality on the technological yields and the quality in terms of water binding capacity, texture and sliceability is studied in a polysphosphate free, high quality cooked ham model. In addition the gel forming ability of the exudate has not been studied before and was also investigated, as this can give valuable information regarding the sliceability (holes, ruptures) of the end product.

2. Material and methods

2.1. Selection of raw ham meat

144 chilled raw pork hams, i.e. Musculus semimembranosus (SM), M. semitendinosus, M. adductor and Biceps femoris (BF) (weighing between 5540 and 9245 kg) were purchased from a local meat wholesale supplier. The hams were selected 12 h post mortem by measuring the pH and the electric conductivity in the SM of the hams using a pH probe (Hanna Instruments, Temse, Belgium) and Pork Quality Meter (PQM, mS) probe (I-INTEK, Aichach, Germany), respectively. In order to evaluate the influence of the raw ham quality on the technological yields and end quality of the cooked hams, the raw hams were divided in three quality classes according to the pH, i.e. (1) superior (pH 5.6–6.0), (2) inferior (pH 5.2–5.6), and (3) a mixture of both qualities (ratio superior:inferior was approximately 1:1). After deboning, trimming and defatting (24 h post mortem), pH, PQM and colour (L', a', and b'-values, MiniScan EZ 4500 L 45°/0° with 8 mm viewing area size, illuminant D65 and 10° standard observer, Hunter Associates Laboratory, Inc., Reston, VA) of the SM and BF of the hams were measured. All measurements were done on each individual ham in triplicate, both on the SM as well on the BF.

Table 1

<table>
<thead>
<tr>
<th>Steps</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Time (min)</td>
<td>7</td>
<td>1</td>
<td>52</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Temperature (° C)</td>
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<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>RPM</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Vacuum (%)</td>
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<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

2.3. Technological yields

Of each ham, the masses (g) of the raw (deboned and defatted) hams (mRAW), of the tumbled ham (mTUM), and of the end product (mPROD) were determined in order to calculate the following technological yields:

- Tumbling yield (%): TUY = 100 %. \( \frac{m_{TUM} - m_{RAW}}{m_{RAW}} \).
- Cooking loss (%): COL = 100 %. \( \frac{m_{PROD} - m_{TUM}}{m_{TUM}} \).
- Total yield (%): TOY = 100 %. \( \frac{m_{PROD}}{m_{RAW}} \).

TUY was determined during processing (after tumbling) while COL and TOY were analysed after 7 days storage at 4 °C.

2.4. Water holding capacity of the raw tumbled hams

After tumbling, per ham, one sample of the core as well as one from the surface layer of the BF were taken. The water holding capacity (WHC) of the grounded raw ham muscles was measured based on the filter paper press (PPP) method. A weight of 1 kg was placed for 5 min on 0.3 g meat sample, which was placed on a Whatman No 2. filter.
paper between two plexi glass plates. The fluid loss, caused by the pressure of the weight, was absorbed in the filter paper, forming an outer circle while the meat sample formed an inner circle on the paper. Both areas were measured using a digital planimeter (Placom KP-90 N; Topcon, Tokyo, Japan). The WHCFPP was expressed as the ratio area meat/area meat + water (cm²/cm²).

To evaluate the capability of additional swelling of the raw tumbled ham (as part of the WHC), a centrifugation test was conducted after adding 0.500 g demineralized water to 2.000 g raw ham sample in the test tube. After the water was adsorbed, the test tube was centrifuged at 10 °C for 10 min at 9500 g (Universal 320 R, Hettich zentrifugen, Tuttinglen, Germany) to expel the weakly bound water. The supernatant was removed and weighed as a measure of the capability for additional water uptake (WHCH₂O) by the raw tumbled meat.

\[
\text{WHC}_{\text{H2O}} = \frac{m_{\text{added water}} - m_{\text{supernatant}}}{m_{\text{added water}}} \times 100\%.
\]

Positive values for WHC_{H2O} indicate an additional water uptake, while negative values are indicating a loss of loosely bound water.

