The use of elastography to measure quality characteristics of pork *semimembranosus* muscle

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Received 2 December 1998; received in revised form and accepted 22 February 1999

Abstract

The objectives of this study were to determine if ultrasonic strain image analysis could estimate pork eating quality parameters (such as fresh color, drip loss, and Warner/Bratzler shear). Intact *semimembranosus* (SM) muscles (cap off) were analyzed for ultimate pH (pH<sub>ult</sub>). Forty-five SM muscles were selected from the larger allotment of fresh hams over a 3-week period. The SM muscles were selected based on high and low pH<sub>ult</sub> in an attempt to represent a wide range of pork quality. Ultrasonic strain images were obtained perpendicular to the SM muscle fibers of an 8-em cube. Radio-frequency data from each SM were obtained from a field-of-view (FOV) of 40×30 mm<sup>2</sup> and digitized for each compression step. Tissue displacements were computed for each compression step. Tissue strains were computed from displacement data located in the FOV representing areas of harder and softer muscle tissue and converted to gray scale images at 256 levels. Tissue irregularity of hardness and softness was measured using Fractal dimension and Haralicks parameters. Twenty-one Fractal dimension (FR) parameters, at two neighborhood distances (N), from each strain image and nine Haralicks' (HAR) textual parameters (inter-pixel distance = 1) were analyzed for each image. The variable FR<sub>4/4</sub> had a −0.279 correlation with SM ultimate pH (p<0.10); FR<sub>6/8</sub> correlated to WB shear force at 0.325 (p<0.05); and FR<sub>21/8</sub> had a correlation coefficient of 0.364 with intramuscular fat (p<0.01). Linear regression equations generated from FRN and HAR parameters for intramuscular fat (R<sup>2</sup>=0.468), Warner/Bratzler shear (R<sup>2</sup>=0.360), and 30 h drip loss (R<sup>2</sup>=0.208). Although elastographic measurement was significantly correlated to shear (p<0.05), a better understanding of physical meat texture is necessary before elastography can be used to identify superior quality pork. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Pork quality; Ultrasound; Elastography; Texture parameter

1. Introduction

Elastography uses ultrasonic pulses to quantitatively measure tissue displacement, or strain, in response to an externally applied stress whereby an ultrasonic image is generated, the muscle is compressed, followed by capture of another ultrasonic image. Comparison of pre- and post-compression signals within the ultrasonic region of interest display strain values associated with the lean tissue. The computed strain values related to harder and softer regions within the ultrasonic field of view (FOV) are displayed in the form of a gray scale image, termed the elastogram by Ophir, Cespedes, Ponnnekanti, Yazdi, and Li (1991). Within the elastogram (strain image), lighter pixels correspond to softer, more elastic structures (Ophir, Miller, Ponnnekanti, Cespedes, & Whitaker, 1994). Ophir et al. (1994) reported that with the use of ultrasonic elastography it was possible to identify structures in beef *longissimus* and *semimembranosus* muscles that are not typically seen, or not well identified, by standard ultrasonic techniques. The texture seen in the strain image is characterized by a complex network of circular features consistent with the appearance of the muscle bundle network seen on the cut lean surface at the samples region of interest (Kallel, Berg, Miller, & Ophir, 1998). These circular areas appear relatively inelastic in the strain image and are
surrounded by regions of higher strain (more elastic regions) that may be related to muscle bundles sliding over one another, perimysial connective tissue, or intramuscular fat. An elastographic strain image displays areas of harder and softer tissue components within the lean tissue that is being evaluated.

Efficient production of high quality, lean pork will require animals with a high percentage of carcass lean combined with acceptable eating quality characteristics such as intramuscular fat, tenderness, and juiciness. The objective of this study was to determine if ultrasonic strain image analysis could be used to estimate pork eating quality parameters attributed to meat toughness (Warner/Bratzler shear), drip loss, and intramuscular fat.

