sausage. The reaction is greatly accelerated at low pH values, and the compound formed cannot be reconverted to the pink cured meat pigment; it only becomes brighter green on reduction. Upon continued exposure to nitrite, these green intermediates may be even further degraded to yellowish and colorless compounds. These reactions were studied using the protein-heme complex. Because of the difficulties involved, the reaction of nitrite with the corresponding hemochromes has not been so thoroughly investigated. The latter reaction is of interest with respect to discoloration in cooked cured meats. Fox and Thomson (*7*) isolated a nitrite-green hemin, but the reaction has not been observed as the result of direct action of nitrite on a hemochrome.

Conclusions

Much of our knowledge of heme chemistry has come from physiological and technological studies. One of the pressing needs of the field today is to determine to what extent known chemical and biochemical mechanisms are applicable to meat physiology and technology. In many cases this means development of new techniques or improvement of old in order to determine the course of color changes in fresh and cured meats and meat products.

It is clear that progress in all phases of meat processing lies in automation of processes and standardization of the raw material, the live animal, and the products made therefrom. To do this, increasing sophistication is required in chemical and technological studies on all aspects of meat processing, including color chemistry. Perhaps some of the more exciting and pertinent studies in solving meat color problems are being made today in the field of molecular biology, specifically in relating of the structure of a molecule to its function. Such studies in simpler organic molecules have always been the basis for the improvement of desirable properties by structural alteration. With the heme pigments, little work along classical chemical lines has been possible, for the structure of the protein part of the molecule has only very recently been defined. Thanks principally to the work of Perutz and coworkers (*14*) on horse hemoglobin and Kendrew and coworkers (*10*) on whale myoglobin, the structures of the heme pigments are probably the most thoroughly documented of any protein. For heme pigment chemists in general, and the meat color chemist in particular, this means it is now possible to relate color changes, which reflect the changing function of the molecule, to changes in structural features of the molecule, opening up the possibility of controlling these changes at the molecular level.

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CHEMISTRY OF MEAT QUALITY

Influence of Processing Procedures on the Chemistry of Meat Flavors

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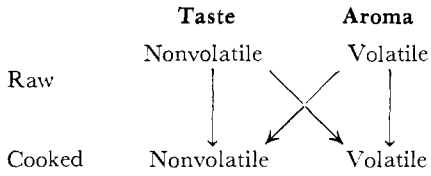
With recent advances in the identification of some meat flavor components has come some chemical understanding of why meat processing may cause flavor changes. Fully developed meat flavor has been attributed to carbonyls, amines, ammonia, and volatile compounds containing sulfur along with certain compounds in an aqueous system, of which inosinic acid is of major importance. Curing, smoking, canning, irradiation, and freeze-drying apparently either alter the qualitative composition of the flavor system or disturb the quantitative relationships by the addition of extraneous chemical substances, by unavoidable chemical changes which are the direct result of the processing, or simply by the loss of compounds responsible for flavor production.

RECENT ADVANCES in the identification of compounds associated with the flavor of beef, pork, lamb, and chicken have made it possible to compare fresh and processed meat flavor components and have shed some light on the chemical changes which may affect the flavor of processed meats. Such comparisons will be discussed in this review and an attempt made to draw some conclusions and point out directions for further research.

Meat flavor can be considered to consist of four components: the nonvolatile and volatile fractions from both raw and cooked meat (Figure 1). The flavor components associated with the raw meat include the precursors of the cooked meat flavor, although the precursors themselves may have little flavor. The nonvolatile and volatile components are associated with the taste and aroma, respectively. Both of these components of the raw or precursing flavor may form



Meaty flavor: Water solubles
Species flavor: Fat solubles

Figure 1. Meat flavor

volatile and nonvolatile compounds which contribute to the cooked flavor primarily by the action of heat. Thus, the cooked flavor is far more complex than the raw flavor or flavor precursing compounds. Most investigators generally agree that the fundamental meaty flavor is associated with the water-soluble components of meat and that it develops in the broth, with the evolution of some volatile components, when meat is heated. The species flavor apparently is associated with the volatile compounds which arise mainly from the fat, but which may also originate from the protein portion by degradation or oxidation of the carbon skeleton of amino acids.

