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Materials Properties, Oral Processing, and Sensory Analysis of Eating Meat and Meat Analogs

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Abstract

To increase the appeal of plant protein–based meat analogs, further progress needs to be made in their sensory perception. Given the limited number of studies on meat analogs, this review focuses on structure, oral processing, and sensory perception of meat and subsequently translates the insights to meat analogs. An extensive number of publications has built the current understanding of meat mechanical and structural properties, but inconsistencies concerning terminology and methodology execution as well as the wide variety in terms of natural origin limit solid conclusions about the control parameters for oral processing and sensory perception. Consumer-relevant textural aspects such as tenderness and juiciness are not directly correlated to single structural features but depend on an interplay of multiple factors and thus require a holistic approach. We discuss the differences in mastication and disintegration of meat and meat analogs and provide an outlook toward converting skeptical consumers into returning customers.

1. INTRODUCTION

TVP: textured vegetable protein

Historically, animal-based proteins in dairy and meat products are the primary protein source in the human diet. However, recently, environmental awareness and consumer demand have stimulated a substantial increase in the use of non-animal-derived proteins as an alternative. A core element of many meat analog products is textured vegetable protein (TVP), produced via extrusion that converts a mixture of plant proteins and fibers into a fibrous structure that is molded into a dough with other ingredients such as binders, flavors, and vitamins (Bohrer 2019, Kyriakopoulou et al. 2021). Like other food products, factors such as price, sustainability, and nutrition are essential to spark consumer interest, but sensory aspects such as color, flavor, and, most importantly, texture are critical in convincing consumers to buy meat analogs. Quite a few new products with improved resemblance to real meat products have recently come on the market, such as Impossible Foods' *Impossible Burger* and Beyond Meat's *Beyond Burger* (see the sidebar titled Consumable Meat Analogs in Development). For these plant protein–based products to realistically mimic the meat-eating experience, the whole cooking and sensory experience during meat consumption needs to be replicated and hence understood. Although there is literature addressing various individual aspects of meat rheology, oral processing, and sensory analysis (Chen 2009, Lenfant et al. 2009, Stokes et al. 2013), there are only limited examples of combining the various aspects into a holistic understanding of how meat structure and properties determine sensory perception during eating. The reason could be the complex structure, variabilities related to natural origin, or differences in preparation and consumption of meat. However, to facilitate a successful societal transition to meat analogs, it is necessary to understand what factors control meat oral processing and sensory perception and then translate them to meat analogs.

This review summarizes the current state-of-the-art knowledge related to the textural characteristics—structure and rheology, oral processing, and sensory perception—of meat and meat analogs, which is one of the critical decision factors for consumer acceptance. The focus is on quantifying methods and understanding the correlation between structural aspects, material properties, oral processing, and dynamic texture perception. Meat can be defined in many ways, originating from different, sometimes opposing, points of view: scientific, technical, nutritional, regulatory, or religious. For this review, the flesh derived from skeletal muscle and its associated tissues are considered meat. Because of the great diversity between meats of different origins

CONSUMABLE MEAT ANALOGS IN DEVELOPMENT

Most applied protein bases in meat analogs are from plant or microbial origin (Hoek et al. 2011). Despite the great progress made in cultivated meat technology (Edelman et al. 2005, Keefe 2018, Melzener et al. 2021), the availability of these products is still very limited and costly (Coghlan 2013). Products from insect origin are popular academic research topics but rarely present on the market and poorly accepted in Western countries (Schouteten et al. 2016). Tofu (a product based on soy) is one of the oldest meat analogs (Elzerman et al. 2013). Similarly, Quorn is obtained from fermentation but purely based on fungal material (reviewed by Finnigan 2011). Textured vegetable protein (TVP) products produced from soy concentrates became widely available as spongy granules or chunks to shape meat analogs (de Boer et al. 2006). Unfortunately, these were not recognized as desirable by consumers because of their texture uniformity, springiness, dryness, and off-flavors (Elzerman et al. 2013, Richardson 1982). Incorporation of other protein sources (e.g., pea, wheat, fava, lentil, chickpea) and technological advancements improved TVP quality and contributed to better mimicking of meat (Bohrer 2019, Kyriakopoulou et al. 2021, Sadler 2004), spurring the recent acceleration in consumer product diversity.

(Listrat et al. 2016) and trends in meat production and consumption (Milford et al. 2019), the focus is on livestock meat such as pork and beef. Meat analogs are manufactured foods based on ingredients of nonanimal origin that aim to create a similar consumer experience to meat. Alternative names are plant-based meats, meat substitutes, meat alternatives, vegetarian meats, and vegan meats.

ISO: International Standards Organization

1.1. Textural Attributes of Meat (Analogs) in Scope

For both meat and meat analog products, texture is one of the key features determining consumer perception and liking. Although the texture of food products can be described using multiple different attributes, here we focus on tenderness, hardness, and juiciness as the most relevant for meat and meat analogs.

1.1.1. Tenderness. Tenderness is a textural sensory attribute crucial for meat quality appreciation. It is affected by several factors, e.g., marbling, insoluble/soluble collagen ratio, breed, age, sex, and pre- and postmortem factors. However, even though it is often included in meat studies, there is variability in the applied definition of tenderness. According to ISO (International Standards Organization) 5492 (2008), tenderness represents a chewiness level; thus, it is related to the work (energy) required to chew the sample. However, some authors evaluated tenderness as a biting force related to hardness (Hildrum et al. 1994).

1.1.2. Hardness. ISO 5492 (2008) defines hardness as a mechanical textural attribute related to the force required to achieve a given deformation, penetration, or breakage of a product. It is a sensory attribute perceived as a force and not as stress (i.e., force normalized by the cross-sectional area; Szczesniak 2002). Therefore, sample shape and size are important factors for sensory and instrumental evaluations and comparisons. Instrumental hardness examinations define hardness as the maximal force of compression or shearing.

1.1.3. Juiciness. The third relevant sensory attribute is juiciness, an essential contributor to eating quality that plays a crucial role in meat texture, controlling between 10% and 40% of its variability (Winger & Hagyard 1994). Juiciness is estimated to contribute up to 10% of the variation in overall acceptability of meat by consumers (Warner 2017). It is defined as the impression of moisture and lubrication when meat is chewed (Warner 2017).

2. MEAT STRUCTURE

Muscle, connective, and adipose tissues together are considered meat. On a microscale, muscle tissue is constituted of large numbers of myofibrils tied in the form of muscle fibers by endomysium connective tissue. These range from 10 to 100 μm in diameter and measure up to several centimeters in length (Lepetit & Culioli 1994). Their structure has been reported in detail (Damez & Clerjon 2008, Lazarides 1980, Listrat et al. 2016, Stanley 1983). **Figure 1** shows three cuts from the back, ham, and neck of beef and pork meat to illustrate the differences in appearance and structure originating from species and muscle.

