MUSCLE is a highly complex system, and one that is very difficult to study. It is made up largely of proteins and water, with variable quantities of fatty substances, and smaller amounts of minerals and carbohydrates. Many of its properties stem not only from its compositional makeup, but also from the structural organization of the compounds at the molecular, microscopic and macroscopic levels. Until a few years ago, our knowledge of muscle and its reactions was very general and rudimentary. However, in the past 10 years there has been a considerable increase in our information, both in amount and in specific details. I would like to review for you today some of the most recent work.

There are a number of standpoints from which our information on muscle can be considered. Ultimately we are interested in how the properties of muscle tissue influence the quality, palatability and economy of the product in its use as food. But there are many factors in addition to the muscle itself which affect these end results. So I have chosen to concentrate on the effects of heat on certain of the compositional and structural characteristics of muscle which seem to be closely related to the tenderness and juiciness of cooked meat.

Some of the heat-induced changes in meat that are thought to influence tenderness were summarized by Paul (1963). These include changes in moisture, fat, muscle fiber diameter and extensibility, shear, and connective tissue content and characteristics. I propose today to bring some of these up-to-date, and to add some information on water holding capacity, pH, and structural organization.

MOISTURE

Even as seemingly simple a factor as moisture content is not simple, and one soon finds that the routine determination of total moisture by itself does not yield very useful information. Raw muscle is approximately 75% water, but the quantity varies with the species, the muscle being studied, the intramuscular fat, and the pH. The amount of heating used in the usual food preparation procedures will decrease the total moisture to about 60 to 65% of the muscle weight. Let us look in more detail at this water, and the way heat affects it.

Hamm (1960) in a review of meat hydration, points out that water is held in muscle in three ways: (1) by adsorption on the hydrophilic groups of the protein chains; (2) by condensation of randomly oriented water molecules in the hydrated surface, similar to the formation of water molecule clusters in a gas; and (3) by capillary condensation. The first two constitute the true water of hydration of the muscle proteins, and amount to about 5% of the total water content of raw muscle. The remainder
is free water in the classic sense, but is mechanically immobilized within the framework of the muscle proteins. This last segment can be divided into free and bound water with reference to its ease of removal by pressure, and is the portion being considered in the many recent studies of water holding capacity (WHC) of meat.

Hamm and Deatherage (1960) have shown that the major changes in WHC of beef muscle occur between 40 and 50°C, and above 55°C. The decreases in WHC with increasing temperature are paralleled by decrease in the number of acidic groups on the protein chains, and by an increase in pH. They attribute the decrease in WHC between 40 and 50°C to the decrease in electrostatic repulsion between the protein chains due to the disappearance of acidic groups. The decrease in repulsion permits closer packing of the protein chains, with less room for immobilized water. Above 55°C this process continues, but at a less rapid rate. In the range of 60 - 70°C, the meat proteins are almost completely denatured. Fraczak and Pajdowski's (1955) observations on formation of free H₂S indicate that at temperatures of 80°C and above, the muscle proteins are decomposing. Hamm and Deatherage (1960) also note that changes in the connective tissue proteins as well as the muscle fiber proteins influence the changes in WHC, especially the alteration of collagen from the fibrous to the gelatinous state.

Sanderson and Vail (1963) note the decrease in WHC with heating of intact muscle. Ritchey and Hostetler (1964) found that as the internal temperature of beef steaks increased, there was a shift from bound to free water, so that the free water content stayed relatively constant while the bound water decreased until the highest internal temperature (80°C) was reached, at which point both bound and free water had decreased. Sayre, et al (1964) studied water relations during heating of pork. They found a high correlation (rₓᵧ=-0.90**) between rate of heating and amount of loss by evaporation, and suggested that a lower WHC led to increased evaporation of moisture with consequent retardation in the rate of increase of internal temperature. This may be a previously unrecognized contributor to the variability in cooking rate observed in apparently similar pieces of meat.

Another phase in the changes of the total moisture picture in muscle with heating is that of cooking losses. These are often divided into drip loss and evaporation loss with the rule of thumb that drip loss is usually largely fat and evaporation loss largely water. However, it is recognized that this is not literally correct, since the drip will contain some nitrogen, salts and water, while the evaporation losses include all volatile materials. If the heating is done in a closed container, the drip will contain a good deal of water, often as high as 50% of the total (Paul, et al, 1964).

