Does It Look Cooked? A Review of Factors That Influence Cooked Meat Color

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ABSTRACT: Adequate cooking of meat is necessary to inactivate microbial pathogens. This is particularly important for ground meat products and some variety meats where pathogens can be present internally. Consumers are being advised on appropriate temperatures to which meat products should be cooked, and to use a meat thermometer to ensure these temperatures are reached. However, consumers are more likely to assess cooking status by the color of the meat or juice. This article reviews the factors that can influence the final color of cooked meat. In most instances, these factors influence color by modifying the meat pigment myoglobin prior to and during cooking. Many factors can prolong the pink "uncooked" color in meat, including high pH, modified atmosphere packaging, rapid thawing, low fat content, nitrite, and irradiation. Such factors may lead to overcooking and loss of food quality, and consumer rejection. Alternatively, factors that cause "premature browning" of meat, where the interior of the product looks cooked but a microbiologically safe temperature has not been reached, are food safety issues. Pale, soft exudative meats can prematurely brown, as can meats packaged under oxygenated conditions, frozen in bulk or thawed over long periods, or those that have had salts or lean finely textured beef added. Meats cooked from a frozen state or irradiated in aerobic conditions might also be at risk, but this might depend on meat species. In summary, the color of cooked meat is not a good indicator of adequate cooking, and the use of a food thermometer is recommended.

Keywords: meat color, cooked, myoglobin, pathogen, thermometer

Introduction

In the opinion of most consumers, the cooking of meat produces a product of favorable texture and taste. From a food safety perspective, the cooking of meat is necessary to eliminate any associated foodborne pathogens. Microorganisms are introduced to meat surfaces during carcass processing and handling. Pathogenic microorganisms may be transferred to meat from the skin, feathers, feet and eviscerated organs, and from the processing environment (e.g., surfaces, wash water, worker's hands) or with added ingredients such as spices or extenders (Jackson and others 1997).

Bacterial contamination of whole pieces of red meat such as steaks or chops is restricted to the external surfaces, and so long as these are heat seared, the internal tissue can be eaten "rare" with safety. Raw minced meat products, or whole cuts of meat that have been injected or rolled, may have surface organisms spread throughout the product. Internal tissues of livers have also been shown to be contaminated with pathogenic bacteria (Barot and others 1983; Moore and Madden 1998). These meats, and those suspected of carrying parasites, must be cooked throughout to inactivate pathogens.

The food safety messages promoted to the U.S. consumer have changed from judging the doneness of cooked meat on the basis of its appearance to using a thermometer (detailed in Lyon and others 2000). This was in response to increasing evidence that the visual appearance of cooked meats does not necessarily indicate that a microbiologically safe cooking temperature has been achieved. Of most concern is the condition of "premature browning," where the interior of cooked meat is brown and "looks cooked" before a safe cooking temperature has been reached.

The United States Dept. of Health and Human Services (USDHHS) 2005 Food Code (USDHHS 2005) specifies temperature/time rules for food establishments. For example, comminuted fish and meats must be cooked so that all parts of the food are held at 68 °C or above for at least 15 s. Poultry, wild game animals, and stuffed meats shall be held for 15 s at 74 °C. These specifications are sufficient to inactivate most microorganisms and produce a safe cooked meat product, provided pre- and postcook conditions (e.g., storage temperatures) are also controlled.

The United States Dept. of Agriculture (USDA) recommends consumers use a food thermometer to ensure the internal temperature (IT) of steaks, roasts, and fish reaches 62.8 °C, pork and ground beef attains 71.1 °C, and chicken breasts and whole chicken reaches 76.7 °C and 82 °C, respectively (USDA 2005). However, consumer use of thermometers is limited (McCurdy and others 2005). For example, most consumers determine whether ground beef is cooked by observing the color and texture of the cooked meat (Rhee and others 2003). The message to cook meat until the internal portion is no longer pink and the juices run clear is often still promoted (FSA 2006, for example).

The appearance of cooked meat can be influenced by pH, meat source, packaging conditions, freezing history, fat content, added ingredients, and preservation treatments such as irradiation and pressure. These factors change the ratio of different forms of myoglobin; the main pigments responsible for the ultimate color of meat. Most research on cooked meat color has focused on comminuted meats, particularly ground beef products, because of their association with infections of *Escherichia coli* O157:H7.

The objective of this article is to assemble the findings of published research where the cooked color of meat products was studied in relation to the characteristics and handling of the meat. From this information, factors that are an issue for food safety can be separated from those that cause problems with product quality. It is the former group that food safety regulatory authorities are most

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interested in when defining the messages to be included in food safety promotional material.

Myoglobin and Cooking

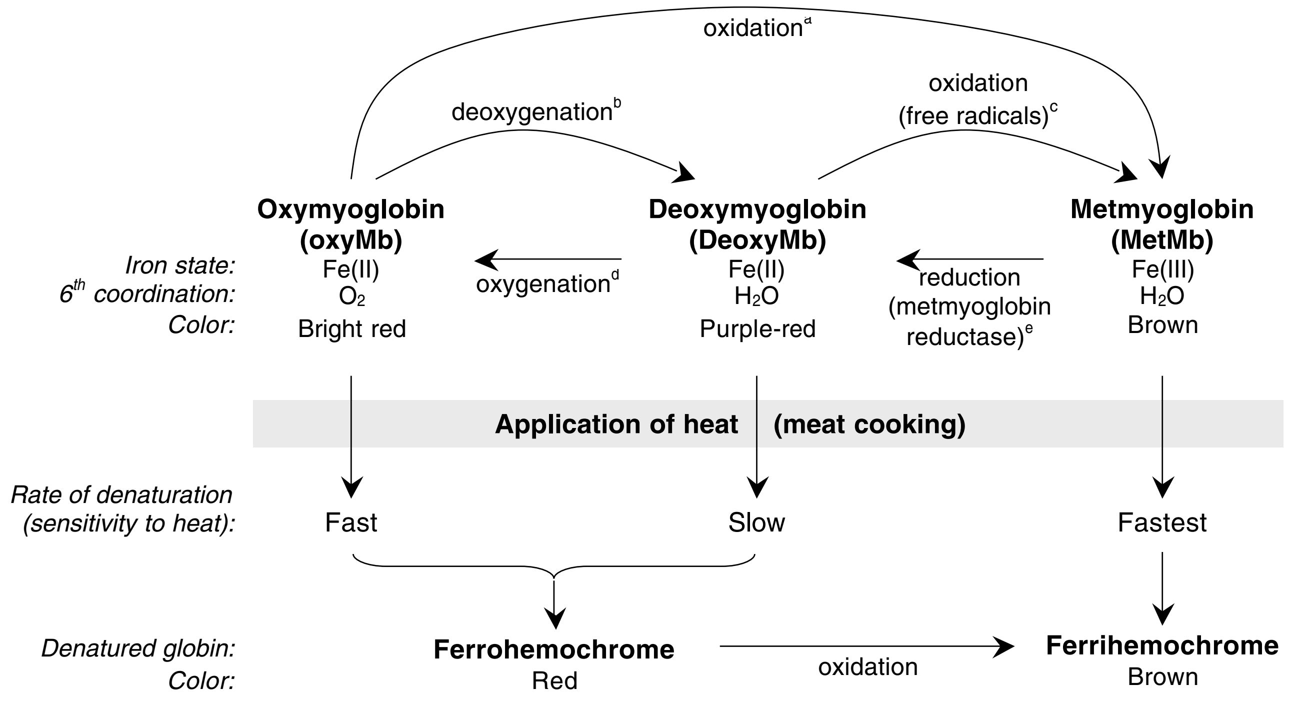
Myoglobin, an oxygen-binding protein found in muscle, is the pigment most responsible for the color of meat, though hemoglobin (the oxygen-binding protein in blood, which has considerable homology) may also be present in small quantities. Myoglobin consists of a globin protein and a heme group containing a central iron atom. The iron atom is attached to the globin and 4 nitrogen atoms, and has a 6th coordination point that can link with structurally compatible substances, usually water or oxygen. While the basic structure of myoglobin does not differ between animal species, small differences in amino acid composition and stability have been noted between pig myoglobin and that of cattle and sheep (Varnam and Sutherland 1995).