Besides morphological differences, the intramuscular connective tissues also differ in collagen and elastin content. Generally, collagen is present in higher concentrations than elastin in the connective tissues, except for some muscles such as *semitendinosus* and latissimus dorsi (Bendall 1967, Lepetit & Culioli 1994). Collagen is rigid and resists tension, whereas elastin fibers are extendable. Elastin fibers are more thermoresistant compared to collagen, which is denatured by heating.

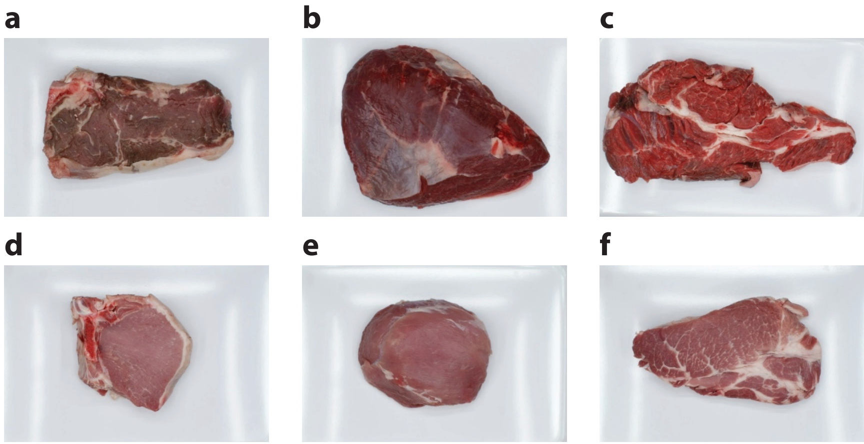

Figure 1

Cuts from (*a–c*) beef and (*d–f*) pork: (*a*, *d*) back, (*b*, *e*) ham, and (*c*, *f*) neck. Images were made as described by Tomasevic et al. (2019).

Collagen denaturation in mammalian muscles occurs at temperatures higher than 65°C (Palka 2003). Denaturation of myofibrillar proteins responsible for toughness occurs at temperatures above 70°C (Palka 2003, Palka & Daun 1999). With animal maturation, changes in the intermolecular cross-links between collagen molecules occur, leading to a shift in the insoluble:soluble collagen ratio and loss of meat tenderness (Cross et al. 1973, Weston et al. 2002). In contrast, no differences in elastin content or collagen:elastin ratio were found between the three stages of bovine maturation, resulting in a poor correlation with meat tenderness (Cross et al. 1973).

Fat is stored around (intermuscular) and within (intramuscular) the muscle. Because the fat around muscles is trimmed during the cutting process, intramuscular fat has a dominant role in beef and pork meat quality. Good examples are Kobe and Wagyu beef, high-quality meats particularly appreciated because of their marbling (Marescotti 2019, Motoyama et al. 2016), which contributes to tenderness (Koch et al. 1993). Intramuscular fat mostly consists of phospholipids, structural lipids, and storage lipids (Listrat et al. 2016). The total content of fats and their proportions vary depending on the muscle, age, breed, genotype, diet, and rearing conditions (Bonnet et al. 2007, Hocquette et al. 2010, Listrat et al. 2016). Finally, the structure and composition of meat are influenced by postmortem factors impacting muscle fibers (reduction of the cross-section and fiber fragmentation), connective tissue (reduction of the perimysium resistance, increase in collagen solubility), and intramuscular fat (enzymatic degradation) (Listrat et al. 2016).

Meat is approximately 75% water, of which 90% is intracellular and 10% is extracellular (Lepetit & Culioli 1994). It has an important role in influencing meat appearance and toughness (Offer et al. 1989). As a meat structural component, water allows diffusion and interactions between enzymes and substrates and determines the plasticity, rigidity, and gelatinization of insoluble proteins (Hughes et al. 2014). Water-holding capacity is a technological parameter related to the ability of meat to retain its water, supposedly improving its juiciness. However, a poor correlation between cooking loss (water and fat) and juiciness was found (Hughes et al. 2014, Pearce et al. 2011), suggesting that other factors are involved. Indeed, Puolanne & Halonen (2010) showed that capillary forces, water-structuring ions, and fibril water surface interactions are relevant as well.

2.1. Methods for Meat Structure Analysis

The most frequently used method in pioneering meat structure studies is electron microscopy (Lazarides 1980, Stanley 1983). It provides visualization and a fundamental understanding of meat microstructure. Pieniazek & Messina (2016) used scanning electron microscopy with image processing to demonstrate a strong correlation between five parameters (energy, contrast, correlation, homogeneity, and entropy) and instrumentally measured texture [hardness, cohesiveness, springiness, chewiness, resilience, and tenderness (shearing force) for two grilled and freeze-dried bovine muscles (semitendinosus and gluteus medius)]. However, because of the complexity of meat structure, several different techniques are needed to get a holistic understanding and modeling of meat quality. Today, a range of biophysical methods (e.g., mechanical, optical, dielectrical, electromagnetic, and X-ray) are used to analyze meat quality related to its structure (Damez & Clerjon 2008) and are available for similar studies of meat analogs (McClements et al. 2021).

Applied spectroscopic methods—based on the interaction between electromagnetic waves and the material—are dependent on meat structure. Spectra of near-infrared spectroscopy were analyzed in terms of prediction for beef sensory characteristics (hardness, relates to the impression on the first bite; tenderness, relates to the impression after the whole mastication; and juiciness); a strong correlation between hardness and tenderness was found using reflection mode, but juiciness was poorly predicted (Hildrum et al. 1994). The results obtained using transmission mode were not satisfactory.

Proton nuclear magnetic resonance (NMR) relaxometry has been used extensively to probe the state of water. The local molecular environment influences the excitation signal of the protons and thereby information about the biophysical/biochemical properties of the sample is provided (Bertram & Andersen 2008, Bertram & Ersen 2004). By adding various disturbing agents,[1] the origin of the multiexponential T_2 relaxation in muscle myowater was studied. Three main components representing different fractions of water for whole, minced, and homogenized pork were extracted (Bertram et al. 2001):

1. The fastest relaxation component is linked to water tightly associated with macromolecules.
2. The intermediate relaxation component is linked to water located within highly organized protein structures, also called T_{21} (Han & Bertram 2017).
3. The slowest relaxation time is linked to the extramyofibrillar water containing the sarcoplasmic protein fraction, also called T_{22} (Han & Bertram 2017).

Microscopic analysis of partially chewed food revealed that most of the liquid inside the fibers was not released during chewing, suggesting that perceived juiciness is linked to liquid identified during the first chew, immediately prior to swallowing, and the ease of forming a swallowable bolus (Reig et al. 2008). Earlier NMR work had linked the relaxation spectrum to the relative pore distribution (Lillford et al. 1980).[2] With respect to juiciness, they observed that the correlation coefficient increases as water with longer relaxation time is included but only down to a relaxation time of $\sim$50 ms, corresponding to the relaxation time of water retained within cooked fibers, supporting the aforementioned conclusion drawn from the microscopic examination of chewed meat. Hence, "a good meat analogue should exhibit a similar relaxation spectral

[1] Dimethyl sulfoxide was added to disrupt the meat membrane, and urea was added to denature the protein.