Nonvolatile Components Contribution to Flavor

Investigating the nature of the flavor precursors of meat, Batzer, Santoro, and Landmann (*2, 21*) separated a flavor fraction from water extracts of raw meat by a double-dialysis procedure and by gel-filtration and ion exchange chromatography. This fraction, when heated, was unique in producing the aroma and taste of cooked beef. The components of this fraction are shown in Table I. The essential components appear to be inosinic acid, the so-called glycoprotein, or mixtures of compounds found in the complete hydrolyzate thereof. The other components when heated singly or in groups with inosinic acid and glucose do not give a meaty aroma. However, their presence in the complete fraction is necessary to add the proper notes to the completely developed meat flavor. The amino acids, particularly serine, glutamine, and asparagine, also appear to be essential. Other amino acids do not produce a typical meaty aroma, although they often give other types of odors associated with foods. Glutamine and asparagine apparently are the main sources of the ammonia found in the volatile fraction of cooked meat.

Working with a less highly fractionated meat extract, Macy, Naumann, and Bailey (*17*) identified the nonvolatile substances which may be involved in the development of flavor in beef, lamb, and pork. Table I shows that the compounds are very similar qualitatively and quantitatively for all three species. Jacobson and Koehler (*11*) likewise noted the presence of glucose, fructose, inositol, and 19 amino acids in water-solubles from lamb. They found free fatty acids or primary amines to be absent. While these compounds were not listed by Macy (*17*), their presence was not specifically sought. No primary amines were found in the flavor precursor fraction of Batzer, although quaternary amines were reported (*21*).

Table I. Flavor-Associated Nonvolatile Components of Raw Meat

	Water-Soluble Diffusate	
Beef Flavor Precursor (2, 21)	*Beef, pork, and lamb (17)*	*Lamb (11)*
Inosinic acid	Ribose	Glucose
Glycoprotein	Glucose	Fructose
Taurine	Fructose	19 Amino acids
$AspNH_2$	17 Amino acids	Inositol
$GluNH_2$	$GluNH_2$	No free fatty acids
Anserine	Carnosine	No primary amines
Carnosine	Anserine	
Creatine	Taurine	
3 Quaternary amines	Inosine	
Hydrolysis of Glycoprotein	Creatinine	
Ser Iso	Phosphoserine	
Glu Leu	Phosphoethanolamine	
Gly β-Ala	Urea	
Ala Pro	1-Me-His	
Levulinic acid	Ornithine[a]	
Glucose	CysAcid[b]	
	Glutathione[b]	

[a] Pork only.
[b] Lamb only.

The first complete analysis of the nonvolatile components of cooked beef extract was reported by Bender, Wood, and Palgrave (*3*), who also carried out an analysis of a water extract of raw beef. The compounds common to both extracts show some quantitative changes due to cooking. Table II makes a comparison of these results with those of Macy, Naumann, and Bailey (*18*), who examined similar cooked extracts of beef, pork, and lamb. In the cooked extract, the compounds which remain are those found in the beef flavor precursor fraction. The general decrease in the amount of each of the compounds indicates that some reaction has taken place during cooking, and that these compounds are involved in the production of sulfides, ammonia, carbonyls, and browning reaction products. Since enough of the nonvolatile compounds are left in the cooked broth, they are able to react further as the cooking time is increased. Brothy or meaty flavor is known to increase in strength with cooking time. It may also be surmised that no great differences exist between beef, pork, and lamb, and, therefore, the nonvolatile flavor components of cooked meat must supply the same flavor to all meats. The inability to distinguish a species difference in water soluble substances from fat-free meat has been amply demonstrated (*2, 7, 9*). Thus, the chemical changes occurring in the nonvolatile flavor compounds when meat is cooked provide the basic meaty flavor. Processes which leach out some of these compounds or disturb their balance or relationship may result in flavor changes. Inosinic acid, or inosine-5′-monophosphate, according to Shimazono (*22*), is the most important constituent in the flavor of meat, and the flavor can be controlled by varying the amount of this compound. In addition, other 5′-mononucleotides, particularly 5′-guanylic acid, when used in conjunction with inosinic acid, have flavor modifying and enhancing properties. Caul and Raymond (*5*) have demonstrated that the effect of inosinic acid is to blend flavor notes and enhance or improve the flavor of soup. Assuming that the same function is performed in meat extracts or broths, the amount of inosinic acid present may affect the intensity of flavor when meat is cooked. Its presence may also affect the taste response obtained when both nonvolatile and volatile components of flavor are present by blending the flavors of each. Therefore, any process which