Myoglobin exists in three main forms, each producing a distinctive color (Figure 1). In living tissue, the physiologically active oxymyoglobin (oxyMb) and deoxymyoglobin (deoxyMb) forms are maintained through the activity of metmyoglobin (metMb) reductase enzymes. These processes decline *postmortem*, and storage conditions become more important in determining the proportion of each myoglobin form present (Warriss 2000). Deoxymyoglobin is found where oxygen is absent, such as in vacuum-packaged meats or in the center of meat portions. The ferrous iron becomes oxidized by free radicals when meat is stored for long periods of time, producing the brown pigment metMb, which also forms where oxygen-dependent meat enzymes and aerobic microorganisms successfully compete with meat pigments for oxygen. Oxymyoglobin is the pigment that produces the favored bright red color of raw meat, and is formed rapidly in the presence of oxygen at normal atmospheric pressure (Varnam and Sutherland 1995).

While hemoproteins, mostly myoglobin, constitute only about 0.5% of the wet weight of red meats, the response of these pigments to heat largely determines the color of cooked meat (Lytras and others 1999). Heating causes denaturation of the globin, which then precipitates with other meat proteins. Denaturation of myoglobin and other proteins begins between 55 °C and 65 °C in meat, and most denaturation has occurred by 75 °C or 80 °C (Varnam and Sutherland 1995; Hunt and others 1999). The rate of myoglobin denaturation slows with increasing meat temperature, and this is likely to be related to the concurrent rise in meat pH with cooking (Geileskey and others 1998).

The 3 forms of myoglobin differ in their sensitivity to heat. Deoxymyoglobin is the least sensitive to heat denaturation, followed by oxyMb, then metMb, though the latter 2 have fairly similar heat sensitivities (Van Laack and others 1996a; Hunt and others 1999). As the globin is denatured, metMb forms the brown globin hemichromogen, also known as ferrihemochrome. The other myoglobins are denatured to the red globin hemochromogen, also known as ferrohemochrome (Warren and others 1996b). The latter is readily oxidized to the former, so ferrihemochrome is present in larger amounts in cooked meats (Varnam and Sutherland 1995).

Adequate cooking of meat produces a color change to off-white, grey, or brown hues, depending on the type of muscle. The ultimate color depends on the extent of ferrihemochrome formation, which in turn is a product of the initial proportionality of the myoglobins, and the final concentration of undenatured oxyMb or deoxyMb



[a] Promoted in acid conditions (*post mortem*)
[b] Where oxygen is absent
[c] Produced by enzymes and spoilage bacteria
[d] Meat exposure to atmospheric oxygen
[e] Enzymes progressively inactivated *post mortem*

Primary references: Lawrie 1974; Varnam and Sutherland 1995; Warren and others 1996b; Baron and Andersen 2002. Also see text.

Figure 1—Characteristics of the myoglobin pigments in meat, their dynamic relationships, and the denatured products formed during cooking

(Varnam and Sutherland 1995; Van Laack and others 1996a). The color of meat can be measured visually, chemically, or instrumentally. Visual assessments usually involve a panel of two or more trained people who assign values according to a preset descriptive scale. Chemical assessments typically measure the concentration of myoglobin as extracted from a sample. Instrumental methods measure light reflectance off a sample. A typical instrumental technique uses a chroma meter to define color in terms of the values L^* (lightness), a^* (redness), and b^* (yellowness), commonly referred to as the Hunter values. Further optical values can be calculated from these measurements, such as hue angle ($\tan^{-1}$ (b^*/a^*)) (Warriss 2000).

The Influence of pH

The amount of ferrihemochrome formation from myoglobin during cooking is affected by initial meat pH. While mammalian muscle has a pH of around 7, normal fresh meat has a pH ranging from 5.4 to 5.6 (Varnam and Sutherland 1995). The carbohydrate glycogen is held in the muscles, but with postmortem reduction of oxygen supply the glycogen is broken down to lactic acid, lowering the pH. This acidification process will continue until either the glycogen is consumed or the low pH inactivates glycolytic enzymes. Where glycogen is limited, such as in animals that are very active, stressed or exposed to cold over a long period prior to slaughter, the ultimate pH of the meat is higher. Meat with a pH above 6.2 tends to have tightly packed water-retaining fibers that impede oxygen transfer and promote longer survival of oxygen-scavenging enzymes, favoring deoxyMb rather than oxyMb. The purple-red myoglobin combines with the closed structure of the muscle to absorb rather than reflect light, making the meat appear dark. This condition is commonly known as dark, firm, dry (DFD) (Adams and Moss 2000; Warriss 2000).