It used to be believed that high initial cooking temperatures would reduce cooking losses by forming a skin or pellicle of coagulated protein on the surface of the cut which would tend to hold in the moisture. This idea was questioned a number of years ago with the finding that high initial oven temperatures to sear the surface of the meat actually increased the cooking losses over those found when using a lower, constant oven temperature. Hamm (1960) reintroduced this concept in his review of meat hydration. However, there seems to be no definitive data to support this as a general concept in meat cookery. Since various studies have shown that cooking losses are influenced by species, grade, muscle, size, shape and

FAT CONTENT

Kauffman, et al (1964b) have reviewed briefly the disagreement among data from a number of laboratories as to the role of intramuscular fat in palatability of cooked meat. In proximate analysis of raw muscle tissue, it is usual to find a highly significant negative correlation between total moisture content and ether-extractable material within the same muscle of carcasses varying in fatness. Also, it is usually found that muscle tissue has a higher content of ether-extractable material after heating than does the raw muscle, even when the data is converted to the dry basis to allow for the water loss during heating. It is usually suggested that this increase in fatty material is due to infiltration of melted fat into the muscle tissue during heating, although very little work has been done to try to determine the reason. Another possibility is that heat may be altering the muscle structure so as to make fatty materials present in the raw muscle more readily extracted by ether.

pH

Another compositional factor in muscle altered by heat is the pH. Heating meat usually increases the pH. For example, Kauffman, et al (1964a) found that pork muscle usually increased about 0.35 units in pH on heating. Hamm and Deatherage (1960) found an increase of about 0.4 pH units in beef, while Paul (1964) found an increase of about 0.3 units in rabbit muscle. Hamm and Deatherage (1960) explored the effect of altering the pH of the raw beef muscle with NaOH or HCl before heating, and noted that shifting the pH below 5.0 or about 6.0 very much decreased the change in pH. Paul (1964), working with muscles immediately post mortem, found that if the pH were still above 5.7, the pH decreased during heating, and attributed this to the speeding up of the glycolytic cycle during the initial stages of heating.

There have also been numerous studies on the naturally-present and/or added ions, on extractability and identification of the protein components, and on the various compounds involved in the contractile mechanism of muscle (for example, Bendall, 1963; Deatherage, 1963). However, the effect of heat on these components has not been studied extensively, with the exception of collagen content. Collagen is usually found to be partially to completely solubilized, the extent of change depending on the duration of heating and the internal temperature reached (Paul, 1963).

STRUCTURAL CHANGES

Muscle also has a definite physical structure which influences its characteristics, and which can be altered by heat. The major structural components are the protein chains of the myofibrils (the contractile mechanism) and of the connective tissue framework which bind the myofibrils into
bundles and link the bundles to the bones. Denaturation of the proteins has already been mentioned in conjunction with the effect of heat on the WHC. It is known that heat denaturation causes changes in the 3-dimensional organization of the atoms and groups of atoms comprising the protein chains. For example, Scheraga (1961) discusses the heat-induced changes in protein fibers of this type, and suggests that as the temperature increases, the molecular organization changes from crystalline to amorphous. However, our knowledge of the changes at this level is still very incomplete.

Several interesting heat-induced changes in structural organization and in staining properties have been observed in beef muscle (Paul, 1963). Small strips of biceps femoris and semitendinosus were heated for various lengths of time at 67°C, then embedded and stained with Weigert's triple connective tissue stain. In raw beef, collagen stains a bright rosy red. After a short time of heating, the collagen strands show bands that stain blue instead of red. As heating is continued, the whole strand stains a dark reddish to blue-purple, then dark grey, and finally the strands disintegrate to a granular form which stains yellow. The collagenous tissue in the semitendinosus shows a similar change. The initial change appears to occur as the tissue passes through the 55-60°C temperature range, within the first minute of heating under these conditions. This suggests that this banding may show up at the shrinkage temperature of collagen, which occurs at about the same temperature range.

The muscle tissue also shows changes in contractile fibers due to heat treatment. In the biceps femoris, the fibers show marked cracking and granulation. Despite the granulation of the muscle fiber itself, the endomysial reticulum surrounding the fibers appears to remain essentially intact. In the semitendinosus much less granulation was observed, but numerous cracks and breaks appeared. Another type of change in the contractile fibers was observed in pre-rigor muscle. The muscle went into rigor during heating, and heat rigor produced a typical banding or clumping of the contractile substance.

I would also like to review briefly some of the very interesting recent reports on the effects of varying degrees of heat and methods of heating on tenderness of beef and pork, as measured by panel scoring and by shear.

One of the problems in studying heat effects on muscle tissue is the variability in degree of heating throughout a large piece of muscle such as a roast. To avoid this, Machlik and Draudt (1963) used cylinders of beef semitendinosus ½-inch in diameter and 1½ to 2 inches long, heating them in test tubes in a water bath. They measured tenderness by Warner-Bratzler shear. Their data show little change in tenderness below 50°C, a marked decrease in shear between 50 and 60°C, an increase between 60 and 70°C, and some decrease above 75°C. They attribute the initial increase in tenderness to collagen shrinkage, the decrease between 60 and 70°C to hardening of the muscle fibers and the subsequent increase about 75°C to the collagen-gelatin transformation. They also point out the large biological variation shown between samples of the same muscle from different animals, even though the heat treatment was the same for all.