[2] Lillford et al. (1980, p. 194) wrote that "the significance of the relaxation times becomes their ability to describe the distribution of distances from water molecules to surfaces, or the local substrate density in a microenvironment." Using various systems, they showed that the membrane theory could not be correct in that model systems without compartments showed similar relaxation behavior to the meat samples.

width" (Reig et al. 2008, p. 519). Bertram et al. (2005) concluded that initial and final juiciness could be correlated to the T_2 relaxation times. By considering the x-loadings for prediction of end juiciness, relaxation times between ~10 and 15 and 60 and 80 ms were positively correlated to juiciness, whereas relaxation times of ~20–35 ms and above 1,000 ms were negatively correlated. All three studies do not provide a full explanation of juiciness. Hence, NMR T_2 relaxation measurements (indicative for the state of the juice inside the meat) are preferably used alongside detailed bolus studies (focusing on the juice loss/saliva absorption of the bolus; see below).

Recently, histology was used to investigate the impact of different cooking methods on meat structure. Optical microscopy of sous vide–cooked pork cheeks showed that collagen was denatured to a much wider extent at 80°C compared to 60°C (del Pulgar et al. 2012). Upon collagen denaturation, collagen-rich meat became softer, confirmed by instrumental texture analysis. Cryo-scanning electron microscopy of the microstructure of various sous vide–cooked lamb longissimus dorsi revealed gaps between fibers for meat cooked at 60°C and 80°C, whereas samples prepared at 70°C were denser and more compact (Roldán et al. 2013). Meat cooked for 6 and 12 hours at 60°C and 80°C also needed lower force for shearing compared to the 70°C treatments, whereas 24 hours at 70°C resulted in the softest product, indicating that cooking time ($p = 0.004$) was more significant than temperature ($p = 0.613$). Other studies confirmed that shrinkage of muscle fibers was highest around 70°C (Hughes et al. 2014, Tornberg et al. 1997).

Supplemental Material >

In summary, because of the wide variability in meat and texture attributes, there is no single technique that correlates well with all texture attributes for one meat and/or for one texture attribute for all meats (for an overview, see **Supplemental Table 1**). NMR analysis of the state of the water, putatively correlated to juiciness, seems to be one of the most promising analytical techniques; however, its value for meat analogs remains to be determined. Ideally, a combination of different techniques is used and tailored to specific aims.

3. MEAT MECHANICAL PROPERTIES

The mechanical properties of meat influence the perception of meat quality from the moment of purchasing, through cooking and, finally, consumption, impacting food oral processing and sensory analysis (Agrawal et al. 1997, Stokes et al. 2013). Meat is a complex, discrete, anisotropic, and composite material (Gy 2004, Honikel 1998, Lepetit & Culioli 1994) consisting of several different entities classified as muscle, connective tissue, or fat. Each of them has unique material properties, but combined they display different behavior. Besides the complex material composition, several other factors influence the accuracy and reproducibility of mechanical testing of meat, e.g., breed, nutrition, age, sex, and pre- and postmortem conditions (Ruiz de Huidobro et al. 2005). Some factors can be contained and controlled, unlike the variabilities related to fibrillar and conjunctive components. The myofibrillar structure is affected by animal rearing conditions, whereas the conjunctive tissue is related to the animal's zootechnical characteristics at slaughter (Damez & Clerjon 2008).

3.1. Methods for Meat Mechanical Testing

Mechanical properties tests are commonly classified into three groups: fundamental, empirical, and imitative tests (**Supplemental Table 2**) (Bourne 2002, Chen 2014, Stokes et al. 2013). Fundamental tests focus on well-defined rheological properties and are usually done under a small strain, preventing the failure of material structure (Chen 2014). Accordingly, results obtained from fundamental tests are valid only for the elastic region, providing data independent of sample geometry and size (Diehl & Hamann 1980). Depending on the test applied (e.g., compression, tension, shearing) clearly defined rheological parameters such as Young's modulus (or deformability modulus as recommended in the case of food materials), bulk modulus, Poisson's ratio, and shear modulus can be obtained.

Empirical tests are designed for practical use in the food industry and are usually done under large strains (under different modes of applied deformation such as compression, puncture, tension, and bending). Typically, they are easier to perform than fundamental tests, but the results are not necessarily clearly defined (Chen 2014). Various types of probes are used to imitate food manipulation with fingers, lips, tongue, incisors, cuspids, or molar teeth (Stokes et al. 2013). They usually result in force/stress versus time/displacement diagrams from which other parameters can be calculated.

Imitative tests are developed to obtain data about food texture from conditions that mimic food mastication. Artificial mouth and masticators replicate processes taking place inside the oral cavity during mastication, providing chewed-like samples (Benjamin et al. 2012, Chen 2014, Woda et al. 2010), which are further analyzed for meat bolus granulometry (Duconseille et al. 2019), food aroma/flavor release (Benjamin et al. 2012, Mielle et al. 2010, Poinot et al. 2009), or bioaccessibility/digestion studies (Peyron & Woda, 2016). Not only does the complexity of meat require standardization of mechanical tests, but ideally methods from all three groups (i.e., fundamental, empirical, imitative) are applied to obtain information about food texture that is as complete as possible (Bourne 2002). However, such integral studies are rarely reported.

One of the oldest methods for quantification of meat mechanical properties is the Warner-Bratzler shear test (Warner 1929), which measures the force of shearing. Nowadays, this is the most frequently used test (Lepetit & Culioli 1994, Wheeler et al. 1997) and follows a standard procedure describing conditions for test parameters, equipment, and sample preparation (Wheeler et al. 2005). Additionally, the tensile test (i.e., resistance to tension force deformation) was proposed as a standard assessment method for meat (Romero de Ávila et al. 2014). Shearing tests are often used to quantify either meat tenderness or hardness. Both tenderness and hardness are reported using the shearing test results, but caution with interpretation should be taken. Meat toughness is a characteristic evaluated during the whole mastication process (Brown et al. 1996, Hildrum et al. 1994) or after a few chews (Duizer et al. 1996). Therefore, tenderness is more related to energy, whereas shearing is often seen as an imitative action of cutting the food with incisors and, consequently, it is related to force.

Friedman et al. (1963) developed an imitative method for texture analysis that attempts to mimic first and second bites with a two-cycle compression. Later, this method was adopted for solid food (Bourne 1968) and became known as texture profile analysis (TPA). TPA is often used for instrumental meat texture evaluation (Nishinari & Fang 2018); for resulting parameters, corresponding sensory attributes and definitions, see **Table 1**. However, TPA should only be done knowing the product's nature and the specificities of this test. Otherwise, misuse of TPA data can easily lead to misinterpretation, inappropriate usage of the test probes (e.g., application of the penetration needle instead of the compressing plate), data that cannot be related to the examined product (e.g., springiness in the case of hard candy), or simultaneous consideration of two mutually exclusive parameters, gumminess and chewiness (Szczesniak 1998). Whereas gumminess is suited for semisolid foods, chewiness is intended for solid foods and therefore only one of these parameters should be reported. Furthermore, even though gumminess and chewiness are defined as the energy required for mastication (Bourne 2002, Szczesniak 2002), calculations resulted in units of load or force for both.