Both WHC measurements were performed on samples stored 1 day at 4 °C after preparation.

2.5. Gel forming ability of exudate

After tumbling, exudate of the tumbled hams was collected by taking a homogeneous sample of at least 50 g at the surface of the BF of the hams. To characterize the gel forming ability of the exudate, oscillatory rheology measurements were performed during a controlled heating and subsequent cooling step, simulating the pasteurization of cooked ham. An AR2000ex stress controlled rheometer (TA instruments, New Castle, US) was used, equipped with an efficient Peltier temperature control system and upper heated plate to control the sample temperature precisely. After loading the sample between two 40-mm parallel crosshatched plates (1000 μm gap), the exudate was heated at a constant rate of 1 °C/min from 25 to 68 °C. After holding the sample at 68 °C for 10 min, the sample was cooled to 10 °C at a constant rate of 1 °C/min. These oscillation measurements were performed at a constant frequency of 1 Hz and a strain of 0.04, within the linear viscoelastic region. Storage modulus (G') and phase angle (δ) and the end of the cooling phase (10 °C) were obtained directly from the software (Rheology Advantage, TA version 5.7). The gel forming ability of the exudate was determined at least in duplicate per production process after storing the samples in the freezer (−18 °C) for 3 months.

2.6. Quality attributes of cooked ham

The texture of the SM muscle of the cooked ham was evaluated using a Texture Analyzer (Model LF plus, Lloyd Instruments, Hampshire, England), equipped with a cylindrical probe (diameter 6 mm), as described by Steen et al. (2014). The hardness of the SM and BF was measured as the maximum force (N) required for the penetration of the probe, 2 cm into the muscle at a speed of 100 mm/min. Three replicate slices of 5 cm thickness were tested from each cooked ham.

The evaluation of the sliceability of each cooked ham was performed by slicing 0.75 cm thick slabs using a manual gravity feed slicer (GSP, Bizerba, Balingen, Germany). The visual evaluation was based on two parameters whereby higher scores corresponded to a higher degree of imperfection: (a) rupture (score 0–3) with 0 = no ruptures, perfectly shaped cooked ham; 1 = very small, unclear ruptures, not entirely perfect cooked ham; 2 = clear ruptures but still cohesive cooked ham and 3 = many ruptures with meat pieces falling apart and (b) holes (score 0–4) with 0 = no holes, nicely shaped cooked ham; 1-2-3 = intermediate size and number of holes; 4 = many and/or large holes. Three slices were evaluated from each cooked ham. The texture measurement and evaluation of the sliceability were performed at 4 °C, 7 days after preparation.

2.7. Statistical evaluation

Results are expressed as mean values ± standard error (n = 16 for all parameters expect for gel forming ability where n ≥ 4). Statistical analysis was performed using IBM SPSS Statistics 22. Two-way ANOVA was applied to study the effect of raw ham quality, tumbling time and their interaction on the yields and quality of the cooked ham. In case the two-way ANOVA showed significant (p < .05) interactions, these interactions were further interpreted and Tukey’s post hoc tests were performed.

3. Results and discussion

3.1. Raw ham selection and characteristics

The quality parameters (pH, PQM and colour values) of the raw pork hams, measured during selection and after deboning/defatting of the hams are shown in Table 2. As intended in the experimental set-up and statistically demonstrated in Table 2, the raw hams were divided into three quality classes based on the pH values measured 12 h post mortem on the SM with significant (p < .05) higher pH-values related to higher quality classes. Although the pH slightly changed between the time of selection (12 h post mortem) and the time of deboning the hams (24 h post mortem), significant (p < .05) pH differences between the three different quality classes were maintained.

With regard to the PQM values, no significant differences between the superior and mixed quality class could be observed. Only the inferior class showed significantly (p < .05) higher PQM-values.

