CHEMICAL AND PHYSICAL BASIS OF TEXTURE IN HORTICULTURAL PRODUCTS[1]

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Food quality is generally expressed through its three components: color or appearance, flavor, and texture. Each of these are elusive quantities difficult to define. Texture has often been characterized by the use of descriptive terms such as *hardness*, *mealiness*, and *grittiness* (Table 1), depending on the product being considered and the particular textural component being characterized. These terms have the ability of evoking relative responses in the mind, but cannot provide quantitative information in terms of measurable physical properties. The terms *elasticity*, *plasticity*, and *viscosity* can often provide such information, but unfortunately, do not lend themselves easily to applications in such complex, often heterogeneous, systems as foods. The various devices for measurement of textural parameters represent a compromise between the descriptive, qualitative properties and the absolute descriptions that rest on universal units of force, time, and distance. Under strictly defined conditions, these instruments are capable of providing measurements that can serve as valuable guides in evaluating effects of treatments if they are properly based statistically. On the other hand, since microscopic sample sizes are required, little information is obtained concerning the finer details of structure or the relative importance of individual chemical entities.

Table 1. Some descriptive terms of texture.

Subjective terms:		
Hardness	Gumminess	Flakiness
Brittleness	Fibrousness	Fleshiness
Firmness	Mealiness	Flabbiness
Ripeness	Blandness	Lumpiness
Toughness	Smoothness	Oiliness
Tenderness	Chewiness	Grittiness
Crustiness	Juiciness	Springiness
Stickiness	Crispness	Shortness
Objective terms:		
Elasticity	Plasticity	Viscosity

Elements of texture

Texture of a system is determined by the elements that provide the system with structure and organization. In a relatively solid horticultural product these elements are primarily the cell wall and adjacent components along with the total network comprised of cell walls and intercellular cementing substances. In products possessing flow properties such as juices and pastes the structural elements are composed of suspended solids and dissolved polymeric components. Texture is a function of its elements, and of their quantity, composition and arrangement. Since these are variables which depend on life functions during the pre- and postharvest periods and on conditions during processing, it is clear that texture exists in a dynamic flux and that the direction of changes in texture can not be anticipated unless the reactions, both physical and chemical, that affect the structural elements are known.

Physical vs. chemical approach

An edible plant part can be considered as a rather simple system composed of cell walls arranged in a pattern to give cellular units and tissues. In evaluating by a physical approach the importance of the cell wall on the over-all textural characteristics, it is necessary to know where and by how much cell sizes vary, thickness of the cell wall, amount of pre-stress (or turgor), elasticity of the cell wall and other factors that are either difficult or impossible to obtain. From this realization follows that the only practical clue to the physical properties of the elements of texture is often the chemical composition and the chemical and biochemical reactions involved. This approach has the further advantage of offering possibilities of altering the texture to suit some particular need or maintaining desirable textural characteristics.

Texture of cooked potato

It is impossible here to survey the textural problems in the whole field of fruits and vegetables. Instead I have chosen to illustrate the concepts discussed above by drawing on my experience with potato tubers and particularly with reference to cooked potato tissue. The problems encountered with potato texture are in many respects similar to those observed in other vegetables, and the discussion that follows may therefore apply to a wider array of problems.

The causes of differences in texture among cultivars and among tubers grown under different climatic conditions is still the subject of a debate that has its origin as far back as the early 19th century. The textural characteristics of concern are most often referred to as *mealiness* and *waxiness.* Instrumental methods based on determination of physical properties have provided objective evidence for the existence of differences, but little insight into the cause of the differences. Numerous compositional studies have on the other hand established significant correlations between these textural characteristics and the starch content of the tubers. From that basis certain points of view have gained prevalence that there is created a *swelling pressure* within the cells when the starch grains undergo gelation during thermal processing (2). The swelling pressure is presumed to be related to the starch content and is believed to cause rupture of the cell wall and/or cell separation. This view is found in most authoritative texts on the subject. Yet, there is no reason why a cell should swell or increase in size, when the starch in its interior undergoes gelation in the absence of mass transfer to the cell. Certainly, there is no net gain in mass in the processing of a baked potato. Other evidence in favor of the swelling pressure has also been presented. Cells of cooked potato appear to take on a spherical shape when inspected in the microscope in the absence of external water. It seemed clear that the latter event could best be explained by the existence of an internal pressure being exerted on the cell wall. However, an alternative explanation is equally plausible: If the cell wall loses some of its configurational integrity by solubilization of pectic substances during cooking and retains some of its elastic properties, the same event should logically take place. The cell wall in its pre-stressed condition resulting from tensions developed during growth, would in this case exert pressure on the cell content: Relaxation of the cell wall tensions should then lead to a striving for a minimum surface area, that is, a spherical shape.