Understanding objective measures of meat mechanics and their correlation with sensorially perceived texture will facilitate the design of acceptable meat analogs. As mentioned, by applying shearing and tension, different meat mechanical properties can be determined, although the proper test selection is crucial for detection sensitivity. A study on the impact of aging on reducing

Table 1 Parameters of instrumental texture that can be obtained using TPA and corresponding sensory definitions[a]

Parameter	TPA definition	Sensory definition
Springiness (elasticity)	Deformation at which sample can recover for the duration between two compressions; it is calculated by subtracting the time elapsed from beginning of the first compression to the beginning of the second from the time constant for clay (dimensionless)	Rapidity of recovery from a deforming force and the degree to which deformed material returns to its original condition after deforming force is removed
Fracturability (brittleness)	Force or load at which first fracture occurs (expressed in units of Newtons or grams)	Attribute related to cohesiveness, hardness, and the force necessary to break a product into crumbs or pieces
Hardness	Force or load at maximal deformation of the first compression (expressed in units of Newtons or grams)	Force required to achieve the given deformation, penetration, or breakage of a product
Adhesiveness	Work required to overcome adhesive forces between the sample and test probe; it is calculated as area of the negative peak (expressed in units of Jules)	Force required to remove the material that sticks to the mouth or a substrate
Cohesiveness	Extent to which sample can be deformed until it breaks; it is calculated by dividing the area of the second positive peak with area of the first positive peak (dimensionless)	Degree to which a substance can be deformed before it breaks, including the properties of fracturability, chewiness, and gumminess
Gumminess	Energy required for mastication of a semisolid food. This parameter is better suited to the products of low hardness and high cohesiveness; it is calculated by multiplying hardness and cohesiveness	Attribute related to cohesiveness of a tender product
Chewiness	Energy required for mastication of a solid food. This parameter is better suited to the products; it is calculated by multiplying gumminess and springiness	Amount of work required to masticate a solid product into a state ready for swallowing

[a]TPA definitions are based on Bourne (2002) and Szczesniak (2002); sensory definitions are following the ISO standard 5492 (2008).
Abbreviation: TPA, texture profile analysis.

myofibrils' strength concluded that the shearing test is better correlated to the tensile strength, whereas the penetrometer test is better suited for measurements of adhesion between the fibers (Bouton & Harris 1972). Literature further suggests that both methods are known to correlate well with taste panels (Bouton et al. 1971). Although regression equations were established between meat tenderness and juiciness and objective measurements (Instron compression, Warner-Bratzler shear, and cooking loss), these were highly dependent on how the samples were presented to the subjects (as cubes or thin strips cut along or across the fibers), resulting in different outcomes (Bouton et al. 1975). Hence, a multicomponent approach is needed to correlate objective measurements to sensory perception (e.g., shear, compression, and cooking loss influencing tenderness perception). Unfortunately, this is not yet straightforward, as correlation studies mostly suffer from a lack of predictive power because different tests are either related to different sensory attributes or too focused on isolated details (Ruiz de Huidobro et al. 2005). As Harris & Shorthose (1988) indicated, meat can be regarded as essentially a two-component system made up of muscle fibers and intramuscular connective tissue. In a single piece of meat, sensory perception of tenderness is influenced by both muscle fiber and connective tissue toughness. They showed that Warner-Bratzler shear force values are related more to the myofibrillar strength, whereas the Instron compression is linked more to the connective tissue strength.

4. ORAL PROCESSING

TI: time intensity

Oral processing describes the manipulation and processing of food in the mouth from the first bite to swallowing (Chen 2014) and is elementary to consumer perception of critical textural attributes of meat and meat analogs. A tridimensional model has been proposed in the literature, describing the breakdown path (degree of structure, degree of lubrication, and time) of foods during oral processing (Hutchings & Lillford 1988, Lucas et al. 2002, Shama & Sherman 1973). Many factors are relevant, like food formulation (Oladiran et al. 2018); the influence of age, gender, and ethnicity (Ketel et al. 2019); food shape, size, and addition of condiments (Van Eck et al. 2019a,b); and culinary methods (Djekic et al. 2021). Stokes et al. (2013) reported the stages of oral processing combined with sensory perception, on the basis of which Ilić et al. (2019) built a flowchart for modeling. Distinguishable segments are first bite and subsequent chews, further chewing leading to food size reduction and mixing with saliva, agglomeration and bolus formation, transportation inside the oral cavity, and, finally, swallowing.

4.1. Application of Oral Processing Methods for Meat

In pioneering oral processing studies, model foods such as gels, bread, biscuits, and cheeses were used to obtain consistent data (Funami 2017, Wang & Chen 2017). In contrast to such more homogeneous foods, which have one or two structural entities, meat is a more complex material: Its structural complexity and natural variability impact the quantitative and qualitative understanding of meat oral processing. In vivo, ex vivo, and in vitro techniques are used to understand the oral processing dynamics (Stokes et al. 2013). The high complexity stimulated the development of a wide range of in vivo methods (reviewed in **Supplemental Table 3**) to observe oral processing through its stages.

Supplemental Material >

Hutchings & Lillford (1988) compared a tender, juicy steak and tough, dry meat in their aforementioned three-dimensional mode for oral processing, showing that these have different breakdown pathways: The tender, juicy steak demands less extra lubrication and time to be masticated and swallowed and undergoes fewer structural changes than tough, dry meat. Duizer et al. (1996) coupled instrumental texture analysis, mastication behavior, and time intensity (TI) in a single study to correlate the tenderness of beef to relevant parameters. Among the five types of meat with different tenderness, the number of chews and chewing time varied, but the mastication rate remained unchanged, suggesting that the rate of chewing was not influenced by tenderness. Electromyography, used to monitor muscle activities during consumption and sequentially to determine mastication patterns to understand variabilities in meat tenderness perception, revealed significant differences among the subjects in absolute values as well as in the chewing patterns, illustrating the complexity and individual variability of the whole mastication process (Braxton et al. 1996, Brown et al. 1996). Meat samples with higher shearing force values were more demanding with respect to chewing activity and saliva incorporation. Also, the toughest meat retained higher shearing forces through the mastication (shearing forces for meat sample, bolus after seven seconds of mastication, and bolus from the moment of swallowing were determined) (Mioche et al. 2002b). Similar data were obtained while investigating differences between young and elderly meat consumers, wherein the elderly applied less chewing force and more chews and used larger total muscle work (Mioche et al. 2002a). Consequently, boluses collected from elderly consumers were more force resistant, pointing to the poorer mastication efficiency of the elderly.