As for the colour parameters, it is clear from Table 2 that the different quality classes, in this research determined by pH, showed no significant difference in lightness (L⁎) or redness (a⁎) while the b⁎ values (yellowness) were significantly (p < .05) higher with decreasing quality. Other studies (Bendall & Swatland, 1988; Lindahl, Henckel, Karlsson, & Andersen, 2006; Van de Perre et al., 2010) did not only show a negative correlation between the pH measured 24 h post mortem and b⁎, but also between pH and L⁎, attributed to protein inactivation of oxygen-consuming enzymes and protein denaturation (Lindahl et al., 2006).

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quality class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Superior</td>
</tr>
<tr>
<td>pH</td>
<td>5.77 ± 0.01a</td>
</tr>
<tr>
<td>SM₁₂h</td>
<td>5.70 ± 0.02b</td>
</tr>
<tr>
<td>BF₂₄h</td>
<td>5.74 ± 0.02b</td>
</tr>
<tr>
<td>PQM (mS)</td>
<td>10.4 ± 0.5ab</td>
</tr>
<tr>
<td>SM₁₂h</td>
<td>11.5 ± 0.5a</td>
</tr>
<tr>
<td>BF₂₄h</td>
<td>15.4 ± 0.3a</td>
</tr>
<tr>
<td>Colour</td>
<td>47.32 ± 0.49a</td>
</tr>
<tr>
<td>L⁎ SM₄₀m</td>
<td>46.92 ± 0.36a</td>
</tr>
<tr>
<td>a⁎ SM₄₀m</td>
<td>10.02 ± 0.30a</td>
</tr>
<tr>
<td>b⁎ SM₄₀m</td>
<td>12.95 ± 0.27b</td>
</tr>
<tr>
<td>BF₂₄h</td>
<td>15.73 ± 0.21a</td>
</tr>
<tr>
<td>SM₁₂h</td>
<td>18.46 ± 0.19b</td>
</tr>
</tbody>
</table>

Mean values and standard errors (n = 48) are presented. One-way ANOVA was carried out to evaluate effect of quality class. Superscripts a-b: different small letters indicate significant differences (p < .05) between different quality classes.
by means of the filter paper press method (WHCFPP), samples of the injected ham and thus a decreased TUY.

However, during extensive tumbling, a great part of the excreted proteins can be released from the cells. After tumbling, part of these proteins can be adsorbed during tumbling, the expected tumbling yield TUY should be lower than the TUY at 5 h 30. During tumbling, mechanical damaging of the meat structure occurs whereby the salt soluble meat proteins are solubilized proteins, increasing the WHC of the tumbled hams. How-ever, the positive impact of tumbling on the mechanical functional-ization of the proteins, reflected as the WHCFPP, is limited. Increasing the tumbling time to 26 h did not further enhance the WHCFPP, which is probably due to maximum solubilization of the proteins at a tumbling time of 26 h. As far as the authors are aware there are no studies available regarding the WHC of tumbled hams, so comparison with other literature was not possible. Furthermore, it has to be noted that the mean values for the WHCFPP of SL samples were higher than those of C of the same tumbled ham (Table 3). This is probably attributed to more extracted and solubilized proteins of the surface exudate sample compared to the core sample, which increases the WHC.

As discussed earlier, TUY is not influenced by the quality class. However, as for the WHCFPP of SL, the superior hams showed significantly (p < .05) higher values than the hams of the inferior and mixed quality classes while no significant difference could be obtained between the latter.

While the WHCFPP is a measure of the ability of proteins to retain the water adsorbed during tumbling, the centrifugation test conducted after the addition of extra water to the tumbled meat (WHCH₂O) gives an idea of the possibility of additional water uptake. In line with the results of the WHCFPP, differences between the WHCH₂O of the C and SL were observed. In the core samples, mainly negative WHCH₂O values were measured. This indicates that even the water which was initially already present in the tumbled hams could not be retained during the centrifugation test. Furthermore, regarding the investigated variables, only the impact of tumbling time was significant (p < .05) for the core samples. In comparison to the shortly tumbled hams (5 h 30), a significant (p < .05) increase of WHCH₂O was seen after longer tumbling processes. After 19 h tumbling, the core samples were able to retain a small percentage of the added amount of water. However, a further increase of the tumbling time could not contribute to an improved WHCH₂O. Moreover, as the mean WHCH₂O-value after 26 h tumbling was slightly negative, it seems that a prolonged tumbling process may even slightly decrease the ability to retain water, however these trends were not significant.