A pale, soft, exudative (PSE) condition can be found in meats with a low ultimate pH. PSE mainly affects pigs, though PSE-like characteristics have been observed in poultry meats, and occasionally beef. PSE meat forms when animals undergo acute stress immediately prior to slaughter. *Postmortem*, glycogen levels are still reasonably high, and the acidification processes are accelerated so that the pH falls rapidly, while the muscle is still warm. The combination of high temperature and low pH causes protein denaturation, water loss, and an open muscle structure. The low pH also tends to promote oxidation of oxyMb and deoxyMb to brown metMb, which combined with high light scattering from the meat surface, gives the meat its pale color (Adams and Moss 2000; Warriss 2000).

The PSE and DFD conditions have been shown to influence the cooked color of pork. Ground pork patties made from PSE meat did not appear pink after cooking to time/temperature regimes ranging from an IT of 62.8 °C for 3 min to IT 82.2 °C for 1 s. Equivalent "normal" patties were pink at 62.8 °C and 65.6 °C (1-min holding), and very slightly pink at 71.1 °C (1-s holding) (Lien and others 2002b). A similar pattern was observed for PSE boneless pork chops cooked to the same time/temperature combinations. DFD pork chops have also been tested, and under all cooking conditions, these were more pink than normal or PSE meat (Lien and others 2002a). Myoglobin denaturation is faster in PSE pork when compared to normal pork, particularly at temperatures below 71 °C. It is possible that the open fibers and lower pH of PSE meat may predispose myoglobin to greater heat denaturation, and faster browning (Lien and others 2002a, 2002b). The lack of redness and the greater proportion of heat-sensitive metMb in raw PSE meat might also enhance yellowness.

Several studies have identified a correlation between raw beef pH and the amount of undenatured myoglobin remaining in the cooked product, which itself correlates with red color. When compared to beef of normal pH, the proportion of myoglobin denatured during cooking in high-pH beef is less, and a more intense red color is measurable. Using absorbance as a measure of myoglobin denaturation, the proportion of myoglobin denatured in ground beef at a normal pH of 5.50 was higher than the same meat with the pH adjusted to 6.50 when both formulations were cooked to a variety of ITs (Trout 1989). A range of beef cuts were used to produce patties with variable pH and when grilled to an IT of 71 °C, red and pink color was still evident to panelists in patties with a pH greater than 5.7 (Mendenhall 1989). Similarly, when commercially prepared ground beef patties of variable pH were cooked to an IT of 71 °C, those with a pH less than 5.9 were invariably associated with a brown cooked color, and red cooked color occurred mostly in patties with a pH of 5.95 or above (Van Laack and others 1996b). In ground beef with the pH artificially adjusted, patties with elevated pH required higher final endpoint temperatures to denature similar amounts of myoglobin to patties with lower pH (Brewer and Novakofski 1999).

The effect of pH on the color of cooked meat has also been observed in meats other than pork or ground beef. The inside rounds of beef from young bulls were processed into roasts and cooked to an IT of 63 °C in a waterbath. Slices from the anterior end and middle were analyzed instrumentally, and roasts with high pH (>5.6, mean 6.5) were found to have higher L^*, a^*, and b^* values than normal pH (5.3 to 5.6, mean 5.5) roasts, that is, they were significantly redder (Swan and Boles 2002). Raw chicken breast of higher pH is associated with a darker appearance, and this relationship somewhat persists with cooking. Fletcher and others (2000) found that steam cooking "lighter than normal," "normal," and "darker than normal" chicken breast (pH 5.76, 5.84, and 5.93, respectively) produced cooked products with Hunter optical values that could be related back to the raw meat pH and color. It was found, however, that the color variability with pH was not as pronounced in the cooked product as when in raw form. Even when the chicken was marinated prior to cooking, cooked darker meat (mean pH 6.10) was associated with more redness (Qiao and others 2002).

The extent to which pH affects the cooked color of meat appears to vary between meats from different animal species. In a comparison of ground pork, turkey and beef (pH adjusted to 5.5, 6.0, 6.5, or 7.0) cooked to various target ITs, all meats had a redder appearance and lower myoglobin denaturation with higher pH, but at higher temperatures (76 °C and 83 °C), these effects were more persistent in the turkey, irrespective of pH. For example, at a target IT of 83 °C, myoglobin denaturation was at or close to 100% in beef and pork at all pH levels, but turkey samples were still spread between 75% and 95% depending on pH. However, for all species any pH-induced differences in color were reduced with increased cooking temperature (Trout 1989).

Evidently, a relationship exists between pH, myoglobin content, and myoglobin denaturation, and the final color of cooked meat. The influence of pH may even dominate other factors that can affect cooked meat color, such as fat content, freezing, and rate of thawing (Berry 1998; Berry and others 2001). A satisfactory explanation for this relationship is currently lacking, though it is likely that several factors might be interacting. These factors might include the initial form of the myoglobin (for example, deoxyMb is less heat-sensitive and more stable at higher pH than other myoglobin forms), the condition and structure of the muscle fibers (for example, DFD vs. PSE), and the denaturation processes of other meat proteins, including enzymes, which could also be affected by pH and to which myoglobin denaturation is intricately linked.

There have been some studies that suggest the pH-effect on color is not always predictable, and this provides some evidence for the complexity of the pH/color relationship. In the studies of Van Laack and others (1996b), beef patties with higher pH values were not always associated with a red cooked color and the authors admit to the interference of "other (unknown) factors." Thirty percent of the color variation that was observed in these studies was attributed to the initial myoglobin concentration in the raw products. Certainly, meat from different animals or from muscles of the same animal can vary in their myoglobin content (Varnam and Sutherland 1995). Additional variation (33%) was attributed to the reducing capacity of the meat (Van Laack and others 1996b). This has also been shown to influence the myoglobin form and the extent of meat browning, but will be detailed in later sections.

In another study, pork loin chops of 2 pH groups (pH 5.4 to 5.5, pH 5.6 to 5.7) cooked to 3 endpoint temperatures could not be separated by their Hunter values immediately after cooking (Mancini and others 2005). The small difference in pH between these groups could be one explanation, as could the high (>71 °C) temperatures studied. Ground lamb with a pH lower than normal (pH 5.38, normal pH 5.70) demonstrated much slower denaturation of myoglobin when cooked (Lytras and others 1999). The authors suggested that the low pH of the raw meat had denatured the proteins that ordinarily would be available to interact with myoglobin during cooking, so the myoglobin became more stable in the absence of these reactants. However, low pH favors the formation of brown metMb, and also destabilizes deoxyMb (Varnam and Sutherland 1995).

