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Review

Understanding postmortem biochemical processes and post-harvest aging factors to develop novel smart-aging strategies

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A B S T R A C T

Postmortem aging is a value-adding process and has been extensively practiced by the global meat industry for years. The rate and extent of aging impacts on meat quality characteristics are greatly affected by various biochemical/physiological changes occurring during the pre-rigor phase through post-rigor aging processes. This should also mean that the positive aging impacts on eating quality attributes can be further maximized through establishing specific post-harvest aging strategies. In this review, we propose the smart-aging concept, which is to develop innovative template strategies through identifying optimal aging regimes to maximize positive aging impacts on meat quality and value. The concept requires a good understanding of the physical, biochemical and post-harvest factors that affect the aging of beef. This knowledge coupled with the ability to non-invasively determine muscle composition early postmortem will create opportunities to tailor the process of muscle conversion to meat and the subsequent aging processes to deliver meat with consistent and improved eating qualities and functionality.

1. Introduction

Providing consistently high-quality meat products to meet consumer satisfaction is critical to the continued success of the meat sectors (Smith, Tatum, & Belk, 2008). Beef palatability characteristics, such as tenderness, juiciness, and flavor, are considered to be among the most important value-determining factors affecting consumers' meat purchasing decision (Savell et al., 1987; Smith, Tatum, and Belk, 2008). In fact, numerous studies have reported that consumers are willing to pay premiums for meat products with guaranteed eating quality (Miller, 2001; Polkinghorne & Thompson, 2010; Polkinghorne, Thompson, Watson, Gee, & Porter, 2008).

Post-harvest meat processing practices, particularly aging, are well-documented to play a pivotal role in the establishment of beef palatability. Noticeable improvements in eating quality occur during aging through the action of proteolytic systems inherent in meat. Postmortem aging is a value-adding process and has been extensively practiced by the global meat industry for years. Various forms of aging are practiced, ranging from traditional carcass hanging to packaging sub-primals or portion-cuts in vacuum bags for a certain duration of cooling storage. While postmortem aging has a substantial positive impact on the development of meat palatability in general, the specific conditions to maximize aging impacts on meat quality attributes have not been fully established.

Controlling key factors that affect the rate and extent of aging impacts is highly relevant to the development of effective strategies to improve meat quality and value. Thus, in this review, we propose that the effects of postmortem aging impacts can be optimized by identifying specific aging parameters and applying them for targeted meat eating quality outcomes. The strategies involved in tailoring aged-meat outcomes to fit purposes is termed "smart-aging". Smart-aging can be defined as a broad conceptual system to lead to a development of innovative template strategies to improve meat quality and value through specifically tailored/controlled post-harvest aging conditions. Given the impacts of aging on meat quality are highly dependent upon various biological/biochemical and post-harvest processing factors, the comprehensive understanding of those key factors is highly relevant to the development of effective smart-aging strategies to maximize the positive impacts of aging. Further, although the term, aging, generally implies extended cold-storage of fresh muscle far beyond the onset of

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rigor, it has been well-established that early postmortem biochemical processes have profound impacts on proteolytic enzyme activities, subsequently affecting the aging potential for meat tenderization (Dransfield, 1994; Hwang & Thompson, 2001; Melody et al., 2004; Ouali et al., 2006). Also, the role of apoptosis and anti-apoptotic function of heat shock proteins in meat tenderization have been highlighted by various studies (Herrera-Mendez, Becila, Boudjellal, & Ouali, 2006; Ouali et al., 2013; Sentandreu, Coulis, & Ouali, 2002). Therefore, it is essential to understand the early postmortem biochemical processes to develop an effective smart-aging strategy.

In this review, therefore, we will first discuss a brief overview of postmortem aging impacts on meat quality attributes. Then, we will elaborate the effects of early postmortem biochemical processes and their subsequent impacts on aging response and meat quality. This section will focus on the role of apoptosis and anti-apoptotic functions of heat shock proteins in meat tenderization. Next, we will overview various types and conditions of postmortem aging practices, particularly focusing on characterizing how dry-aging influences meat quality attributes. We will also try to introduce some of the experimental evidence that illustrate potential (or research gaps/opportunities) in order to lay the groundwork for developing novel smart-aging strategies to maximize aging impacts on meat quality and value. Since smart-aging related research has been predominantly conducted in beef, this review will mostly focus on beef muscles, although some studies in other species will be also covered as additional references.

2. Postmortem aging impacts on meat quality attributes

2.1. Palatability

During the conversion process of muscle into meat, substantial biochemical/biophysical changes occur in muscle, and these changes directly influence meat quality attributes (Brewer & Novakofski, 2008; Huff-Lonergan, Zhang, and Lonergan, 2010; Kim, Warner, & Rosenvold, 2014; Koohmaraie, 1996; Kristensen & Purslow, 2001). Significant improvements in meat palatability attributes occur through cytoskeletal myofibrillar protein degradation by endogenous proteases during aging process (Huff-Lonergan & Lonergan, 2005; Kemp, Sensky, Bardsley, Buttery, & Parr, 2010; Kim et al., 2014; Kristensen & Purslow, 2001; Lepper-Blilie, Berg, Buchanan, & Berg, 2016; Spanier, Flores, McMillin, & Bidner, 1997). Tenderness, juiciness and flavor are the currently-established major beef palatability attributes (Robbins et al., 2003) with tenderness considered to be the most influential beef palatability attribute (Miller, 2001; Miller et al., 1997; Savell et al., 1987). In this regard, therefore, significant improvement in tenderness is the primary driver for extended postmortem aging of meat, and thus, has been the most extensively studied.