Tuomy, et al (1963) heated strips of beef semimembranosus cut to fit metal tubes 7/8-inch in diameter and 8 inches long. These were immersed
in a water bath for heating, and the zero readings taken when the center of the sample reached the bath temperature (3 to 8 minutes, depending on the temperature being studied). They found an initial toughening of the meat due to heat. Exposure to temperatures of 140 or 160°F up to 7 hours did not increase the tenderness. At higher temperatures (180 to 210°F) the tenderness increased gradually, more rapidly with higher temperatures. The initial toughening, which they attribute to protein denaturation, is demonstrated by the shear-press (L.E.E.-Kramer) data, since the raw meat had an average shear-press reading of 122 pounds, as opposed to 328 pounds at 140°F and 491 pounds at 210°F. The tenderization at the higher temperatures they suggest as at least partly due to the collagen-gelatin transformation, but believe other factors must be present also, as the beef at 190°F had not attained the limiting tenderness value even after 7 hours exposure. Perhaps granulation of the contractile fibers was also occurring.

Sanderson and Vail (1963) investigated the effects of heating longissimus dorsi, semimembranosus, and semitendinosus of beef to internal temperatures of 140, 158 and 170°F. They used both large blocks as roasts, and strips 1/2 - 3/4 inch in cross section heated in tubes. They evaluated tenderness by Warner-Bratzler shear. They found that increasing internal temperature did not change the tenderness of longissimus dorsi, but that the other 2 muscles increased in tenderness with increasing temperature. They suggest that the difference in response between the muscles was due to connective tissue, since the 2 round muscles have a higher connective tissue content than the longissimus dorsi, so that one would get a different balance point between the toughening due to hardening of the contractile fibers and tenderization due to softening of collagen. These muscle differences resemble those reported by Cover et al (1962, 1962a, 1962b, 1962c).

Bramblett and Vail (1964) studied beef round muscles wrapped in heavy foil and roasted at 155 and 200°F, to an internal temperature of 149°F. They evaluated tenderness by panel scores, number of chews, Warner-Bratzler shear, and L.E.E.-Kramer shear-press. They found that roasts cooked at 155°F were more tender by all measures than those cooked at 200°F. These results seem somewhat in contradiction to those of Tuomy, et al (1963), until it is recognized that their heating times at 155°F were very much longer than those used by Tuomy and coworkers.

Tuomy and Lechnir (1964) reported a study of tube heating of pork longissimus dorsi. The results differed from those they obtained on beef in that the pork muscle showed appreciable tenderization with time at temperatures of 150°F and above. Also, pork showed a greater tendency than meat to disintegrate at the longer heating times and higher temperatures. With beef, the disintegration was observed after 7 hours at 210°F, and appeared to involve the muscle fibers themselves. In pork, the connective tissue holding the fibers together disintegrated after 4 hours at 210°F or 5 hours at 200°F. They found the same initial toughening of pork on heating that had been observed in beef, the raw pork having a shear-press reading of 120 lbs., while the zero time readings for the heated pork varied from 251 at 140°F to a maximum of 439 at 190°F.

SUMMARY

In considering the effects of heat on muscle tissue, some of the recent work dealing with moisture content, water holding capacity, pH, fat
content of lean, microscopic changes, and changes in tenderness have been reviewed. When one tries to put together results from many laboratories and projects, the numerous factors which can influence such data must be kept in mind. In addition, in dealing with heat changes in proteins, it must be remembered that these are a function not of time or of temperature alone, but of the time-temperature complex. We are making real progress in sorting out the heat induced changes in muscle tissue, but much remains to be done.

REFERENCES


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DR. PRICE: Thank you, Dr. Paul. Let us lower the temperature drastically and rather than volatilizing this water let's crystallize it. We asked Dr. B. J. Luyet from the American Foundation of Biological Research here in Madison to discuss the next topic. Dr. Luyet is a native of
Switzerland and has a list of honorary degrees after his name that would take too long to mention. He has worked as a professor of biophysics at Rockefeller Institute and St. Louis University. His work has been concerned primarily with the biological effects of low temperature, the mechanics of freezing and the survival of frozen protoplasm. He perhaps becomes noted to meats men through his discussion that was presented in 1959 at the American Meat Institution Foundation Research Conference. We welcome Dr. Luyet to the Conference to present the topic "The Effects of Freezing on Muscle Tissue". Father Luyet.

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