While there can be some variation, there is enough evidence to suggest that a strong relationship exists between the pH of raw meat and cooked meat color. Generally, meat with a pH above normal slows the denaturation of myoglobin, and the meat can still remain pink when cooked to the recommended IT. High pH meat is not uncommon in the domestic market, particularly if animals have been chronically stressed prior to slaughter (Trout 1989). Of 295 U.S. samples of raw beef, 106 (36%) were above the normal pH range of 5.3 to 5.7 (Mendenhall 1989). The pinkness associated with properly cooked high pH meat is perhaps more an issue for food quality than food safety. Consumers may perceive that high pH meat is less cooked, and will proceed to continue cooking to higher temperatures or for a longer time, with subsequent losses in quality (e.g., texture, juiciness, yield). One potential food safety issue with high pH meat is that consumers who use thermometers to judge doneness may begin to doubt their accuracy when a meat product still appears to be undercooked, and thermometer use might cease. Of more importance are meat products that visually appear cooked before a safe IT has been reached. This "premature browning" has been shown to occur in PSE pork products, and could be an issue for other low pH meats.

The Influence of Meat Source

The species of animal, the age of the animal at slaughter, and the anatomical location of the muscle from which meat is sourced can all affect final cooked meat color. To an extent, this is explained by differences in myoglobin content. Beef, for example, contains between 4 and 10 mg myoglobin/g wet tissue, but this value might reach 20 in older animals. Pork contains no more than 3 mg myoglobin/g wet tissue. Male animals typically have higher myoglobin concentrations than females, and muscles with higher work loads, such as the leg muscles, are darkened by greater myoglobin content (Varnam and Sutherland 1995). The condition of the animal at slaughter and postslaughter processing influences meat quality and subsequent color changes, and in many aspects, this is related to the effects of pH, as described above. However, one study (Liu and Berry 1996) has found that even with strict control over manufacture (formulation and pH) and handling, batches of meat can inexplicably vary in the final cooked color.

In chickens, meat from defrosting immature birds can be darkened as hemoglobin moves out of the porous, incompletely calcified walls of the bones to accumulate in the tissues. Temperature change (for example, freezing, reheating) can also darken poultry meat by causing cell degradation and migration of hemoglobin pigment from the bone. For example, darkening of meat on thigh pieces can be related to pigment migration from the femur (Lyon and Lyon 2002). So, while myoglobin and hemoglobin are both important, the latter is more influential on poultry meat color (Boulianne and King 1998). When cooked, tissues with more heme pigment will appear darker than, for example, breast meat (Lyon and Lyon 2002). Chicken leg quarters (bone-in) were cooked to an IT of 75 °C or 85 °C. At 75 °C, the meat adjacent to the bone retained more redness than the surface. The redness of the meat adjacent to the bone was amplified if the portions were chilled above 0 °C prior to cooking compared to chilling at <0 °C, though cooking to 85 °C negated color differences attributed to chill temperatures (Lyon and Lyon 2002).

Differences in cooked color have also been observed in beef sourced from assorted muscles. The myoglobin in ground beef patties prepared from sirloin (*longissimus dorsi*) denatured at a faster rate during cooking than in patties made from shoulder steak (chuck) or shin. The pH and concentration of myoglobin was similar in all raw cuts (Geileskey and others 1998). A similar effect has been observed in ground lamb, where myoglobin denaturation during cooking was faster in sirloin than shoulder or leg steaks, though only at temperatures <70 °C (Lytras and others 1999). Since the rate of myoglobin denaturation was measured in these studies, the differences cannot be explained by variability in gross myoglobin content. The authors suggested that final meat color might be influenced by different concentrations and thermal stabilities of reactant proteins in the muscle groups. The extent of denaturation of these proteins during cooking would in turn influence the extent of interaction with, and denaturation of, the myoglobin, which itself comparatively shows very little difference in stability and reactivity between muscles (Geileskey and others 1998; Lytras and others 1999). This theory has also been proposed to account for differences in the rate of myoglobin denaturation between animal species. For example, minced lamb sirloin demonstrated a faster rate of myoglobin denaturation during cooking than beef sirloin (Geileskey and others 1998). However, the pH and hemoprotein content of the lamb was lower than that of the beef, which possibly influenced this result.

Earlier work had suggested that meat sourced from older animals would brown quicker than cuts from young animals during cooking (Marksberry 1990). In another study (Hague and others 1994), ground beef from A-maturity (young at slaughter) and E-maturity (old at slaughter) carcasses were compared for color when cooked to a variety of ITs. No differences in meat color or color of expressed juice were observed with carcass maturity at any temperature. Of concern in this study was that patties cooked to 66 °C and 71 °C were only distinguishable by instrumental measurements, and were not visually different. Patties cooked to different temperatures were only visually different when observing the color of the expressed juice (Hague and others 1994). The browning of these patties at lower temperatures may have masked any effect on cooked color that might arise from carcass maturity.

From a food safety perspective, meats that remain pink once a safe cooking temperature has been reached are not of concern. This is the case for meats darkened by the proximity of bone and chilling conditions. Premature browning could possibly occur in meats sourced from older carcasses, though current results are conflicting.

The Influence of Packaging

The extent of myoglobin oxygenation or oxidation of the iron moiety (redox potential) plays an influential role in rate of browning and the final cooked color of meat (Figure 1). In most raw meat products the myoglobin form will be largely influenced by the atmospheric conditions created by packaging and display conditions.

Well-oxygenated ground meat contains a higher concentration of oxyMb, though the extent of oxyMb formation can vary with animal species (Varnam and Sutherland 1995). Deoxymyoglobin is more prevalent where oxygen interaction with the meat has been inhibited, such as in vacuum packaged meat. OxyMb is more sensitive to heat denaturation than deoxyMb, and well-oxygenated meats, such as fresh meats without packaging or in aerobic packaging, will brown faster when cooked. In a series of cooking experiments, oxygenated pork was found to appear visually less pink than deoxygenated pork when cooked to temperatures ranging between 65.6 °C and 76.7 °C (Lien and others 2002b). Beef patties where myoglobin was predominantly oxyMb were very red in the raw state compared to purple-red deoxyMb-dominant beef, but once cooked to 55 °C, the well-oxygenated meat was brown while the deoxygenated meat still appeared red and undercooked (Hunt and others 1999).

Even small changes in the length of time a product is packaged can alter myoglobin oxygenation. Killinger and others (2000) compared the cooked color of patties made from ground beef freshly packaged under oxygen-permeable film to the same packaged product stored overnight in a refrigerator. Patties made from stored meat contained more deoxyMb and were redder when cooked compared to freshly packaged ground beef. Similarly, patties made from the outer portion of a meat pack were browner than those from the inner portion when cooked, and contained less deoxyMb.