Proteolysis is the predominant factor influencing impacts of postmortem aging on meat tenderization. The rate and extent of the aging response and subsequent meat tenderization are dependent upon various factors such as species, animal age, diet, breed, individual muscle, marbling content, and/or aging condition (Bratcher, Johnson, Littell, & Gwartney, 2005; Gruber et al., 2006; Smith, Tatum, and Belk, 2008). Although it varies, most rapid and substantial changes in meat tenderness occurs between 3 and 7 days postmortem, and then the rate of beef tenderization declines with time (Koohmaraie & Geesink, 2006). However, a substantial increase in meat tenderness of beef from mature animals or muscles with high background toughness was also reported for extended aging up to 28 days (Colle et al., 2016; Hutchison, 2007; Phelps et al., 2016; Santos et al., 2016; Stelzleni, 2006). This could be due to the decrease in mechanical strength of the intramuscular connective tissue through the proteolytic action of endogenous enzymes, resulting in increased collagen solubility, decreased breaking strength, and dissociated structural integrity of muscle connective tissue with the extended aging (Dutson, Smith, & Carpenter, 1980; Lewis, Purslow, & Rice, 1991; Nishimura, 2015; Nishimura, Fang, Ito, Wakamatsu, & Takahashi, 2008; Nishimura, Liu, Hattori, & Takahashi, 1998; Stanton & Light, 1990; Wu, Dutson, & Carpenter, 1981). As proposed by Nishimura (2015), the strength and structural integrity of collagen fibrils is stabilized by proteoglycan, which can be degraded during postmortem aging, exposing more active sites for potential degradation enzymes (e.g. lysosomal glycosidase or β-glucuronidase) to further weaken the structural integrity and thus tenderize meat. Another proposed theory involves two populations of connective tissue: the weak population of connective tissue that responds to postmortem aging (and cooking process) through proteolysis of enzymes, partially corresponding to meat tenderization, while the strong population of connective tissue would not be affected by proteolysis and thus would remain to define background toughness (Purslow, 2014).

Considerable increases in savoury/beef flavor occurs during the process of aging (particularly dry-aging) as a result of liberation of flavor-related compounds, these include nucleotide compounds; Maillard reaction-related sugar fragments, such as glucose; other flavor related volatile compounds such as *n*-aldehydes (e.g. pentanal and hexanal) and ketones, which also include lipid oxidation-related products (Maga, 1994; Martins, Jongen, & Van Boekel, 2000; Yaylayan, Keyhani, & Wnorowski, 2000). The umami/beefy taste and flavor characteristic of aged meat results from a complex interaction between sulfur containing amino acids, aspartic acid and glutamic acid, nucleotide compounds, and β-histidyl dipeptides (Dashdorj, Amna, & Hwang, 2015). Postmortem energy metabolism also results in an increase in sugar fragments through degradation of glycogen content, which in turn increases substrates that are responsible for the Maillard reaction (Martins et al., 2000; Yaylayan et al., 2000). Further, it has been reported that a prolonged aging regime (over 28 days) tremendously increased volatile compounds that are important to aroma development (Ba, Park, Dashmaa, & Hwang, 2014; Watanabe et al., 2015).

While it is generally agreed that aging improves meat flavor, not all studies reported that noticeable positive role of extended aging has on meat flavor development (Brewer & Novakofski, 2008; Lepper-Blilie et al., 2016). Spanier et al. (1997) reported that 4 days of aging at 4 °C improved desirable flavor traits, such as sweetness and beefy flavor, but with longer aging, increasing undesirable traits like bitterness and sourness were detected. Campo, Sañudo, Panea, Alberti, and Santolaria (1999) also found prolonged aging (up to 21 days) to increase global flavor intensity coupled with livery odor development in loins from different breeds. Aging decreases the concentrations of glycogen and glucose 6-phosphate significantly from day 4 to day 15 (Meinert, Schäfer, Bjergegaard, Aaslyng, & Bredie, 2009), while prolonged aging increases the ribose content of meat (Koutsidis et al., 2008). Prolonged aging also releases free fatty acids, which then react with proteins and other flavor precursors to affect the aroma and/or flavor of aged meat (Wang et al., 2013). Since free fatty acids are more prone to oxidation and can accelerate the loss of product due to off-odor and off-flavor, aging regimes should be controlled to maximize desirable flavor and minimize off-odor and flavor.

A positive impact of aging on juiciness of beef steaks has been reported (Campo et al., 1999; Teye & Okutu, 2009). Given there is a general positive correlation between sensory tenderness and juiciness (de Lima Silva, Contreras-Castillo, & Ortega, 2007; Guzek, Glabska, Wierzbicki, Wierzbicki, & Cierach, 2012; Otremba et al., 2000; Shackelford, Wheeler, & Koohmaraie, 1995), improvements in tenderness with aging may have synergistic effects on other perceived palatability, such as juiciness. In fact, some studies proposed a "halo effect," where improved tenderness could boost the perceived juiciness of meat, and vice versa (Hughes, Oiseth, Purslow, & Warner, 2014; Jenkins et al., 2011). Most recently, an improvement of juiciness coinciding with the early activation of calpain-2 was found, which suggests postmortem proteolysis may play a role in juiciness development (Colle et al., 2018). Juiciness is highly dependent on the moisture retention ability of cooked meat, but interestingly, lack of strong correlation was