When using sufficient subjects (minimally 10–12), correlations between instrumental texture and variables like mastication behavior, saliva incorporation, and size of bolus particles can be obtained. Whereas beef with different cooking grades (from medium rare to very well done) showed no differences with respect to the number of chews and consumption time

(Pematilleke et al. 2020), different culinary methods (e.g., cooking, grilling, and sous vide) to prepare pork ham resulted in different oral processing behavior (number of chews, total exposure time, chewing rate, eating rate, number of chews per gram, chewing cycle duration) (Djekic et al. 2021). Both studies showed an increase in saliva uptake, the number of bolus particles, and oral processing parameters for harder samples. Hence, positive correlation coefficients were obtained for texture parameters (hardness, springiness, and chewiness) and oral processing (number of chews, chewing duration, saliva incorporation, and number of bolus particles), whereas these texture parameters negatively correlated with the area of bolus particles (Pematilleke et al. 2020). The higher cooking loss resulted in tougher meat confirming these differences, which led to the highest mastication efforts (Djekic et al. 2021). Following in vivo studies, ex vivo methods are used to examine the boluses formed. Analysis of the meat bolus granulometry at different mastication times showed changes in its mass and moisture content, confirming the complexity of the mastication process (Djekic et al. 2021, Lenfant et al. 2009, Yven et al. 2005). Some studies revealed material breakdown during the mastication while at the same time increasing bolus moisture content (Djekic et al. 2021, Lenfant et al. 2009). Otherwise, it has been seen that meat texture also affects the mechanical properties (shearing force) of the bolus (Yven et al. 2005).

In general, tougher meat consistently demands higher shearing forces for bolus processing (Mioche et al. 2002b), but increasing food hardness leads to better comminution and smaller mean particle size (Chen et al. 2013). For meat bolus evaluation, bolus shearing is more suitable than particle size analysis, as meat is a cohesive material, whereas analysis of particle size better fits brittle materials such as carrot. Still, particle analysis of meat boluses is often both qualitative and quantitative (Djekic et al. 2021, Pematilleke et al. 2020). Particle distribution of meat boluses collected at three different times during mastication (7 chews, 15 chews, and a moment of swallowing) showed variation depending on the origin of the starting material (**Figure 2**). These boluses were also analyzed for moisture content (**Table 2**), suggesting a trend toward higher moisture content with larger bolus particles at swallowing, confirming better cohesiveness. The required number of chews to consume a cubical sample of meat showed a good correlation with temperature, suggesting higher temperatures, leading to higher cooking losses and tougher meat, and therefore requiring more chews (**Table 3**). More recently, Aguayo-Mendoza et al. (2019) examined meat oral processing using video analysis (consumption time, eating rate, number of chews, chewing rate, and cycle duration were obtained), which supports the drawing of stronger conclusions in relation to the biophysical measurements.

4.2. Structural Breakdown and Evolution of the Meat Bolus During Chewing

Another critical aspect that influences how meat is perceived is the evolution of the bolus during chewing. Lillford and coworkers (Reig et al. 2008; Lillford 2001, 2011) argued that during chewing, initially, delamination of fiber bundles and fibers occurs, but only a few fibers are actually broken. In other words, the primary structure failure occurs in the connective tissue. Additionally, after this disintegration, a reassembly process into a swallowable bolus takes place. Hence, they proposed that the toughness parameter is primarily determined by the separation of fiber bundles and fibers from each other (Reig et al. 2008), as illustrated in **Figure 2**. That could explain why, depending on the type of meat (e.g., the amount and strength of connective tissue) and cooking process, the chewing experience can be quite different.

This process of fracture and reassembly is a key aspect to keep in mind when designing meat analogs. Meat analogs typically are more homogeneous and, in an uncooked state, browner than animal meat burgers (**Figure 3**). Lillford (2011) postulated that the failure in sensory properties of early examples of alternative meats was because they had a different breakdown behavior than

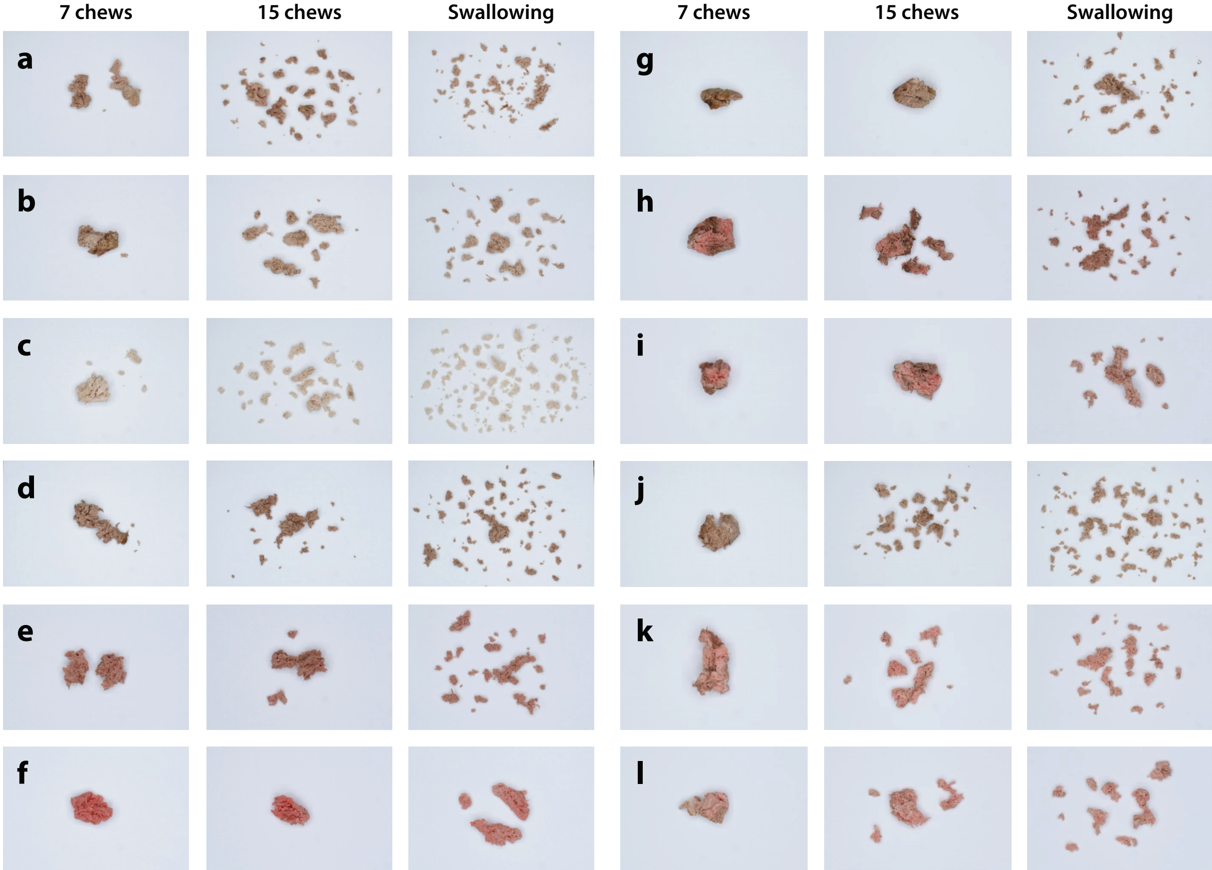

Figure 2

Meat boluses obtained after 7 and 15 chews and at the moment of swallowing. Cubical samples (20 × 20 × 20 mm) of cooked products (with indicated inner temperature after roasting) were used. (*a*) Pork ham (72°C), (*b*) pork neck (72°C), (*c*) pork back (72°C), (*d*) beef ham (72°C), (*e*) beef ham (66°C), (*f*) beef ham (60°C), (*g*) beef neck (72°C), (*h*) beef neck (66°C), (*i*) beef neck (60°C), (*j*) beef back (72°C), (*k*) beef back (66°C), and (*l*) beef back (60°C). The images were made using the computer vision system described by Tomasevic et al. (2019) and following the procedure for bolus analysis described previously in Djekic et al. (2021).