Similarly, the oxidative state of the iron moiety will affect cooked meat color. Long-term storage of meat increases the proportion of metMb, which results in the brown color not favored by consumers. MetMb is also the most sensitive to heat denaturation, the browning of meat during cooking is rapid. Ground beef artificially oxidized or reduced to increase the proportion of metMb or deoxyMb, respectively, then cooked to an IT of 55 °C were easily distinguishable by color. When compared to cooked patties with an unaltered redox potential (visually pink), reduced meat appeared the most red inside, and oxidized meat the least (Warren and others 1996a). In a similar study the oxidized meat was notably brown, even when raw (Hunt and others 1999). The variation in reducing capacity measured from samples of commercially prepared beef patties was found to correlate with myoglobin denaturation during cooking, such that patties with lower reducing capacity browned internally at lower temperatures (Van Laack and others 1996b).

Modified atmosphere packaging is used to prolong meat shelf-life. The most common condition used for fresh beef is an atmosphere of 80% oxygen and 20% carbon dioxide. Under these conditions the oxygen promotes production of oxyMb and the red color is stabilized. The use of 0.4% carbon monoxide (CO) with 30% carbon dioxide and the balance as nitrogen has been approved for meat packaging in the United States. The CO binds with myoglobin and forms the pigment carboxymyoglobin, which gives meat a stable cherry red color. Vacuum packaging promotes formation of deoxyMb, and meat appears a purple color, which is not so highly favored by consumers (John and others 2005).

John and others (2005) observed differences in beef steak color when grilled to a variety of ITs after storage under modified atmospheres or vacuum (John and others 2005). Meat stored under 80% O_2 was less red and had significantly more myoglobin denaturation after cooking. At an IT of 66 °C, the visual panel score for steaks stored under 80% O_2 was between "slightly pink" and "tan, no pink," and they were visually done at 71 °C. Steaks stored in the presence of 0.4% CO retained a comparatively redder appearance after cooking, and were very similar to cooked steaks that had been stored under vacuum. Meat from these treatments was easily identified as being undercooked at 66 °C, and internal redness was prolonged such that it was still visually detected at an IT of 79 °C. The same trend has been found in similar studies with ground beef (Van Laack and others 1996a; John and others 2004), though in the study of Van Laack and others (1996a) the beef stored under oxygen-permeable film contained a significant concentration of metMb rather than oxyMb, probably as a result of precook freeze-thaw handling. Storage of injected beef steaks under an alternative oxygen-free atmosphere, 80% nitrogen and 20% CO_2, still resulted in cooked steaks that had less myoglobin denaturation and more red color when compared to those stored under 80% O_2 (Seyfert and others 2004a).

To summarize, the oxidation and oxygenation state of myoglobin is dynamic in meats and will be influenced by storage conditions and packaging. The pigment state at time of cooking could influence the cooked color appearance (Warren and others 1996a). Meats that contain higher concentrations of oxyMb or metMb will brown quicker with cooking than those with higher proportions of deoxyMb (Lien and others 2002b). Meat stored under normal atmospheric conditions that is either very fresh (high oxyMb) or has had prolonged storage (high metMb), or storage of meat under a modified atmosphere of 80% O_2 (high oxyMb), could appear visually well cooked when a safe internal cooking temperature has not been achieved.

The Influence of Freezing History

In a study by Van Laack and others (1996a), the internal color of beef patties cooked from fresh was redder than the same formulation of patties cooked from a frozen state. In turn, the internal color of patties cooked from frozen was redder than that of patties thawed prior to cooking, and premature browning was evident in the thawed samples (Van Laack and others 1996a). This indicated that a relationship existed between the freezing history of the patties prior to cooking and the final cooked color. The effect does not appear to be predictable and may depend on the species from which meat is sourced. Pork patties cooked after thawing retained a redder appearance than those cooked from frozen, with the latter appearing fully cooked at the lowest target IT (62.8 °C) (Lien and others 2002b).

The lengths of time under frozen storage or thawing both affect the cooked color of beef patties. When 17 beef patty products were cooked from a frozen state after a brief period in storage, the internal color of 47% of the products was visually classified as red or pink at an IT of 71 °C. After frozen storage for a year, 94% of the products were red or pink when cooked from frozen to IT 71 °C (Van Laack and others 1996b). When investigating the effect of thawing time, frozen ground beef patties were cooked (IT 71 °C) from frozen, after 30 min thaw at 25 °C, or after 6, 12, 18, or 24 h thaw at 7 °C. Products cooked after thawing had a more well-done appearance than those cooked from frozen, and had lower a^* values and higher hue angles (so less pink-red), and increased Mb denaturation, despite having shorter cooking times than those cooked from frozen. The effect was enhanced with longer thawing. It was also observed in this study that one product with a pH of >6.0, which would usually appear undercooked at safe cooking temperatures, still appeared well done when cooked after thawing. The link between pH and color may be lost after a freeze thaw cycle (Van Laack and others 1996a), though this is contradicted by other authors (Berry 1998; Berry and others 2001).

Several publications (USDA 1998; Lyon and others 2000, 2001; Berry and others 2001) have addressed the relationship between freezing history and cooked meat color through more detailed investigations. All of these studies investigated the impact on the cooked color of ground beef with different freezing history (stored frozen as patties or as bulk mince) and thawing conditions (2 h at room temperature, 4h under refrigeration or microwaved). Cooking involved grilling to ITs of 52.7 °C, 65.6 °C, 71.1 °C, and 79.4 °C. The freezing history and thawing conditions interacted to modify the cooked color of the patties when compared to freshly prepared and cooked beef patties, and a large number of outcomes were observed. Typically, ground beef stored as bulk and formed into patties just prior to cooking showed a higher incidence of premature browning. For example, as many as two thirds of the patties formed from ground beef frozen in bulk and thawed overnight in a refrigerator had turned brown at IT 65.6 °C, despite incomplete thawing and shorter cooking times (USDA 1998; Berry and others 2001). It was also more common for the juices of patties formed from bulk frozen ground beef to have no pink or red color at temperatures less than 71 °C (Lyon and others 2000). While patties prepared from bulk-frozen beef were the least red upon thawing and cooking, at equivalent ITs fresh beef patties were significantly redder, and beef stored frozen as patties and thawed before cooking were the reddest. The cooked colors of the patties stored frozen did not significantly change with thawing method (room temperature, under refrigeration or in the microwave) in any of the studies. All of these methods were rapid thawing techniques, and it is more likely that the time of thawing has more effect than the method, which might account for the greater browning observed in the bulk frozen beef (Van Laack and others 1996a; Lyon and others 2001).