Table II. Changes in Nonvolatile Flavor Components of Meat during Cooking

Composition	*Beef (3)*	*Beef, Pork, Lamb (18)*
Ala	+[a]	−[b]
Ser, Thr, $AspNH_2$, Gly, Met, Iso	−	−
Taurine	−	−
P-serine	−	−
P-ethanolamine	−	+
Carnosine	−	−
Anserine	−	−
Carnitine	−	−
Creatine	−	−
Inosinic acid	+	Pres.
Lactic acid	−	
Urea	−	Abs.
Ammonia	+	
Reducing sugar	Abs.	Ribose abs. Glucose—

[a] + = Increase over amount in uncooked extract.
[b] − = Decrease over amount in uncooked extract.

may tend to remove or increase the amount of inosinic acid will affect the flavor of the product. The addition of inosinic acid as a seasoning and flavor enhancer in meat products is a common practice in Japan, and is finding some limited applications in this country.

Since the nonvolatile flavor material is relatively constant for all species, it follows that the taste differences between pork, lamb, and beef must be due to differences in the composition of volatile fractions which are produced on cooking. This was demonstrated by Hornstein and Crowe (*9*) who found that lamb patties prepared with water-extracted lean meat were tasteless. When the water extract was again added, the patties tasted meaty but were not characterized as lamb. The typical mutton odor was obtained only from the lamb fat. When the lamb flavor precursors were removed from the fat by extraction, heating the fat did not generate a lamb odor. The heated lean meat extract produced a weak disulfide odor, along with slightly more ammonia than was obtained with similar extracts of beef and pork.

Volatile Components Related to Flavor

Unfortunately, information on the volatile materials of raw meat is lacking. The closest approach is a list of compounds found by Wick (*24*) for enzyme-inactivated beef (Table III). These volatile components do not correspond closely to those found in beef cooked to the well done stage, but are more similar to those found in cooked chicken and in cooked dry cured ham. (Tables IV and V).

Carbonyl compounds make up a large portion of the volatile flavor fraction from cooked lamb, chicken, and beef (Table IV). Free fatty acids may or may not be present, but alcohols and esters are singularly absent. The individuals making up each class or category differ considerably from species to species, and these differences may account for the different flavors. These lists show only the compounds which have been identified and are only partially complete. As work progresses, some of the qualitative differences may disappear, but different quantitative relationships will undoubtedly still exist when the lists are complete. The complexity of the volatile fractions from meat is a little overwhelming until one considers that the compounds common to all make up the largest portion of the flavor fraction: ammonia and hydrogen sulfide, or other sulfhydryl compounds. This agrees with the results of Pippen and Eyring (*20*), in which they stated that the volatile portion of chicken flavor was primarily ammonia and hydrogen sulfide. The relatively minor amounts of the other constituents must add the characteristic flavor notes for the particular variety of meat. It therefore becomes difficult to generalize on reactions which occur during processing of meat to cause flavor changes, unless the type of meat is specified. However, the results of some flavor studies on typical processed meats may elucidate chemical changes which may be related to flavor alterations.

