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Microstructure of Potato Products: Effect on Physico-Chemical Properties and Nutrient Bioavailability

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ABSTRACT

Understanding the microstructural changes of raw potato during processing is critical if food properties want to be controlled properly, because there is a causal connection between structure and functionality. Major structural elements contributing to potato products identity and quality are plant cells, cell walls and starch granules. During processing, which can be viewed as a series of restructuring and reassembling operations, these elements are modified, which generates changes on the product properties. For example, texture is a sensory attribute of uppermost importance for the preference of potato products. The abundance of starch inside the cells, and the shape and size of starch granules modified during different processing, have been reported as important factors for the final texture, as well as the structure of the cell wall polymers. Thus, microscopy techniques for examining food microstructure are necessary to understand structure-property relationships and their effects on chemical stability, physical properties and nutrient bioavailability of potato products. Image processing and image analysis techniques provide the required quantitative data for the analysis and design of food microstructure. In addition, it is necessary to improve the quality of existing foods and to create new products that satisfy consumer's demands of healthy foods, which will be based on interventions at the microscopic level.

Keywords: physical properties, potato processing, quantitative microscopy, starch digestion

CONTENTS

INTRODUCTION

Potato is one of major foods in many regions of the world. Until the early 1990's, most potatoes were grown and consumed in Europe, North America and countries of the former Soviet Union. Since then, there has been a dramatic increase in potato production and demand in Asia, Africa and Latin America. In 2007 the amount of potato destined either for direct consumption or for processing was over 300 million tons (FAO 2008).

The processing of vegetables involves a wide spectrum of operating conditions quite different from the physiological ranges. The living tissue may be exposed at extreme operating temperatures, from freezing to frying, which will affect the quality of the final product. The final quality of potato products will depend to a great extent on the preser-

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Invited Review

vation of the cellular integrity after processing. Hence, a better knowledge of the changes of the potato structure during processing is of the utmost importance to improve quality and nutritional value (González-Martínez 2003).

As potatoes are mainly consumed cooked or fried, heat treatments are commonly used in potato processing, which result in drastic chemical, physical, and structural changes in the tuber tissue (Miranda and Aguilera 2006). These structural changes can be observed and quantified by microscope studies. Hence, microstructural studies may improve the understanding of the underlying mechanisms of food processes and changes on food properties. Furthermore, microscope studies provide not only qualitative information, but also quantitative data suitable to modeling (Aguilera and Germain 2007). For example, images of raw potato cells under the microscope shows discrete cells, cell walls and starch granules in the cell aqueous interior (Lewicki and Pawlak 2005). This structural information is the minimal requirement to begin a microscopy study of the processing of potatoes, since each of these elements can respond individually to the external variables (Aguilera and Lillford 2007).

On the other hand, the influence of plant food structure on bioavailability of many bioactive components of foods is an area that has been poorly researched. The delivery of nutrients from foods is attenuated by the structure of the food and the way in which it is digested (Southon and Faulks 2002). Disruption of the natural matrix may influence the release, transformation, and subsequent absorption of certain nutrients in the digestive tract (Parada and Aguilera 2007). For instance, starch (the most abundant carbohydrate in potato) gelatinizes in the cooking process. Starch digestibility improves during processing and is affected by cooking methods. During cooling the gelatinized food starch molecules begin to crystallize and resistant starch is formed (Tahvonen *et al.* 2006).

This review is an attempt to relate how the changes in microstructure, wich can be quantified by image analysis, affect the physicochemical properties and nutrient bioavailability of thermally processed potato product. Section 2 describes the different structures that compose the potato tuber. Section 3 presents the main thermal processes used in potato processing, and some effects on potato microstructure are exposed in Section 4. Section 5 illustrates important images techniques available for food science and selected examples of the important features of processed potato cells. In section 6 the relations structure-properties for potato products are revised. Section 7 discusses the effect of potato microstructure on nutrient bioavailability and its effect on human nutrition. Finally, some conclusions and future trends are presented.

THE MICROSTRUCTURE OF THE UNPROCESSED POTATO

To characterize the microstructural changes during processing of potato products, understanding "microstructure" as the organization of elements within a food and their interactions (Aguilera *et al.* 2000), is necessary to study the different structures or elements that compose the potato tuber (**Fig. 1**). In this way, the potato structure is divided into the bud and stem ends, the latter situated on the stolon. The bud end of the potato is richer in eyes than the stem end. The outer skin consists of a layer of corky periderm, approximately ten cells deep, formed by dead cells that do not contain starch or protein grains, and have thicker cell walls than parenchyma cells (Fedec *et al.* 1997; Miranda and Aguilera 2006). In turn, cell sizes within the same tuber differ considerably in relation to the sample collection site. Two areas were distinguished in the potato tubers, the pith and internal parenchyma (Gancarz and Konstankiewicz 2007).