There is uncertainty over the changes in myoglobin chemistry brought about by freezing history that influences color. Van Laack and others (1996b) could not attribute changes in myoglobin denaturation or a* value brought about by frozen storage to any differences in reducing capacity, concentration of metMb or cooking method, though the differences in product formulation and cooking from frozen are likely to have had some influence in their study. Ben Abdallah and others (1999) compared the concentration of each form of myoglobin between raw beef cuts that had undergone a freeze–slow thaw cycle and fresh beef cuts. When both were stored at 2 °C in the dark in gas-impermeable film, the previously frozen meat contained significantly more metMb and less oxyMb than the fresh meat for most of the experiment. The high concentration of metMb would have increased the rate of formation of brown color if this meat were cooked.

Several hypotheses have been summarized by Ben Abdallah and others (1999) to explain the increase in metMb brought about by freezing. Proposed processes include autooxidation (the nonenzymatic spontaneous oxidation of myoglobin by free oxygen), cell membrane disruption brought about by freezing, which allows catalysts of oxidative reactions to come into contact with myoglobin (perhaps in a more concentrated form in unfrozen liquid pockets), and disruption of the metaglobin-reducing enzyme system through disruption of enzyme structure or function during freezing. Lyon and others (2001) have also suggested that slow freeze–thaw rates may damage the myoglobin protein, promoting faster denaturation or oxidation during cooking and increasing the possibility of premature browning. However, none of these hypotheses account for patties that are cooked from frozen or after a short thaw (for example, microwaving), where the formation of brown color during cooking is limited (Lyon and others 2000).

Physical factors are probably also important. Berry and others (2001) suggested that patties prepared from bulk frozen beef mince were less cohesive than other preparations, so heat transfer was better during cooking and browning was more rapid. Lien and others (2002b) proposed that pork patties cooked from frozen might brown earlier through a combination of greater thermal conductivity (2 to 3 times greater in frozen than thawed meat) and absorption of more energy (the energy released as ice crystals convert to water is absorbed). So at a common endpoint temperature, frozen patties would have absorbed more energy than thawed patties, and this should increase browning. This does not explain the opposite observation for beef patties, where those cooked from frozen remain redder than those cooked after thawing (Van Laack and others 1996a).

It is clear that freezing history will affect the color of cooked ground meat so that cooking to an IT of 71 °C will not predictably produce a patty that "looks cooked," though further studies are needed to investigate the mechanisms behind these observations. Cooking from frozen or after rapid thawing generally prolongs pink color, though this might differ with meat type. Alternatively, patties that have been formed from bulk frozen beef or that have been slowly thawed could appear brown at unsafe cooking temperatures.

The Influence of Fat Content

There is an increasing trend for consumers to favor meat products lower in fat, such as beef patties prepared with lean meat. Some publications have indicated that fat content does not influence the cooked color of meat in any readily discernable way (Troutt and others 1992b; Berry 1994; Berry and others 2001). For example, beef patties with fat content between 5% and 30% were cooked to an IT of 71 °C or 77 °C. When raw, the lower fat patties were distinctively darker red, but when cooked the concentration of fat did not affect surface color, uniformity of surface color, or internal color (Troutt and others 1992b).

Other studies suggest that the fat content of meat may have some effect on the final cooked color, with higher fat patties appearing less pink (Berry 1998; Berry and others 2001). In beef, the oxidation state of lipids and pigments are closely linked, so that an increase in one similarly increases the other (Varnam and Sutherland 1995). There is enough evidence to confirm that, at least in raw meat, myoglobin has an important role in the oxidation of polyunsaturated lipids (Baron and Anderson 2002). While the oxidation processes involved in meat cooking will alone increase metMb and ferrihemochrome, the effect could be augmented where the fat content is higher. The relationship between lipid and metMb oxidation is not fully understood, though it might involve the formation of free radicals or oxygen depletion during lipid oxidation (Monahan and others 2005).

While fat content might influence the cooked color of meat, it is probably not as influential as other factors that alter cooked color, particularly high pH and freezing history (Berry 1998; Berry and Bigner-George 2000). None of the publications cited above expressed any concern over premature browning due to fat concentration alone. The only food safety concern relating to fat and meat color lies where commercial establishments, such as burger restaurants, cook meat products according to set time/temperature regimes that have been based on producing a safe and visually cooked product. Fat is an efficient conductor of heat, and higher fat meats will reach target ITs quicker than those with less fat (Troutt and others 1992b; Liu and Berry 1996). If these regimes are applied to lower fat formulations without modification, it is possible that meat products will fail to reach safe ITs. However, visual assessment of the low fat product after the established cooking structure will quickly indicate that a food safety problem may exist.

The Influence of Added Ingredients

A number of ingredients may be added to meat prior to cooking. This is more common for comminuted meats, where ingredients might include extenders such as soy protein, nonfat dried milk or cereals (for example, bread crumbs, rusk), as well as salt and spices (ICMSF 1998). The composition of ground beef might also be altered by the addition of lean finely textured beef (Van Laack and others 1997). Some of these ingredients have been shown to affect the cooked color of meat.

The addition of sodium chloride (NaCl) or sodium tripolyphosphate ($Na_5O_{10}P_3$) can increase myoglobin denaturation. Trout (1989) demonstrated that when ground beef patties with concentrations of NaCl between 0% and 3% were cooked to a range of ITs, the higher NaCl concentrations increased the percentage of myoglobin denatured. The browner color was particularly obvious at lower temperatures (52 °C to 66 °C). In the same study, the myoglobin denaturation in ground beef with 0.5% $Na_5O_{10}P_3$ was 5% to 10% greater than without the additive. This result was not affected by modification of the pH (Trout 1989). In a similar study, the rate of myoglobin denaturation in ground beef with 1.5% to 3% NaCl was almost twice that of salt-free meat, and in ground lamb with 2% NaCl, the myoglobin denaturation rate was 2 to 3 times faster than the salt-free control at lower temperatures (55 °C and 60 °C), and still consistently faster at higher temperatures (65 °C to 75 °C) (Lytras and others 1999). The presence of salt will cause faster browning of meat, and may cause meat to be visually assessed as cooked before microbiologically safe cooking has occurred.