For the samples taken at the surface of the tumbled BF muscle (SL), in comparison to the WHCH₂O-values of the core samples (C), the same
trend can be observed. Furthermore, although not significant for the core samples, the ham quality also affects the WHC_{H2O} of the surface samples, resulting in a significantly (p < .05) higher value for the superior ham quality. In cooked ham products, water retention is dependent on protein extraction and gelation (O’Neill et al., 2003). Taking that into account, the significantly higher WHC of the superior ham class is probably attributed to less denaturation of proteins caused by a higher pH of the raw meat.

Since the means for the WHC_{H2O} measured at the surface layer were all positive and higher than the ones measured in the core, it can be concluded that the mechanical action of tumbling time has a more pronounced positive effect at the surface layer. The greater impact of the tumbling process on the disruption of the meat cells in the surface layers of the hams (Rejt, Kubicka, & Pisula, 1978) may result in a more easy salt-induced swelling of the myofibrils when the endomysium layer, which encloses the muscle fiber, is weakened (Trout, 1988).

With regard to the WHC, measured by both methods, it is clear that the use of superior raw hams and an intermediate tumbling time (regardless of the raw ham quality) for the production of cooked ham is preferred.

### 3.3. Cooking losses and total yield

A significant (p < .05) interaction was found between the impact of tumbling time and raw meat quality on cooking loss (COL). From Fig. 1, it is clear for all quality classes, although not significant for the inferior quality class, that an increase in tumbling time from 5 h30 to 19 h resulted in a lower COL which can be explained by the higher degree of solubilization of the myofibrillar proteins. However, a further elongation of the tumbling time from 19 h to 26 h did not result in a further decrease of COL (%). For the inferior quality hams, the positive effect of tumbling time is not significant, probably due to partial denaturation of proteins which cannot be fully compensated by a longer tumbling process. Li et al. (2011) investigated the effect of tumbling time on the quality attributes of cooked ham. Although the investigated tumbling times (2, 4 and 6 h) were shorter and the muscles were diced into cubes for the production of restructured cooked hams, compared to the present study, Li et al. (2011) also observed lower cooking losses with a longer tumbling time. Regarding the total yield (TOY), no interaction could be obtained between both variables. It can be seen in Table 3 that a longer tumbling time resulted in a significantly higher TOY of the cooked ham production (p < .01), irrespective of the raw ham quality. However, in accordance to COL, TOY was not influenced when the tumbling time was increased from 19 h to 26 h.

Furthermore, with regard to the impact of raw ham quality, higher cooking losses for cooked hams processed with inferior quality compared to the superior class were only significant (p < .05) for 19 h tumbling time, as seen in Fig. 1. As for TOY in Table 3, inferior ham quality resulted in cooked hams with significantly (p < .05) lower total yields compared to the superior ham quality class.