2. Materials and methods

2.1. Sample selection

Hams were delivered in a refrigerated truck from Hormel Foods (Austin, MN) to the Rosenthal Meat Science and Technology Center (College Station, TX) arriving between 3 and 4 days post-slaughter. Hams were weighed upon arrival, and dissected into knife-separable subcutaneous fat, lean, intramuscular fat, and bone. The intact semimembranosus (SM) muscle (cap off) was analyzed for ultimate pH (pH_{ult}) by insertion of a Hanna pH meter (model HI9025C, Hanna Industries, Italy). Forty-five SM muscles were selected from the larger allotment of fresh hams over a 3-week period. The SM muscles were selected based on high and low pH_{ult} in an attempt to represent a wide range of fresh pork quality.

One 2.54-cm thick steak was removed perpendicular to the muscle fiber arrangement from the center of the SM muscle. Steaks were cooked on a Farber-ware Open-Hearth electric broiler until they reached an internal temperature of 35°C. Steaks were then turned and cooked to an internal temperature of 70°C. Cooking temperature was monitored with thermocouple wire inserted into the geometric center of the steak. Cooked steaks were placed on a tray and covered with clear plastic wrap and allowed to cool to approximately 23°C. Six 1.27-cm-diameter cores were removed parallel to the longitudinal orientation of the muscle fiber from the center of the steak. Each core was then sheared in the center by the Warner/Bratzler shear (WBS) machine and an average shear calculated. Two 20-g samples (of approximately similar volume) were cut from the remaining muscle tissue, weighed, suspended for 30 h in ham netting at 4°C, then re-weighed for determination of 30 h drip loss. L*-values were recorded as an average of three separate measurements obtained along the fresh cut surface of the SM muscle using a Minolta chromameter (model CR-310; Minolta Corporation, Ramsey, NJ) standardized to a white tile. A second steak was removed from the SM, trimmed of external fat, and analysis of intramuscular fat (IMF) was determined by ether extraction.

2.2. Strain Image Acquisition

A section of SM muscle (approximately 80×80 mm²) was removed parallel and perpendicular to the muscle fiber arrangement, vacuum packaged, and delivered to the Ultrasonics Laboratory in the Department of Radiology at the University of Texas Health Science Center (Houston, TX) 4 or 5 days postmortem. Ultrasound data were obtained perpendicular to the muscle fibers using a Diansonic Spectra II (Diansonic Inc., Milpitas, CA) medical ultrasound scanner equipped with a 5 MHz linear array transducer inserted into a central window opening of a custom rectangular aluminum compression plate. Muscle samples were precompressed to allow acoustic contact with the lean surface. Samples were incrementally compressed in a step of approximately 0.5% applied strain. Compression was controlled electronically by computer generated instruction. Radio-frequency data consisting of 100 A-lines (radio-frequency signals) were obtained from the muscle samples from a FOV of 40×30 mm² and digitized for each step. Tissue displacements in the FOV were computed by a cross-correlation technique on successive radio-frequency signal pairs (Ophir et al., 1991). Cross-correlation analysis of the pre- and post-compression radio-frequency frames was used to obtain tissue displacement estimates to generate a strain image. A window size of 1.8 mm with 60% overlap was used for all samples. Comparison of pre- and post-compression signals localized strain values can be determined from the lean sample and converted to Young's modulus (YM; YM = stress/strain) values. Tissue strains were computed from displacement data using a least-square-strain-estimator (Kallel & Ophir, 1997). Each strain distribution was converted to gray scale images of 256 levels. The lighter areas within the image correspond to areas of higher strain (an application of inverse YM) which are more elastic (Fig. 1).

2.3. Image Analysis

Ultrasonic images of biological tissue typically have a degree of randomness associated with both the random nature of the measured structure in addition to the random noise generated by reflection of the ultrasonic signal. The randomness associated with ultrasonic images and the biological tissue can be exploited with elastography that maps the strain (relative hardness and softness) of the biological tissue relative to the compression applied to the surface of the meat sample. Textural features have
been widely used to perform image classification and image segmentation. Two textural approaches were used in extracting features from the images.

The first textural approach extracted second order statistical features from the image co-occurrence matrices (Haralick, Shanmugan, & Dinstein, 1973). Co-occurrence matrices were derived in four spatial directions 0°, 45°, 90°, and 135° at an interpixel distance of 5 and then averaged to account for all spatial orientations. Haralick’s parameters (Haralick et al.) serve as good discriminators of various strains depicted in the elastographic images. The Haralick’s features extracted from the resultant co-occurrence matrix were (1) maximum probability; (2) moments; (3) contrast; (4) homogeneity; (5) entropy; (6) correlation; (7) information measure of correlations (1) and (2), and (8) angular second moment as described in Haralick et al. and Haralick and Shapiro (1992).