It seems clear that evidence of a different nature must be forthcoming if this debate is to lead to improved insight and practical results. Starch content, although it appears to be an important factor, is not the only factor that has been found to influence potato texture. A theory of any validity concerning cooked potato texture must also consider the effects of calcium, cell size, organic acids, the amylose-amylopectin ratio, and starch retrogradation, as well as factors dealing with the composition of the cell wall and enzymes affecting cell wall constituents (Table 2).

Table 2. Factors influencing texture in cooked potato.

Factor	Effect on Mealiness[z]
Starch (SP. G., Total Solids)	+
Calcium	–
Organic acids (citrate)	+
Cell size	+
Age and storage	–
Starch retrogradation	–
Amylose-amylopectin ratio	–
Pectin	(–)
Pectin free carboxyl	(–)
Pectin methylesterase	(–)
Potassium	(–)
Magnesium	(–)
Membrane thermostability	(+)

[z] + = increases mealiness
– = decreases mealiness
( )= tentative effect

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Thermal expansion

Another theory, originally presented in 1935 (10), but now largely forgotten in preference to the one just cited, appears to be more soundly based. This states that *sloughing* or cell separation is due to the thermal expansion of the tissue during cooking. It seems reasonable to believe that considerable shear stresses, both radial and tangential, will be generated in the tuber interior depending on the module of elasticity and the tensile strength of the cell wall. Under certain circumstances the limit of elasticity of the weakest point will be exceeded. In a mealy potato the weakest point is evidently the middle lamella, while the weakest point in a waxy potato is, according to this reasoning, the cell wall proper, resulting in cell rupture and exudation of gelatinized starch. Viewed in this manner the problem of cooked potato texture is reduced to a consideration of the factors that influence the cell wall and the middle lamella. It seems, at least as an immediate impression, that starch content would have little to do with texture, while the cell wall would be a major factor. However, as is often the case, the truth probably lies somewhere between the opposing views.

The factors listed in Table 2 have been shown or implied to play a role in determining the textural characteristics of potato tubers. Calcium is a frequently used additive in canning practices and has the effect of toughening the cooked tissue, reducing sloughing and rendering the product less mealy (8). The simplest explanation for this behavior is interaction of calcium with the pectic substances of the cell wall in the formation of calcium bridges. Addition of organic acids, particularly citric acid, results in increased sloughing and cell separation (12). The known ability of these acids to form coordination complexes with calcium suggests that they compete with the pectic substances for calcium and thereby reduce the interaction of calcium with the cell wall constituents. Cell size (3) probably influences texture through its effect on the internal expansion stresses. For a given relative expansion the stresses in any one direction in the cell wall will be proportional to the original diameter of the cell. Maximum shear will develop between adjacent layers of small cells (vascular bundle region) and large cells (cortical region). This is precisely where the most severe sloughing takes place.

Starch

A major proportion of the total calcium of the tuber is present in the starch grains (4). It seems reasonable to believe that high starch content would make less calcium available to the cell wall and, thereby, weaken it. Starch content has been found to be well correlated with cell size (3). Thus, it would indirectly give rise to high shear stresses during thermal expansion and have a positive effect on meaIiness. Also, it is reasonable to expect that competition for photosynthates exists between starch production and cell wall production. Such competition effects are well known between other cell constituents such as starch and protein, or between oil and protein in the soy bean. A potato cultivar which is genetically programmed to deposit relatively large quantities of starch would therefore tend to deprive the cell wall of its constituents and produce a relatively weak cell wall or middle lamella. However, evidence for this latter phenomenon is still not available.

The changes that occur in potato tubers during storage are complex and incompletely understood. But perhaps the most significant changes are the reduction in turgidity due to dehydration and loss of starch due to respiration. Turgor reduction would be expected to result in relaxation of shear stresses in the cell surface and an increased ability to tolerate thermal expansion without exceeding the elasticity limit. Loss of starch would result in release of calcium, which now would become available for reinforcement of the cell wall constituents. Both of these factors would therefore be expected to result in loss of mealiness, which is the common experience. Gel formation and retrogradation of the gel has been shown to influence texture in products subject to chilling or extended cooling periods (11). The extent to which retrogradation takes place is evidently a function of the nature of the starch, particularly the amylose-amylopectin ratio. Diffusion of amylase has been postulated to strengthen intercellular adhesion (7); and releasable amylose was observed to be particularly prominent in low-starch tubers (11). The over-all effect of these occurrences would seem to lead to cell wall strengthening, but the relationship to texture is not quite clear.