### 3.4. Gel forming ability of exudate

The gel forming ability of the exudate was studied by simulating the pasteurization process (i.e. heating and subsequent cooling step) in a oscillatory rheometer. In order to study the effect of tumbling time and raw ham quality, G’ values at the end of the cooling process (G’_{end}) were statistically analysed. These results are presented in Fig. 2. There was no interaction between tumbling time and ham quality. Furthermore, only tumbling time had a significant effect (p < .05) while G’_{end} was not influenced by ham quality. Increasing the tumbling time from 5 h30 to 19 h resulted in a significantly higher G’_{end} (p < .05), while δ hardly varied (results not shown), indicating a higher gel forming ability of the exudate. From literature it is clear that tumbling is applied to increase the diffusion of the brine and to extract and solubilize the myofibrillar proteins in the presence of salt (and polyphosphate) (Pioselli et al., 2011; Rakotondramavo, Rabesona, Brou, de Lamballerie, & Pottier, 2019). During the tumbling process, the extracted solubilized proteins at the surface of the tumbled ham create a sticky layer of exudate (Hullberg & Lundstrom, 2004; Pancrazio et al., 2015). During pasteurization, denaturation and gelation of the proteins in the exudate occur which acts as a sort of glue, ensuring the bonding of the muscle.
mass and contributing to the sliceability and texture of cooked ham (Pioselli et al., 2011; Rakotondramano et al., 2019). Lachowicz et al. (2003) investigated the effect of tumbling time (2, 4, 6, 8, 10 and 12 h) on the viscosity of exudate from three pork ham muscles. They concluded that the exudates of the muscles became more viscous with increasing tumbling time, with a maximum viscosity obtained after 12 h tumbling. Although they did not give an explanation, the increased viscosity is probably attributed to more extracted proteins in the exudate. The effect of a longer tumbling time (from 5 h30 to 19 h) on the increase of $G'_\text{end}$ in the present study may also be explained by more extracted proteins present in the exudate, leading to more protein denaturation and the formation of a more aggregated protein gel-network during the process simulation. However, a further increase from 19 h tumbling time to 26 h did not affect $G'_\text{end}$, which is an important finding of this study since the exudate is responsible for the binding of the ham parts upon pasteurization. This means that increasing the tumbling time from 19 h to 26 h will not generate a stronger aggregated protein-gel network, resulting in stronger binding of the ham parts. The fact that a longer tumbling time (26 h) did not result in an increase in $G'_\text{end}$ may be attributed to maximum solubilization of the proteins at a tumbling time of 19 h. As far as the authors are aware, no studies are available regarding extended tumbling times and the effect on the gel forming ability of the exudate so comparison with literature could not be made.

3.5. Quality of the end product

In Table 4, the investigated quality characteristics of cooked ham are shown.

Statistical analysis showed no interaction between both factors for hardness SM. Raw ham quality affected hardness SM of cooked ham while tumbling time had no impact. The fact that tumbling time did not affect hardness is in contrast to Pancrazio et al. (2015) who concluded that the hardness of cooked ham increased with a longer tumbling time while the opposite effect was concluded in the study of Lachowicz et al. (2003). As seen in Table 4, in general, hardness SM was significantly (p < .05) higher for the cooked hams prepared with superior ham quality than those prepared with inferior ham quality. From literature, it is clear that the functional properties of the myofibrillar proteins, like gelling properties, are strongly influenced by the pH (Sun & Holley, 2011). Consequently, it is likely that the significantly (p < .05) higher hardness of the cooked hams prepared with superior ham quality with a higher pH can be attributed to the better gelation properties resulting in a harder texture of cooked ham. Zhang and Barbut (2005) investigated the effect of high, normal and low pH broiler breast meat on the textural and rheological characteristics from chopped cooked meat pieces mixed with 0.6 M sodium chloride solution. They also saw a significantly higher hardness for the high pH meat compared to the low pH meat, attributed to the formation of a more rigid gel during cooking.

For the evaluation of the sliceability, a significant (p < .01) interaction was obtained for both parameters (ruptures and holes). From Table 4, it is clear that processing cooked hams with superior ham quality (high raw pH) results in good sliceability quality with only small imperfections (ruptures and small holes) in the cooked hams, even at a short tumbling time. This is in contrast to cooked hams prepared with lower raw ham quality (inferior class) and thus lower raw ham pH that showed clearly more holes and ruptures at 5 h30 tumbling time. Indeed, as Muller (1991) stated, hole formation is greater in cooked hams prepared with low pH meat than hams with high pH meat. Furthermore, for the inferior and mixed ham quality class, a significant (p < .05) reduction of holes, to the same extent as cooked hams prepared with superior ham quality, was obtained when the tumbling time was increased. This reduction of holes at longer tumbling times may be attributed to the significantly (p < .05) higher gel forming ability ($G'_\text{end}$) of the exudate (Fig. 2), responsible for the binding of the ham parts. For the ruptures, however, tumbling time only positively affected the mixed quality class while the inferior ham quality class was not influenced by tumbling time, resulting in cooked hams with more ruptures compared to the other ham quality classes with higher raw ham pH. These results are in agreement with Hugenschmidt et al. (2010), who investigated the sole effect of pH (24 h post mortem) on the level and amount of destructured zones in cooked ham and stated that cooked hams prepared with raw hams with pH-values lower than 5.5 (inferior ham quality) can result in more destructured zones in the cooked hams compared to raw hams with pH values above 5.7 (= superior ham quality).