The second textural approach viewed the strain image as a Fractal surface. If the gray level values are considered to be heights protruding above a plane, then the image can be treated as a rugged surface. Gray level surface areas were measured at several resolutions. The area decreased at higher resolutions as finer details started disappearing. This change relative to scale, gave a measure of surface roughness at various scales. For a pure Fractal object, the ratio known as Fractal dimension (FD) remains the same at all scales. However, for non-Fractal surfaces (such as an elastogram image) the FD changes at each scale thereby depicting the underlying texture. The analysis used a neighborhood of 4 and 23 scales to generate 21 Fractal signatures that were equal to 2-FD (Peleg, Noar, Hartley, & Noar, 1984). High values of signatures at small scale imply high-frequency information, similarly higher values of signatures at large scales result from significant low-frequency information. Effectively various values of signatures translated into different underlying strains in the meat (i.e. the strength of a signature reflected the strength of a strain).

2.4. Statistical Analysis

Gray scale thresholds were classified for nine Haralick’s parameters and 21 Fractal signatures. Stepwise linear regression analysis (SAS, 1991) was used to identify independent variables significant (p < 0.05) for estimation of drip loss, IMF, WBS, SM muscle lightness ($L^*$-value), and SM muscle pH.

3. Results and Discussion

Ultimate pH is not a pork quality measure, but rather a predictor of quality parameters such as drip loss and meat color. The correlation between pHUlt and drip loss has been reported to range between −0.38 to −0.61 (van der Wal, de Vries, & Eikelenboom, 1995). Kauffman and Animal Science 405 (1997) reported a correlation of −0.47 and −0.53 between pHUlt and percentage lean sample drip loss (%drip) representing the ham and loin, respectively. Correlation coefficients between FR4N4
and FR2N8 and pH_{ult} were −0.279 (p = 0.07) and −0.256 (p = 0.08), respectively. Individual elastography parameters were not significantly correlated (p > 0.05) to drip loss and L* value (Table 1).

Direct measurement of carcass or individual muscle pH and/or light intensity with a pH meter or chromameter is considerably less labor intensive than elastography. Traditional methods to estimate meat palatability or tenderness are also quite laborious and time consuming. The most common instrument used for objective measurement of meat tenderness is the Warner/Bratzler shear device that measures the amount of force necessary to shear through a cylindrical sample of meat. Time is needed for removal of a steak, cooking, cooling, coring and shearing. An ultrasonic means for identification of tender meat could be performed by noninvasive means. The Fractal parameter, FR2N8, was significantly correlated (p < 0.05) to WB (r = 0.325; Table 1). Strain image analysis of fresh lean tissue may provide a non-invasive means of determining muscle tenderness. Houghton and Turlington (1992) provide a review of ultrasonic applications for feeding and finishing meat animals, reporting the range of correlations between ultrasonic image analysis and beef marbling to range

### Table 1

Correlation coefficients for selected strain-image textural features (Fractal and Haralick) and quality parameters derived from fresh pork *semimembranosus* muscle

<table>
<thead>
<tr>
<th>Shear force</th>
<th>pH in GM</th>
<th>pH in SM</th>
<th>Drip loss</th>
<th>L* in SM</th>
<th>%IMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4N4</td>
<td>NS</td>
<td>NS</td>
<td><em>−0.279</em>**</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR5N4</td>
<td>0.289***</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR6N4</td>
<td>0.312**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR7N4</td>
<td>0.317**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR20N4</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR21N4</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR22N8</td>
<td>NS</td>
<td>NS</td>
<td>−0.256***</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR6N8</td>
<td>0.325**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>FR21N8</td>
<td>NS</td>
<td>−0.344**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* FR = Fractal parameter; N = Fractal parameter neighborhood distance.

* p < 0.01; ** p < 0.05; *** p < 0.10.