Table III. Volatile Components of Enzyme-Inactivated Beef (*24*)

Nonirradiated	*Irradiated*	
Ethanol	Ethyl acetate	Acetone
2-Propanol	Hexanol	Nonane
Butanol	Octanol	Decane
2-Butanol	Butanal	1-Decene
2-Butanone	Heptanal	Undecene
Acetoin	Decanal	Dodecane
Isovaleraldehyde	Undecanal	1-Dodecene
Hexanal	Phenylacetaldehyde	Tridecane
Octanal	Methional	1-Tridecene
Nonanal		Tetradecane
Benzaldehyde		
Benzene		

Changes in Composition Caused by Processing

Canning. The process of canning, according to Brennan and Bernhard (*4*), causes alterations in beef flavor because nontypical volatiles are formed. An examination of headspace gases from jars of beef heated at 122° C. for 90 minutes indicated that the compounds other than ammonia, H_2S, methanethiol, and ethanethiol did not correlate with any of the compounds found by other workers. The two major constituents not previously reported were propanethiol and butanethiol. Their formation was directly attributed to the processing conditions, and was suggested as the reason canned beef tastes different from boiled or roasted beef. Since the beef tissue had no typical meaty flavor while the broth had an intense beef taste, the headspace constituents were considered to arise from the broth. The composition of the headspace gas remained constant for a 5-month storage period.

Luh *et al.* (*16*) likewise found that different canning processes caused alterations in the composition of flavor volatiles and, consequently, in the taste of the final product. Minced beef was heated at 77° C. and canned. The closed containers were processed for 42 minutes at 122° C. in a retort. Another sample was sterilized at 150° C. for 31 seconds, cooled to 40° C., and canned aseptically. The aseptic product was described as raw in taste, while the retorted product had a full flavor and was preferred by the judges. Chemically, the major difference between the volatiles from the two products was that the retorted product contained three times as much hydrogen sulfide, but no methyl mercaptan. Apparently, the longer heating time caused a destruction of methyl mercaptan accompanied by an accumulation of hydrogen sulfide. The aseptic samples on the other hand did contain methyl mercaptan, and were higher in free fatty acid content, while the retorted samples were higher in amino nitrogen. In the retorted product

Table IV. Volatile Compounds from Cooked Meat

Beef		*Chicken (15)*		*Lamb*	
(25)	*(10)*			*(11)*	*(9)*
H_2S	H_2S	NH_3	Hepta-2,4-dienal	H_2S	Sulfides
NH_3	NH_3	H_2S	Deca-2,4-dienal[a]	NH_3	NH_3
Dimethyl sulfide	Formaldehyde	Acetaldehyde	Acetone	Acetaldehyde	Formaldehyde
Acetaldehyde	Acetaldehyde	Propionaldehyde	2-Butanone	Propionaldehyde	Acetaldehyde
Diacetyl	Acetone	Butyraldehyde	Acetoin	*n*-Hexanal	Acetone
Acetone		Pentanal	Diacetyl	Methylisopropyl ketone	C_6 ┐
Formic acid		Hexanal	Eight others	2-Methylcyclopentanone	C_{16} ├ Carbonyls
Acetic acid		2-Heptenal			C_{18} ┘
Propionic acid		2-Decenal		Absent: Acetone	C_9 ┐
Butanoic acid		2-Undecenal		Fatty acids	C_{10} ├ Enals
Isobutyric acid				Primary amines	C_{11} ┘
(no alcohols)					Absent: Fatty acids

[a] From triglyceride.

Table V. Volatile Compounds from Dry Cured Smoked Ham, Smoke, and Other Cooked Meats[a]

Ham (19)	*Smoke (19)*
Formaldehyde (L)	Formaldehyde
Acetaldehyde (C B L)	Acetaldehyde
Propionaldehyde (C L)	
Isobutyraldehyde	Butyraldehyde (*6*)
Valeraldehyde (C)	Valeraldehyde
Isovaleraldehyde (B)	Isovaleraldehyde
Diacetyl (B C)	Diacetyl
2-Butanone (C B)	2-Butanone
Acetone (C B L)	Acetone
Formic acid (B)	Formic acid
Acetic acid (B)	Acetic acid (*6*)
Propionic acid (B)	Propionic acid (*8*)
Butanoic acid (B)	
Isocaproic acid	
Ammonia	
Methylamine (—L)	
Hydrogen sulfide	
Disulfides	

[a] L = lamb, B = beef, C = chicken.

the increase in H_2S along with the increase in amino nitrogen would suggest a stronger flavor, as well as a different flavor, from meat cooked in the usual manner but not canned.