From these results it is clear that for the production of cooked ham, injected with a brine that contains no polyphosphate, superior ham quality and a higher tumbling time (19 h or 26 h) are both equally important in achieving a high quality cooked ham with a low cooking loss and a high total yield. This is probably even more important when the brine would contain less salt. As Bombrun, Gatellier, Carlier, and Kondjoyan (2014) demonstrated that non-salted meat resulted in a lower breaking stress between two pieces of tumbled meat compared to salted meat. On the other hand, in case polyphosphate and/or binding agents such as starch would be added to the brine, these ingredients contribute significantly to the technological properties of cooked ham (Resconi et al., 2016). In this case, raw ham quality and tumbling time would probably have less impact on the technological properties.

Table 4

Effect of tumbling time and raw ham quality on texture and sliceability of cooked ham.

<table>
<thead>
<tr>
<th>Tumbling time (TT)</th>
<th>Quality class (QC)</th>
<th>Average by TT</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Superior</td>
<td>Inferior</td>
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<tr>
<td>Textures</td>
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<tr>
<td>Hardness SM</td>
<td>21.3 ± 0.8</td>
<td>20.7 ± 0.7</td>
</tr>
<tr>
<td>19 h</td>
<td>22.1 ± 0.6</td>
<td>20.3 ± 0.7</td>
</tr>
<tr>
<td>26 h</td>
<td>22.2 ± 0.6</td>
<td>19.0 ± 0.5</td>
</tr>
<tr>
<td>Slicability</td>
<td>21.9 ± 0.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.0 ± 0.4&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ruptures</td>
<td>1.4 ± 0.1&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>2.3 ± 0.1&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>19 h</td>
<td>1.3 ± 0.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.1 ± 0.2&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>26 h</td>
<td>0.9 ± 0.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.4 ± 0.1&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Holes</td>
<td>1.6 ± 0.1&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>2.4 ± 0.2&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Mean values and standard errors (n = 16) are presented. Two-way ANOVA was performed to evaluate effect of quality class (QC) and tumbling time (TT). Superscripts a-b: different small letters indicate significant differences (p < .05) between different quality classes. Superscripts 1–2: different numbers indicate significant differences (p < .05) between different tumbling times. Superscripts A-B: different capital letters indicate significant differences (p < .05) for TT × QC.
4. Conclusions

Both WHC and TOY of phosphate-free high quality ham were higher when superior ham quality was used compared to inferior quality, resulting in a harder texture and better sliceability. Furthermore, a higher tumbling time influenced the WHC and TOY positively and led to a better gel forming ability of the exudate. In case of polyphosphate-free cooked hams produced with inferior and mixed ham quality, this resulted in a better sliceability (less holes).

For the production of high quality polyphosphate-free cooked ham, it is clear from this study that the use of superior ham quality combined with an intermediate tumbling time (19 h) results in superior technological properties. These influencing factors probably become less important when the brine composition is less critical, i.e. when phosphate and/or other binding agents are used. However, raw hams with inferior quality or mixed quality hams can also be used for the processing of high quality cooked hams when a sufficiently long tumbling time is applied (19 h). Yet, in order to fully characterize the quality of these end products, sensory (consumer) evaluation needs to be performed, in addition to the technological properties included in this study.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgement

The authors thank the Flemish government agency for Innovation by Science and Technology (IWT) and cooperating companies for the funding of TETRA project 130 195 ‘Kookham Doorgelicht’.

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