### Table 2

Prediction equations for estimating quality parameters derived from fresh pork *semimembranosus* muscle

<table>
<thead>
<tr>
<th>Equation number</th>
<th>Dependent variable</th>
<th>Independent variable(a)</th>
<th>Intercept</th>
<th>β values(b)</th>
<th>R²</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>pH of SM</td>
<td>HAR6, HAR2, FR3N4</td>
<td>11.860</td>
<td>−0.0068</td>
<td>0.258</td>
<td>0.297</td>
</tr>
<tr>
<td>(2)</td>
<td>Drip loss</td>
<td>HAR3, HAR6, FR1N8</td>
<td>−10.963</td>
<td>0.0534</td>
<td>0.208</td>
<td>2.34%</td>
</tr>
<tr>
<td>(3)</td>
<td>L* in SM</td>
<td>FR12N4, FR1N8</td>
<td>40.277</td>
<td>−47.9794</td>
<td>0.180</td>
<td>3.50</td>
</tr>
<tr>
<td>(4)</td>
<td>% Intramuscular fat</td>
<td>FR21N8, FR1V4, FR2N8, HAR7, FR3N8</td>
<td>4.4057</td>
<td>61.9395</td>
<td>0.468</td>
<td>1.53%</td>
</tr>
<tr>
<td>(5)</td>
<td>Shear force</td>
<td>FR6N8, HAR4, HAR3, HAR7</td>
<td>−31.9156</td>
<td>11.6753</td>
<td>0.360</td>
<td>1.01 kg</td>
</tr>
</tbody>
</table>

(a) Fractal dimension parameters are defined as FR = Fractal parameter; N = Fractal parameter neighborhood distance. Haralick’s parameters are HAR2 = inverse difference moments; HAR3 = contrast; HAR4 = homogeneity; HAR6 = correlation; HAR7 = information measure of correlation −1/2.

(b) Independent variables significant at p < 0.10 according to stepwise regression analysis.
from 0.20 to 0.91. The authors believe that the ability of real-time ultrasound to predict marbling remains unclear and requires further investigation. Advancements in ultrasonic equipment and the use of artificial intelligence have provided improved ultrasonic evaluation of marbling since Houghton and Turlington. Brethour (1994) reported that estimating marbling score in live cattle from ultrasonic images, using pattern recognition and neural network procedures, could predict USDA carcass marbling scores within 0.42 marbling score units. Marbling in pork has decreased with increased selection for leaner genetics (Goodwin, Miller, Berg, & Christian, 1998). Ragland, Broendum, Baas, and Christian (1997) found marginal success for determination of IMF from ultrasonic scans of porcine m. longissimus. Evaluation of textural parameters within traditional live animal ultrasonic images was obtained on market weight pigs. Pearson and Spearman correlation coefficients between actual and predicted IMF were 0.70 and 0.69, respectively. Sather, Bailey, and Jones (1996) found that real-time ultrasonic images of either live pigs or pork carcass longissimus muscle were unable to accurately evaluate IMF or subjective marbling score. Fractal dimensions from Elastography images of lean tissue samples in this study had small correlations to IMF. The correlation coefficient between FR21 N8 and IMF was 0.364 ($p < 0.01$; Table 1).

Table 2 includes linear regression equations incorporating textural parameters for estimation of five different quality attributes. Eq. (1) uses two Haralick and one Fractal parameter to explain 25.8% of the variation in SM pH with a residual standard deviation (RSD) of 0.297 pH units. Eq. (2) explains 20.8% (RSD = 2.34%) of the variation associated with drip loss and Eq. (3) explains 18.0% (RSD = 3.50 $L^*$ units) of the variability of light intensity. Eq. (4) uses four Fractal parameters and one Haralick to do a marginal job of estimating the percentage of chemically defined intramuscular fat, accounting for 46.8% of the variation with a RSD of 1.53%. Eq. (5) was capable of explaining 36.0% of the variability associated with kg of shear force with a RSD of 1.01 kg.

Haralick’s textural parameters and Fractal dimension have been extensively utilized for texture analysis, and serve as good discriminators of various strains associated with ultrasonic imaging of biological tissue. More research is necessary to understand the physical texture of meat and how it relates to elastic and non-elastic regions within an elastogram.

Acknowledgements
Funding for this research was provided in part by a grant from the National Pork Producers Council.

References