Freeze-Drying. Freeze-drying of raw meat, when properly carried out, results in little change in flavor or texture. This can be reconciled with the present concept of flavor development in that the flavor precursors in the lean portion are not volatile and, therefore, are not removed during the lyophilization of the moisture. However, in a comprehensive study of freeze-dried beef, Thomson, Fox, and Landmann (*23*), found that flavor and texture deterioration took place during storage of meat samples which had a residual moisture content of greater than 1.7%. The deterioration primarily involved oxidation of the reducing compounds normally present, and browning reactions. It is conceivable that the oxidation of carbonyl compounds and fats and the virtual removal of amino compounds and sugars in the browning reactions could so alter the flavor-producing materials that when the meat is rehydrated and cooked, an entirely abnormal pattern of flavor volatiles and nonvolatiles is obtained. This would explain the flat, paperlike taste described for samples which had undergone extensive deterioration in storage. No actual examination of the volatile compounds has been made, however. Freeze-dried cooked meat also has been described as having less flavor than freshly cooked meat. This may be ascribed to the loss of the volatile flavor components formed on cooking during the process of lyophilization.

Irradiation. One process known to cause marked flavor changes in meat, especially in beef, is irradiation. The effects of irradiation on flavor have been quite extensively studied so that more information is available for chemical comparisons of possible flavor constituents for this process than for any other. A list of volatile components of irradiated beef has been published by Wick, as shown in Table III. One compound believed to be of major importance in the irradiation off-flavor is methional, but undoubtedly the other compounds influence the final flavor or odor. Profound changes appear to occur in all the substances making up meat when it is irradiated. Both degradation and condensation reactions of the carbon chains evidently occur, and new compounds are formed, giving rise to a series of volatile materials which differ greatly from those normally produced in heating meat. Enough of the normal precursors of flavor remain to produce the basic taste, but the additional compounds give an added flavor of their own, producing the off-flavor. In addition to the volatile components, alterations of the nonvolatile flavor components also occur. One such alteration is in a lipid component, possibly sphingomyelin. Batzer and Santoro (*1*) have shown that this fraction gives rise to an off-flavor which remains after irradiated meat is cooked, and which is quite distinct from the sulfur-type odor present in irradiated meat.

Curing and Smoking. One of the more important processes to which meat is subjected is curing and smoking. Here we are dealing not only with flavor produced by the meat, but also with the flavor produced by the addition of curing ingredients and smoke. In the case of fermented sausages, the fermentation products which accumulate also add their notes to the total flavor. Curing ingredients can be considered to add a salty flavor to the meat, along with a certain degree of sweetness dependent upon the amount of sugar which is used. The deposition of smoke on the meat product also introduces typical flavor notes which are foreign to the basic meat flavor, but which are readily recognized as smoke flavor. The products of fermentation usually impart an acidic and somewhat pungent, easily recognized flavor. However, apart from these extraneous flavors, the meat ingredient, whether ham or sausage, contributes to the desired flavor. Because its typical flavor differs from either raw or cooked meat, some reactions must occur which produce flavor compounds different from the usual pattern. Some indication of this is evident in the results of a study by Ockerman, Blumer, and Craig (*19*) in which the volatiles from dry cured hams were identified. Country style hams weighing 14 to 16 pounds were cured 2 days per pound at 4° C. with a mixture of NaCl, sucrose, and KNO_3. After being cured the hams were soaked for 2 hours in cold water, then smoked at 21° C. by burning hardwood sawdust. They were then aged at 23° C., at 60% relative humidity for 6 to 24 months. The volatile compounds found when these hams were cooked are shown in Table V, along with a partial list of volatile compounds found in smoke. Other than the ammonia, methyl amine, H_2S, and disulfides, which are not reported as being present in smoke and must, therefore, have come from the meat itself, the only compounds which have not yet been found in smoke are propionaldehyde, butanoic acid, and isocaproic acid. These acids, together with the methyl amine, and disulfides, appear to be unique for dry cured smoked ham. The authors, however, point out that while the total quantity of carbonyl compounds increased during aging, the relative ratios were constant, with the exception of the 2-butanone which increased disporportionately. Both the number and quantity of free fatty acids increased with aging. These results would suggest that oxidative deamination and mild oxidation of fats are the primary reactions responsible for the production of these volatile flavor components. A number of the volatiles listed for cured ham appear also in the lists for beef, chicken, and lamb. These are indicated in Table V.