PME and pectin

The last factors listed (Table 2) are still tentative since independent verification of the basic observations have as yet not been published. These relate to reactions affecting the cell wall during thermal processing. We obtained evidence for activation of pectin methylesterase (PME) at temperatures between 60 and 70°C and a simultaneous loss in methoxy groups of the pectin as well as increase in bound divalent metal (4). A very significant increase in toughness of the tissues occurred as a result. Our hypothesis concerning the details of this mechanism is illustrated in Fig. 1. It is evident that several of the factors already discussed play a role. A new factor, the ionic strength of the vacuolar solution (primarily expressed through the concentration of potassium), is postulated to be involved in the reaction through activation of the enzyme bound by the cell wall.

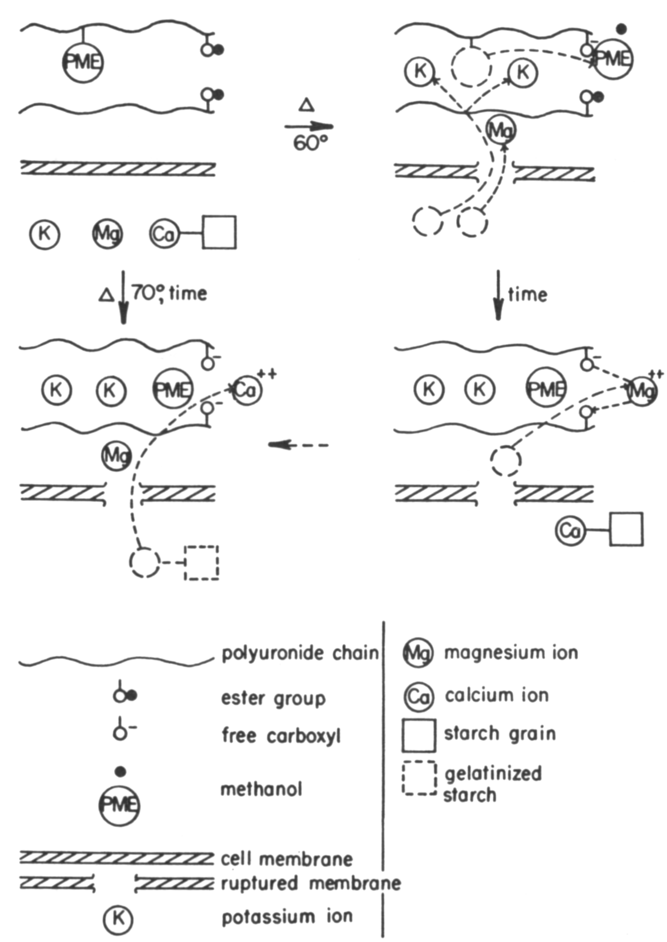

Fig. 1. Proposed mechanism of the firming effect of cooked potato. PME bound to the polyuronide chains in the cell wall (upper left) is separated from the cell interior by the plasmalemma. Upon heating to the vicinity of 60°C (upper right) the plasmalemma is injured and cations, predominantly K, diffuse into the cell wall. The increase in cation concentration causes release and activation of PME which proceeds to hydrolyze the methyl ester groups of the pectin. With time, cross linkages are formed between adjacent carboxyl groups by means of available divalent cations (center right). Upon further heating to the vicinity of 70° (center left), starch grains are gelatinized and the freed Ca made available for further cross linking of polyuronide chains. The same end result is achieved by direct heating to 70° and allowing time for diffusion of the cations.

Enzyme inhibitors and activators

Similar systems to the one just described for potatoes are known to function in other vegetables. Thus, PME has been found to affect the texture of processed tomatoes, snap beans, broccoli and cauliflower among others (13). The mechanism by which the enzyme becomes activated would seem to be of some importance in determing the extent to which it is allowed to alter the cell wall constituents before thermal activations set in. In the example cited, the activation is believed to be performed by membrane breakdown with the consequent release of solutes and solubilization of the enzyme. But other mechanisms are probably also operative. In fresh strawberries we have observed that the native PME apparently is activated by invading fungi, either directly or as mediated by a small, fast-diffusing substance that rapidly permeates the whole fruit.

We are just beginning to become aware of such factors as activators and of their counterparts, the enzyme inhibitors. Pressey's work on the invertase inhibitor (9) is just one example of developments that may have far-reaching consequences in processing.