meat, with chewing producing particles that did not reform into a coherent bolus. As illustrated in **Figure 4**, there is still a discrepancy between the evolution of the bolus of current commercial plant-based burgers and real meat burgers, with the former disintegrating faster and to a much larger extent. Finally, there is quite some individual variation in the breakdown process, with some consumers prepared to swallow at a significantly lower degree of structure disruption than others (Lillford 2000).

5. SENSORY ANALYSIS

Perception of sensory attributes during food consumption is crucial for its acceptance and quality appreciation. The five human senses process information about the food product from the moment of first sight until swallowing and even afterward (e.g., retronasal odor and aftertaste). The quantification of sensory perception during meat consumption is made challenging by overlapping stimuli, differing intensities, and structural complexity. During food oral processing,

Table 2 Moisture content of meat and boluses obtained after 15 chews and from the moment of swallowing[a]

Meat type	Cooking end-point temperature (°C)	Moisture content (%)		
		Cooked product	Bolus after 15 chews	Bolus at the moment of swallowing
Pork ham	72	65.6 ± 1.7	70.6 ± 0.9	73.9 ± 2.0
Pork neck	72	62.2 ± 1.2	70.1 ± 2.5	76.9 ± 3.2
Pork back	72	62.0 ± 1.6	64.5 ± 4.2	71.8 ± 3.0
Beef ham	72	65.9 ± 3.1	71.1 ± 2.4	76.6 ± 1.3
	66	64.7 ± 0.8	73.4 ± 1.8	74.8 ± 2.1
	60	64.6 ± 1.5	75.9 ± 2.4	76.3 ± 2.6
Beef neck	72	65.2 ± 2.1	68.0 ± 5.1	76.0 ± 1.9
	66	62.5 ± 1.6	68.3 ± 2.3	81.4 ± 1.3
	60	64.6 ± 1.5	72.0 ± 3.0	81.5 ± 3.7
Beef back	72	61.2 ± 1.5	69.0 ± 2.1	73.2 ± 2.1
	66	63.8 ± 1.7	72.2 ± 0.4	75.4 ± 1.9
	60	65.7 ± 2.4	73.2 ± 1.7	75.1 ± 2.3

[a]Determined by drying to constant mass as described in ISO 1442 (1997).

Table 3 Number of chews required to process a meat sample toward swallowing

Meat type	Cooking end-point temperature (°C)	Number of chews to swallowing
Beef ham	72	47.7 ± 1.5
	66	42.3 ± 2.1
	60	26.0 ± 1.0
Beef neck	72	69.7 ± 0.6
	66	67.3 ± 1.2
	60	62.0 ± 2.6
Beef back	72	43.7 ± 3.2
	66	36.7 ± 1.2
	60	25.7 ± 1.2

food structure degradation, and bolus formation, perception of sensory attributes undergoes a continuum of changes diffusing sequences and intensities (Stokes et al. 2013). Several sensory methods are used to describe a product (qualitative sensory analysis) and evaluate the intensity of selected attributes (quantitative sensory analysis) (**Table 4**).

Figure 3

Commercial burgers. Plant-based: (*a*) pea protein base and (*b*) soy protein base. (*c*) Beef based. The images were made using the computer vision system described in Tomasevic et al. (2019).

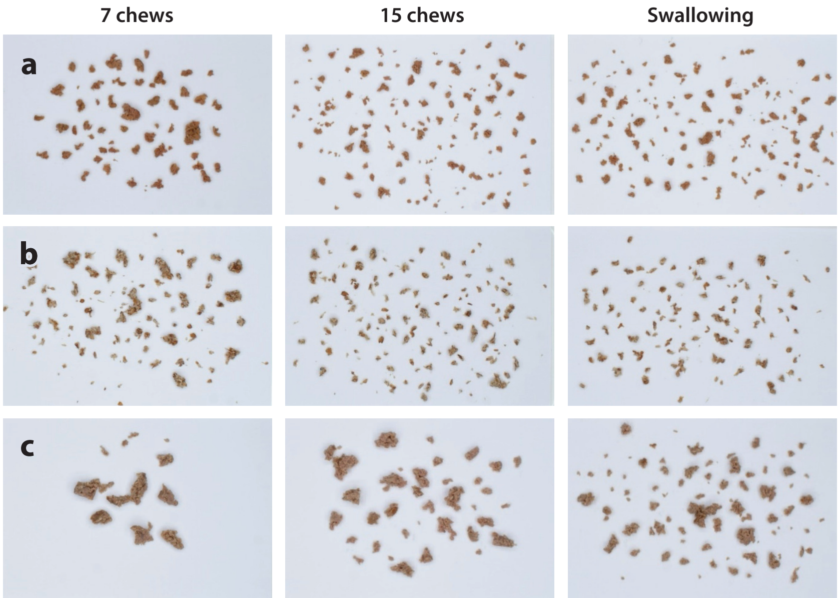

Figure 4

Boluses obtained after 7 and 15 chews and at the moment of swallowing. (*a*) Pea-based burger (72°C), (*b*) soy-based burger (72°C), and (*c*) beef burger (72°C). Temperatures denoted in brackets depict the cooking-end temperature in the center of the product. All burgers were prepared by oven cooking at 200°C until the moment the temperature reached 72°C in the center of the product. Cubical samples (2 × 2 × 2 cm) were used for mastication. The images were made using the computer vision system described by Tomasevic et al. (2019) and following the procedure for the bolus analysis described previously (Djekic et al. 2021).

Table 4 Commonly used descriptive methods in sensory evaluation[a]

Panel	Method	Results
Trained	Flavor profile method	Perceived attributes and intensities of aroma, flavor, and aftertaste
	Texture profile method	Perceived texture attributes and their intensities
	Quantitative descriptive analysis (QDA®) method	Sensory attributes and their intensities; conclusions are made based on the statistically processed data; all groups of attributes (texture, aroma, flavor, taste, appearance) can be analyzed
	Spectrum™ descriptive analysis method	Sensory attributes and their intensities; conclusions are made based on the statistically processed data; all groups of attributes can be analyzed; compared to QDA®, more rigorous roles for the training of the panel and attribute definitions apply
Untrained (consumer)	Free-choice profiling	Individual attribute lists and their intensities; single product profile
	Flash profiling	Individual attribute lists and their ranks; single product profile
	Projective mapping (napping)	Sample grouping; differences between the samples
	Sorting	Sample grouping according to individual preferences; differences in subject perception

[a]Adapted from Civille et al. (2015).