Chemical changes which occur during the processing of sausages have been investigated by Khristov and Kostov (*12*) and by Kostov (*13*). In nondurable sausages, such as frankfurters, which are cooked and smoked, Khristov and Kostov found that volatile reducing compounds, presumably the aldehydes or carbonyls, accumulated during the smoking process, while volatile fatty acids increased mainly during the cooking. In dry sausages, which are cured and smoked but not cooked, the chemical changes related to flavor development occurred throughout the stages of preparation, curing, drying, and aging. Maximum flavor, or best aroma and taste, coincided with the complete disappearance of volatile reducing compounds (carbonyls), the maximum accumulation of volatile fatty acids, free amino acids, creatine, and hypoxanthine. Lee and Webster (*14*) also found that as beef ripens and the flavor increases, the rate of production of hypoxanthine increases. During freezing and frozen storage, the concentration of hypoxanthine remained constant, but during thawing, in a pH range between 5.5 and 6.5, the rate of hypoxanthine production increased greatly. These observations indicate the occurrence of hydrolytic effects on fats and proteins, as well as oxidative effects, or combinations of both. They further substantiate the importance of the entire flavor precursor fraction and pattern of volatiles in meat flavor, as well as indispensability of inosinic acid in flavor production.

Conclusions

Meat flavor appears to be determined by the relative amounts of the various compounds, as well as the type of compounds, present or formed in the nonvolatile and volatile fractions when meat is heated. Most processes to which meat is subjected cause compositional changes in one or both of these fractions, which result in flavor alterations.

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TENDERNESS OF CHICKEN

Relationship between Chemical Properties and Tenderness of Poultry Muscle

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Experiments were undertaken to study the fate of metabolites involved in muscular contraction [adenosine triphosphate (ATP), phosphorylcreatine, glycogen, and lactic acid] during the post-mortem period when tenderness is changing. Chickens were subjected to severe mechanical feather-plucking immediately post mortem (a treatment known to induce toughness). The disappearance of ATP, the chemical reaction most closely linked with the onset of rigor mortis, was accelerated. Other prerigor treatments (freezing and thawing, elevated temperature, excising or cutting the muscle, electron irradiation, and exhaustive electrical stimulation) that accelerated ATP and glycogen disappearance as well as the onset of rigor mortis, also induced toughness that was only partially reversed by prolonged aging. When post-mortem glycolysis was minimized by epinephrine injections, sodium iodoacetate injections, or rapid cooking, the meat was tender without aging. Since these treatments accelerate rigor mortis, it is the acceleration of post-mortem glycolysis, not the acceleration of rigor mortis, which induces toughness.

MANY INDUSTRIAL, university, and government laboratories have actively pursued research on meat tenderness. In addition to its economic importance, tenderness, as a research area, is intensely interesting to the biochemist and the biophysicist. The study of meat tenderness covers the transition of muscle from the living state to the dead state, a period which includes rigor mortis. During this period, the physical properties of muscle tissue change profoundly as do the levels of many of the biochemical compounds in muscle. Research in this area has produced, and should continue to produce, fruitful correlations between the biochemical changes of muscle with its physical properties.

The Western Regional Research Laboratory began a study of the processing variables which influence poultry tenderness about 10 years ago. This project has shown that the steps of the poultry processing operation requiring strict attention by the processor to ensure optimum tenderness are (*10, 13*) scalding, feather-plucking, and aging. Scalding and feather-plucking, although separate steps in the processing line, are interrelated since very mild scalding conditions yield birds that require more severe feather-plucking conditions (and *vice versa*). In general, increasing the severity of scalding, either by raising the temperature of the scald water or by prolonging immersion, or increasing the severity of the feather-plucking treatment, will increase the toughness of the cooked meat. The third step, aging, is essential for the development of tenderness, although the time period involved is much less than that for beef. In contrast to beef, which may require 10 to 20 days for development of optimum tenderness, poultry achieves maximum tenderness within 12 to 24 hours.

This research program, in addition to studying the influence of processing var-