Albersheim's discovery of inhibitors affecting polygalacturonase and other enzymes which affect the cell wall (1) creates new possibilities in raw material control and processing manipulation. Of particular interest are perhaps the protease inhibitors that are discussed by Dr. Liener in another paper in this symposium. The biological function of these inhibitors has been the subject for much speculation since the discovery of the first protease inhibitor by Ham and Sandstedt in 1944 (5). Until quite recently, all the known inhibitors were primarily active against animal or fungal proteses, and there was a natural tendency to assign a protective role to the inhibitors. In 1971, however, Kirsi and Mikola (6) were able to show that a protease inhibitor system from barley which inhibits trypsin and an *Aspergillus* protease, also inhibits a barley protease. During germination the latter inhibitor disappears while the former two remain. Here we have the first indication of a biological control function ascribable to the protease inhibitors. We have in our laboratory obtained evidence for the existence in the potato of an inhibitor active against a series of plant enzymes similar to papain. These developments herald perhaps a new insight into the problems of biochemical control systems in the plant. Obviously the food processor will benefit by being given new means of quality control and an increased opportunity of predicting and controlling the textural characteristics of his products.

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THE INFLUENCE OF MULTIPLE QUALITY REQUIREMENTS ON THE PLANT BREEDER

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Traditionally, plant breeders have been concerned with characteristics such as yield and disease resistance which can be evaluated subjectively or by straightforward objective methods where differences are qualitative and maximum manifestation of the trait is desired. Quality has not been a principal objective in most plant breeding programs; frequently, it has been an afterthought. Once the other desired characteristics have been achieved, there is an attempt to select for adequate quality. The attention that quality characters have received varies greatly among the numerous quality traits. Color, for example, has received considerable attention because of its importance to appearance and consequently salability. In contrast, nutritional value and flavor have been mainly neglected by plant breeders.

Developing a new cultivar is difficult even when the goals can be well stated. Often, quality characteristics cannot be clearly defined. Quality has many facets, and it often means different things to the various groups concerned with a new cultivar. The consumer wants the best appearance and flavor for the money he is willing or able to pay. The processor wants a raw product that will give him maximum case yields of a finished product that sells well and gives maximum return. This may represent high quality, not in absolute terms, but only relatively. Frequently, quality and price are closely related, and the consumer may not be able to afford highest quality. If breeders are able to increase quality of predominant cultivars, higher quality at a reduced price should result. The grower wants a product that meets the grade requirements of the processor or shipper. If the primary requirements are color and freedom from physical defects, these are his chief concerns.

The needs of consumers, processors, and growers are interrelated, and presumably, since the consumer is king, his needs and wishes should have priority. Obviously, this has not happened, as some of the consumer's primary concerns have been almost completely ignored by breeders.

One commonly hears that foods, including fruits and vegetables, are bought not for their nutritional value, but for taste and appearance, and the enjoyment they provide. This situation appears to be changing and through the efforts of various groups, people are becoming more aware of nutrition, and, in the future, there will probably be increased insistence by the consumer that foods have good nutritional value. As a consequence, cultivars which provide this will be more popular.

There is evidence that breeders supported by public funds will have to be more actively concerned with the consumers' needs if they intend to maintain that support. Urban-oriented legislators feel that there are more pressing problems than further increases in production, particularly when overproduction is already a problem. Many of these legislators are skeptical of research they feel will mostly benefit corporate farmers and large processors. However, when a breeder has a program to improve flavor and nutritional value, the benefits to everyone become more apparent.

COMPLEXITY OF BREEDING PROGRAMS

A number of factors contribute to the plant breeder's lack of attention to quality. Most of these are related to the complexity of breeding programs. A major factor is the effect that hybridization and selection for additional traits has on the complexity of a program, which increases exponentially with the number of genes being manipulated (Table 1). From a cross segregating for 21 genes a perfect population of tomatoes, which is one in which each phenotype occurs at least once, would require over 420,000 acres of tomatoes.

To keep a breeding program manageable requires setting priorities. It is simply not possible to develop a cultivar with all of the desired characteristics. The best tasting, most nutritious cultivar is doomed to failure unless it has yield, disease resistance, and the other characters essential to growers and processors. Thus, most quality characteristics necessarily greatly complicate breeding programs. To be successful a high-quality cultivar must also possess all the characters that make

Table 1. Kinds of phenotypes possible in F_2 generation from parents differing by various allelic pairs.

Number of Allelic Pairs	No. of phenotypes in F_2 (additive genic effects)
1	3
2	9
4	81
10	59,049
21	10,460,353,203

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