Nitrite is usually used in the curing process of meats and generates the characteristic and heat-stable red color by binding with myoglobin. Seyfert and others (2004b) suggested that some cross-contamination might occur in facilities producing both fresh and cured meats, whereby fresh meats could unintentionally be exposed to nitrite or nitric oxide. They demonstrated that contamination of precooked ground pork with nitrite would cause a heat-stable pink color to develop upon further cooking. While this might be an issue for meat quality, from a food safety perspective the meat will appear undercooked to a consumer and will be rejected.

Lean finely textured beef (LFTB) is often incorporated into ground beef to produce a lower fat product. The pH of meat products increases with the addition of LFTB, however the myoglobin in LFTB denatures quickly with heat and meat products containing LFTB will brown quicker upon cooking. The processes involved in the production of LFTB render the myoglobin in LFTB more heat sensitive and might also modify the state of other proteins that interact with myoglobin, increasing the rate of myoglobin denaturation during cooking. LFTB also contains a higher proportion of metMb; metMb being the most heat sensitive myoglobin form (Van Laack and others 1997). Van Laack and others (1997) compared the cooked color of normal and high pH beef patties when LFTB was added incrementally. Without LFTB, the high pH meat was predictably redder and visually less well done than beef with normal pH. Addition of LFTB to the high pH formulation increased myoglobin denaturation and decreased redness when cooked. Interestingly the pH was not significantly altered, even with 75% LFTB. In contrast, addition of LFTB to the normal pH formulation increased the pH significantly, and visually the cooked color did not change significantly. It is possible that with addition of LFTB to the normal pH meat the dual effects of increased pH (expect increased redness in cooked meat) and increased myoglobin denaturation (expect decreased redness in cooked meat), balanced one another. Certainly more work is needed to understand this observation.

Other additives do not appear to be important for influencing cooked meat color. Provided the pH of pork chops is controlled, injection of water and phosphate will not affect cooked color development (Lien and others 2002a). Addition of 2% olive oil to ground lamb did not denature myoglobin during cooking at a rate any different to an oil-free control, and myoglobin denaturation during the cooking of ground beef with added polyphosphates (0.3%), soya proteins (1% or 3%), caseinate (2%) or whey (3%) was not significantly different from unmodified controls (Lytras and others 1999). Finally, the addition of dietary fibers (sugarbeet, oat or pea), potato starch and polydextrose® did not affect the internal color of beef patties cooked to at IT of 71 °C or 77 °C (Troutt and others 1992a).

The Influence of Preservation Treatments

Pressure treatment is sometimes used to improve microbiological quality and color of meat, and may impact on cooked color. Jung and others (2003) pressure treated vacuum packed beef steak prior to cooking (IT 65 °C), and analyzed for changes in color. While pressure treatment increased the redness of raw beef, once cooked the color differences between pressurized and nontreated controls disappeared.

Ionising radiation is being increasingly used to extend the shelf-life of fresh meat by inactivating bacteria and parasites. The most common form of irradiation is gamma radiation, where isotopes (principally ^{60}Co and ^{137}Cs) are used to emit electromagnetic radiations (Jay 1996). Low level irradiation does not induce detectable organoleptic changes in most meat products (Adams and Moss 2000), though some rancidity might be noticeable (Chirinos and others 2002), but it can cause color changes that appear to vary by irradiation dose, species and packaging conditions (Grant and Patterson 1991; Nanke and others 1998).

The color change in raw beef with irradiation has been investigated, and most report a dose-dependant browning effect (less red, more yellow). The loss of red color is more evident when the beef is irradiated in the presence of oxygen (e.g., in oxygen-permeable packaging), but minimal when the beef is vacuum-packaged or in carbon monoxide MAP (Fu and others 1995; Nanke and others 1998; Giroux and others 2001; Kusmider and others 2002), though an increase in redness with irradiation has also been reported in raw vacuum packaged beef (Peirson and others 2005). The effects of irradiation are transmitted to cooked color. In a recent study (Peirson and others 2005), the cooked color (IT 60 °C or 71 °C) of ground beef stored briefly under aerobic or vacuum packaging, either fresh or frozen, and irradiated prior to patty formation and cooking, was compared to equivalent nonirradiated samples. Though statistically significant differences were lacking, some trends were evident, particularly at IT 60 °C. Compared to their equivalent controls, the cooked color of patties irradiated in aerobic conditions was less red, and an increase in redness was reported for patties irradiated under vacuum. However, irrespective of packaging, cooked patties that were frozen prior to irradiation were less pink than fresh samples. Bulk freezing and the long overnight thaw are likely to have contributed to this effect (see earlier section on freezing history). Importantly, when cooked to only 60 °C, the color of this prefrozen irradiated beef was indistinguishable from nonirradiated beef (fresh or prefrozen) that had been cooked to 71 °C.

Alternative results have been reported for poultry meats and pork. Raw, irradiated chicken, turkey, and pork are all redder than equivalent nonirradiated meats (Grant and Patterson 1991; Nanke and others 1998; Nam and Ahn 2002). The red color is intensified with increased radiation dose and varies with packaging conditions (e.g., more development of red color with vacuum packaging), but persists with cooking. Breast meat from chickens were packaged under vacuum or aerobic conditions, irradiated, and the color compared to equivalent nonirradiated samples after cooking to an IT of 74 °C. The irradiated fillets were redder than controls, though aerobic storage reduced irradiation-induced redness (Du and others 2002). In testing the effect of irradiation on the cooked color of meats from different poultry species, Millar and others (2002) found that all irradiated cuts were redder than controls, though there were differences between species and muscle type (leg, breast). An increase in red color has also been reported for irradiated precooked pork sausages, particularly if stored under vacuum (Jo and others 2000).

Several hypotheses have been suggested to explain irradiation-induced color change. Nanke and others (1998) suggest that the increase in yellowness of raw beef irradiated aerobically could be due to formation of metMb, which would increase the rate of browning upon cooking. Under aerobic conditions the radiation stimulates lipid oxidation (Kusmider and others 2002) and reacts with water to form free radicals such as hydroxyl (OH) (Chirinos and others 2002). Free radicals promote myoglobin oxidation (Giroux and others 2001), enhancing development of metMb. The addition of free radical scavengers to beef and pork prior to irradiation has been shown to stabilize color (Zhao and Sebranek 1996; Giroux and others 2001). It has been suggested that the increased redness observed in irradiated pork and poultry meats and irradiated vacuum-packaged beef is due to the formation of a carboxy heme pigment, when carbon monoxide produced during irradiation of meat links to the 6th coordination point in the myoglobin and/or hemoglobin to produce red carboxymyoglobin and/or carboxyhemoglobin (Millar and others 2002). Nam and Ahn (2002) also propose that irradiation generates reduced conditions that encourage reduction of the myoglobin iron, and indeed an oxyMb-like pigment has been detected in vacuum packaged irradiated pork and beef (Nanke and others 1998).