TDS: temporal dominance of sensations

TCATA: temporal check-all-that-apply

5.1. Descriptive Sensory Methods

Although descriptive sensory methods are not often used for meat evaluations because they are considered time-consuming and expensive (Torrico et al. 2018), there are examples of their use, albeit sometimes leading to contrasting conclusions. Frank et al. (2016) explored how intramuscular fat, feed, and breed affect beef sensory properties. For this purpose, a trained panel of 10 subjects evaluated orthonasal odor attributes, retronasal flavor attributes after two chews, and aftertaste attributes after swallowing. They revealed a trend for intramuscular fat stimulating beef flavor, sweetness, tenderness, and juiciness. The latter two also correlated with peak force as measured with the Warner-Bratzler test. In contrast, sourness and astringency decreased as marbling increased.

End-point temperatures influenced the intensity of various pork attributes such as juiciness, pink color, and metallic flavor, which decreased with rising temperature, whereas brown color, pork flavor, and graininess increased (Heymann et al. 1990). Surprisingly, the internal end-point temperature did not affect tenderness, chewiness, or sweetness, which may result from the specific definitions used for these sensory attributes. The authors focused on evaluating hardness [the different levels of hardness are soft, firm, and hard according to ISO 5492 (2008)] while defining it as tenderness. As previously explained, tenderness is evaluated after a few chews, and it is related to energy; i.e., tenderness is inversely correlated to the energy required to chew the sample. Hardness corresponds to the force required with incisors to cut or compress the sample. Unlike Frank et al. (2016), who observed perception of tenderness after the predefined number of chews, Heymann et al. (1990) defined tenderness and softness as the same attribute, related to the force required to cut or compress a sample with incisors, which may explain their results.

5.2. Dynamic Sensory Methods

For the scope of this review, we focus on dynamic methods: TI, temporal dominance of sensations (TDS), and temporal check-all-that-apply (TCATA). TI and TDS demand a trained panel, whereas TCATA can also be applied with consumers. ISO 8586 (2012) specifies criteria for selecting the panelists and describes procedures for training and monitoring. Panelists are usually chosen based on their abilities to perceive and evaluate product attributes and communicate their perceptions with others. Selected panelists need to be in good health, motivated, and trained to understand food sensory properties. A wide range for the number of panelists to be included in dynamic sensory evaluations was reported (Pineau et al. 2012), but, generally, the number of panelists needs to be increased if differences between the compared products are small (Civille et al. 2015). Juiciness, tenderness, fibrousness, color, and flavor are generally considered the most important meat quality attributes (Biswas & Mandal 2020, Listrat et al. 2016, Maltin et al. 2003, Torrico et al. 2018, Winger & Hagyard 1994). A study of 13 meat products showed that toughness/tenderness, juiciness, and flavor covered most of the sensory variation (Horsfield & Taylor 1976, Torrico et al. 2018). Meat texture perception was associated with its structural failure (Nollet & Toldrá 2010), and connective tissue distribution and muscle fiber diameter influence bolus formation (Wang et al. 2015).

Time-dependent studies enabled monitoring of dynamics during the continuous changing of meat texture during consumption. Tenderness was defined as a sensory attribute with values ranging from tough to tender. Zimoch & Findlay (1998) defined toughness as the opposite of tenderness, evaluated through the force needed for chewing—the higher the force needed, the tougher the sample. Juiciness was defined as an overall impression of juice released during chewing. Unfortunately, this still did not allow accurate description of meats covering the entire spectrum of different structures; TI data correlated to the instrumentally measured maximal shearing force only for pork samples of medium tenderness (Butler et al. 1996).

Although TDS is considered superior to TI because it provides more valuable information concerning temporal differences (Lorido et al. 2016), its potential is not fully exploited for meat sensory analysis. Only a few studies performed TDS for meat evaluation. In a study with Wagyu beef strip loin, temporal differences between two cooking methods and two fatting periods were confirmed (Watanabe et al. 2019). The major sensory characteristics differed depending on the cooking method and fatting period, revealing that the two cooking methods had specific impacts on texture and flavor profiles. The cooking method (boiling water, sous vide, and grilling) was also the main determinant of pork meat's dynamic sensory perception. Although the meat cooked in boiling water was dominantly firm and fibrous at the beginning of consumption, sous vide and grilled meat were perceived as juicier (Djekic et al. 2021).

TCATA has been used to relate sensory perception to the bolus properties of commercial cooked ham (Rizo et al. 2019), illustrating that softness and hardness were linked to instrumental texture and perception of fibrousness to ham fragmentation during mastication, whereas juiciness seemed to be related to saliva incorporation. The importance of juiciness was confirmed in recent studies as one of the most important drivers of consumer approval of beef and chicken analogs (Precis. Res. 2018).

6. MEAT ANALOGS

Although meat analog consumer products have been available in retail since the 1980s (Keefe 2018), there has been a steep rise in diversity and product offering only during the past few years (Slade 2018; see also the sidebar titled Consumable Meat Analogs in Development for meat analog history). Ethical issues (Hoek et al. 2011) and environmental (McClements 2019) and health concerns (Schouteten et al. 2016, Weinrich 2019) are the most important drivers for the increasing demand for meat substitutes. However, although consumers can be persuaded to try a meat substitute (Weinrich, 2019), sensory perception has been a great hurdle limiting their wide acceptance (Elzerman et al. 2013, Fehér et al. 2020, Hoek et al. 2011, Szejda et al. 2020, Tucker 2014).

Surprisingly, most literature dealing with the importance of the sensory quality of meat substitutes is from a market research perspective, with only a limited number of studies describing the sensory analysis of these products. In a comprehensive study, commercially produced insect-, plant-, and meat-based burgers were compared with respect to perceived liking, quality, nutritiousness, and emotional and sensory perception. Irrespective of the testing conditions (i.e., blind, expected, or informed conditions), plant- and insect-based burgers were less liked compared to meat-based burgers, although under blind testing, overall liking was significantly improved, illustrating the impact of visual cues (Schouteten et al. 2016). The greatest differences were found for juiciness and dryness, with the insect-based burger most frequently referred to as dry compared to the other two. Other studies confirmed that meat substitutes lack sufficient quality in terms of flavor, juiciness, and texture (Elzerman et al. 2013, Schouteten et al. 2016, Szejda et al. 2020). Precision Research (2018) probed a consumer panel with plant-based beef and chicken substitutes; both were rated poorly and, next to a slightly unpleasant aftertaste, several textural attributes (firmness, juiciness, greasiness) were reported as the biggest deficiencies in quality. Consumers basically can be separated into those who expect meat substitutes to be as similar as possible to real meat and those who prefer that the taste and texture not resemble those of meat (Elzerman et al. 2013, Hoek et al. 2011, Szejda et al. 2020). All studies suggest that classical meat-eaters have higher demands concerning the flavor and texture qualities that meat substitutes should deliver.