There is insufficient evidence to suggest that preservation treatments involving pressure generates an issue for food safety, at least in beef, as pressure-induced color change appears to be eliminated with cooking. The persistent pink color of cooked, irradiated pork and poultry, and in many cases beef irradiated under vacuum, will more likely be interpreted as undercooking, and the product will be rejected, or overcooked with subsequent losses in quality. However, premature browning does appear to be an issue for beef irradiated in aerobic conditions or after freeze–thaw.

Cooking Method

Cooking method influences the rate of heat transmission through a meat product and the extent of cooking. There are publications that report the temperature patterns within meat products cooked using various methods (Chen and Marks 1997; Singh and others 1997; Rhee and others 2003), but only one study was identified that compared cooking method with cooked color. Bowers and others (1987) observed that the internal color of beef steaks cooked to the same IT were visually browner when oven broiled compared to roasting. This indicates that cooked color could also be influenced by the method of cooking, though more studies would be needed to report the extent of this effect.

Pink Defect

Pink defect is a condition where well-cooked white meat (pork, poultry) still retains a pink color or develops pinkiness with storage after cooking. The proposed causes include the types of pigments in the meat, preslaughter factors such as genetics, feed, hauling and handling, heat and cold stress and gaseous environment, stunning techniques, incidental nitrate/nitrite contamination, water supply, freezing and processing equipment, and processing ingredients, the use of nonmeat ingredients, cooking methods, and irradiation of precooked products (Holownia and others 2003). There is a large body of literature on this topic, but the condition is an issue for food quality, not food safety. Pinkiness in cooked meat will cause consumers to reject the meat as undercooked, or subject the meat to further cooking. Pink defect will not be reviewed further in this paper.

Conclusions

The color of a meat product once cooked is not a good indication that the food has reached a microbiologically safe IT. Ground, rolled, injected or variety meats require thorough cooking to inactivate any pathogenic microorganisms that might be present internally. The greatest issue for food safety is when the interior of cooked meat is visually brown and "well done," yet the IT is not high enough to ensure the inactivation of microbiological pathogens. This condition, termed premature browning, may occur with PSE meats, and can be induced by storage in high-oxygen modified atmospheric packaging, bulk storage in the frozen state, prolonged thawing, the addition of salts or LFTB, and where beef is irradiated in aerobic conditions (Table 1). At the other extreme, there are numerous factors that prolong pink color in meats, so that they do not appear to be adequately cooked. This condition is more an issue for food quality, where products will be overcooked, and also may bring about economic losses in food service industries through consumer rejection and loss of yield (Table 1).

Clearly, all of the factors reviewed in this paper—pH, meat source, packaging, freezing history, fat content, added ingredients, preservation treatments, and cooking method—will combine to holistically influence the color of cooked meat. Taken independently, the mechanisms by which the properties of the meat are altered by each of these factors appear to be highly complex and often based on hypotheses. Overall, there is little known about the biochemical interactions between myoglobin and other proteins or lipids in meat during the cooking process; understanding these will provide some explanation for the observations summarized in this review. This review has identified several information gaps that might be investigated further. Good biochemical experimentation might better expose the changes in meat induced by pH (e.g., proteins, structure, myoglobin state) and explain how pH appears to influence the rate of myoglobin denaturation during cooking. Other questions that arise from this review are why rapid thawing of frozen meat reduces myoglobin denaturation during cooking yet slow thawing increases this, how myoglobin denaturation is increased in the presence of salt, why the changes induced by addition of LFTB are so dependant on meat pH, and what biochemical processes are responsible for the color changes induced by irradiation. Some of these information gaps might be addressed by future research on meat color. The most recent studies reviewed in this article indicate that the direction of future research is likely to focus on addressing the need for the meat industry to control meat appearance and spoilage. Specifically, further studies to better understand the oxidation processes in meat (before and during cooking) and the effect of emerging packaging and preservation technologies are likely.

In summary, the character of raw meat products available to the consumer at the point of purchase will vary with meat source and processing, and will continue to change with postpurchase handling. The history of the meat will directly affect the color when cooked. On this basis, there can be no confidence in visually inspecting a meat product to ascertain if it is safely cooked, and use of a food thermometer is the most reliable method for guaranteeing the inactivation of foodborne pathogens in cooked meat.

This conclusion has significant implications for food regulatory agencies whose mandate is to release regulations and advice for

Table 1 — Factors that influence the cooked color of meat

Factor		Potential for (on meat cooking) Premature browning[a]	Prolonged pink-red[b]
pH	High		✓
	DFD[c]		✓
	PSE[c]	✓	
Meat source	Close to bone		✓
	Older carcasses		✓?[d]
Packaging	Aerobic/oxygenated	✓	
	Carbon monoxide		✓
	Vacuum		✓
Freezing history	Cooked from frozen	✓ (pork)	✓ (beef)
	Short thaw		✓
	Long thaw	✓	
	Frozen in bulk	✓	
Fat	Low		✓
Added ingredients	Salts	✓	
	Nitrite		✓
	LFTB[c]	✓	
Preservation	Irradiation	✓ (beef/aerobic)	✓ (pork, poultry, vacuum)

[a] An issue for food safety.
[b] An issue for food quality and/or economic loss.
[c] DFD = dry, firm, dark; PSE = pale, soft, exudative; LFTB = lean finely textured beef.
[d] ? indicates conflicting results make the outcome uncertain.

the food industry and the domestic consumer. Fortunately for major food producers and food service companies, the introduction of HACCP programs has already established practices where cooking is monitored through time/temperature methods. However, minor food service companies such as fast food outlets and independent restaurants often still use visual inspection as the main tool to judge if meat is cooked adequately. Certainly, in domestic homes, use of food thermometers is minimal. On a global scale, the United States Food Safety and Inspection Service is at the forefront of change through their major Thermy^{TM} campaign, which promotes regular use of food thermometers and provides instructions for use. The campaign has been developed through extensive research on consumer behaviour and social marketing. Other governmental food regulatory agencies will need to consider research such as has been summarized in this review, in order to define a consistent message targeting the safe cooking of meat.

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