Table 5 Number of chews required to process a burger sample toward swallowing

Burger type	Cooking end-point temperature (°C)	Number of chews before swallowing
Pea-based	72	25.7 ± 1.5
Soy-based	72	14.7 ± 1.5
Beef	72	31.0 ± 2.0

To the best of our knowledge, at the time of writing this manuscript, there was no publication dealing with the analysis of mechanical properties and oral processing of meat alternatives, whose textural properties are consistently reported as being inferior compared to real meat. To visualize textural differences impacting oral processing of plant-based versus beef burgers, boluses were retrieved at various stages of mastication (**Figure 4**). Clearly, the disintegration of plant-based burgers was much faster compared to the beef burger, leading to fewer chews required before swallowing (**Table 5**) and smaller particles (**Figure 4**). Surprisingly, opposite to the various meat types (**Table 2**), there seems to be no correlation between moisture content (**Table 6**) and particle size (**Figure 4**) for the plant-based burgers, suggesting that the differences in the recipe (hence, the protein base and/or other ingredients) could be more relevant with respect to juice release and juiciness perception. Also, in beef patties, other molecules such as salt were shown to be relevant for juiciness perception, with higher salt levels solubilizing the myofibrillar proteins, thereby increasing their water-holding capacity and perceived consumer juiciness (Tobin et al. 2012). Moreover, Cornet et al. (2021) increased the water-holding capacity of meat analogs by controlling the marinade pH and ionic strength, aiming to improve juiciness in consumer products. Hopefully, such insight will allow us to better mimic the textural sensory features of meat-based burgers. To achieve the desired quality of meat analogs, it is crucial to follow a holistic approach that includes ingredients, food properties, oral processing, and dynamic sensory perception.

7. CONCLUSIONS

A fundamental understanding of meat structure is well established (Lazarides 1980, Listrat et al. 2016, Stanley 1983), and technological advancements have led to better visualization (Pieniazek & Messina 2016). Unfortunately, correlations between meat structure, mechanical properties, and sensory perceptions (del Pulgar et al. 2012, Roldán et al. 2013) are still hampered by the variable structural properties of meat. Bourne (2002) suggested that fundamental tests usually do not correlate as well with sensory measurements of texture as empirical tests do, which may result from the incompleteness of rheology in describing all changes occurring during mastication and sensed in the mouth. The use of imitative tests with new instruments (artificial masticators, artificial mouths) could be helpful (Duconseille et al. 2019, Mishellany-Dutour et al. 2011), enabling a better examination and sampling of changes occurring inside the oral cavity during mastication. Moreover, such tools could be of use in understanding the role of salivary enzymes in meat oral processing,

Table 6 Moisture content of burgers and boluses obtained after 15 chews and from the moment of swallowing[a]

Burger type	Cooking end-point temperature (°C)	Moisture content (%)		
		Cooked product	Bolus after 15 chews	Bolus at the moment of swallowing
Pea-based	72	55.3 ± 0.4	62.6 ± 0.1	68.3 ± 1.0
Soy-based	72	46.7 ± 0.1	56.0 ± 0.3	57.7 ± 0.2
Beef	72	55.3 ± 0.4	62.3 ± 1.0	69.0 ± 0.9

[a]Determined by drying to constant mass as described in ISO 1442 (1997).

which could play an important role in the perception of juiciness. The role of salivary enzymes during oral processing of starchy foods was shown before (de Wijk et al. 2004, Joubert et al. 2017). However, next to amylases, the main enzymatic components of saliva are lingual lipases, but we are not aware of any study on their impact during oral processing and sensory perception of meat nor meat analogs. Kulkarni & Mattes (2014) measured the nonesterified fatty acid concentration during oral processing of five plant-derived foods rich in fats (almond, almond butter, olive oil, walnut, and coconut) and hypothesized that lipase activity might be dependent on the level of oral processing effort, i.e., higher effort inducing higher lipase activity. Realizing that meat can be rich in intramuscular fats and meat analogs contain up to 16% plant-based fats (Bohrer 2019), it may be interesting to explore the influence of oral lipases during mastication of meat and meat analogs. Lubrication by saliva during meat oral processing via salivary mucins or salivary viscosity may play a role in lubrication (de Wijk & Prinz 2005) but has not yet been studied for meat nor meat analogs.

Understanding the complex process of eating meat is undoubtedly difficult, mostly due to the complex nature of meat structure and its resulting physical (i.e., mechanical) properties. Additionally, culture, gender, and age affect eating behavior (Ketel et al. 2019). Recently, van Eck et al. (2019a) showed that condiments can influence mastication behavior. Van Eck & Stieger (2020, p. 227) stated that the "smallest facilitation effects are expected for very tough foods like meat, as these foods require intensive structure breakdown by the molars before swallowing regardless of a small increase in lubrication by condiments." Because meat and meat analogs are often consumed with various condiments such as sauces, it would be interesting to explore their influence on oral processing, especially regarding their influence on bolus formation, oral cavity surface lubrication, and friction coefficients.

Recently, an in silico model for oral processing successfully predicted food breakdown (Skamniotis et al. 2019). With advancements in 3D scanning (Dick et al. 2019), further understanding of physical changes during meat consumption may allow for models that better help us understand the meat-eating process (**Figure 5**). Finally, gaining a better insight into the bolus

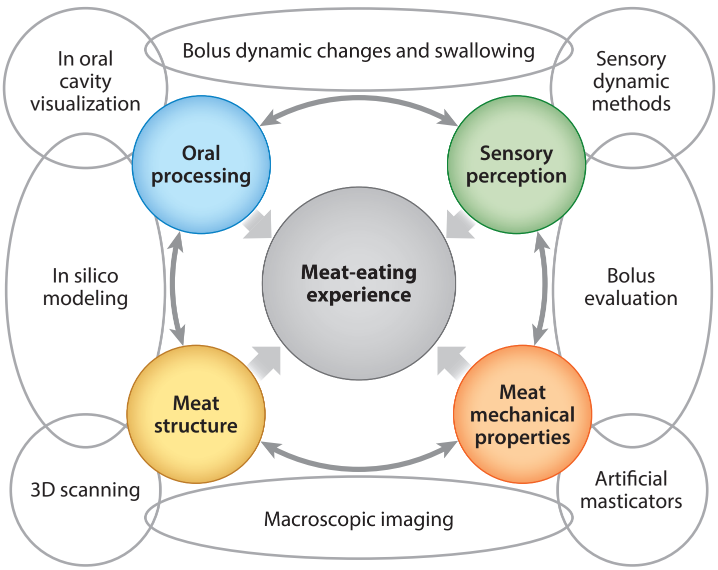

Figure 5

Contribution of new methods to the understanding of meat-eating experience.

evolution and sensory experiences during meat consumption can establish a solid base for designing meat analogs. Here, there is a gap in understanding structure, rheology, and oral processing to control and steer sensory perceptions. Pilot studies of boluses, moisture content, and the number of chews before swallowing plant-based and beef burgers visualized the large differences among these products (**Figure 4**), which need to be overcome to convince meat-eaters to partially or fully replace the meat in their diets (Szejda et al. 2020).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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