Underlying the periderm or skin is the cortex (**Fig. 1**), a thin layer of parenchyma tissue, where the cells normally contain numerous round and oval-shaped starch granules. These cells appear to be the largest in the tuber, with dimension up to 146-189 μm (Fedec *et al.* 1977). Vascular storage parenchyma, high in starch content, lies within the shell of the cortex. Xylem and phloem are found in minute strands or bundles, most of which form a narrow, discontinuous ring (the vascular ring) just within the boundary between the cortex and the vascular area. Storage parenchyma cells adjacent to vascular tissue contain starch granules that are generally small and round. Cells located only three cells away contain oval starch granules that are at least twice as large. Forming a central core, but radiating narrow branches to each of the eyes, is the pith (**Fig. 1**), sometimes called the medulla or water core, where the cells are smaller and have lower starch content. In turn, the internal phloem (perimedullar zone) occupies ~75% of the total volume of the tuber (Jadhav and Kadam 1998). This histological variability of potato tissue is a critical factor when determining

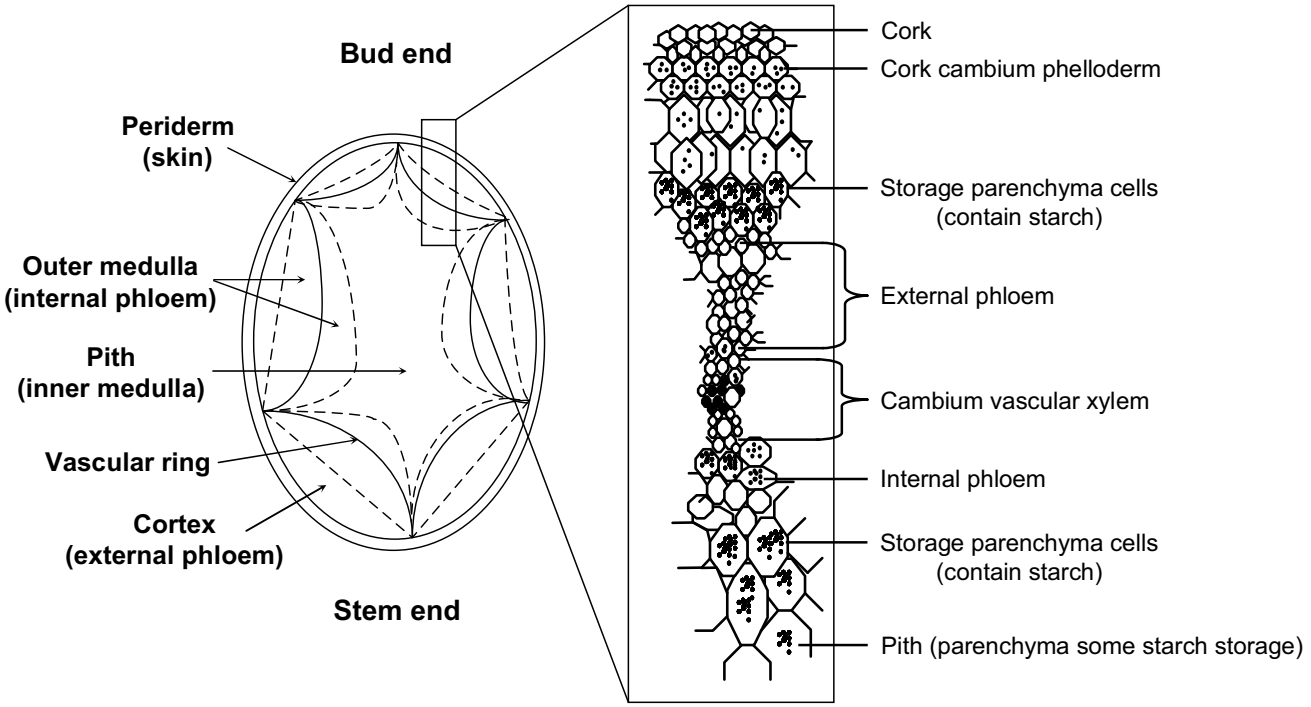

Fig. 1 Schematic of cross section of a potato tuber.

different properties of finished products and the material properties of raw potato can be understood in terms of a combination of cell turgor pressure and cell wall mechanics (Ormerod *et al.* 2002).

The cells in the potato tissue are bound together by a pectin-rich region known as the middle lamella (i.e. outer layer of the cell wall), which is dissolved during heating. In raw potato, the cells contain numerous partially crystalline starch granules, which have a high variability in their distribution and composition and are modified during potato processing (Lisińska and Leszczyński 1989). Thus, these microstructural features, together with the histological variability, make potato tubers extremely anisotropic materials (Miranda and Aguilera 2006) that will generate final products with different physical and sensory properties after processing.

PROCESSING OF POTATO

During the last decades motivations of the food industry has changed with modifications in consumers needs, some of them including: (i) to improve the stability and convenience of foods by preservation techniques which inhibit microbiological or biochemical changes (ii) to expand the variety and appeal of conventional food sources by providing a range of processed foods with attractive flavors, colors and textures; (iii) to provide the nutrients required and respond to consumers health requirements, for instance decreasing the caloric content and delivering potentially beneficial bioactive compounds (Aguilera and Lillford 2007).

In general, all food processing involves a combination of procedures to achieve the intended changes to the raw materials. It is hypothesized that the microstructural changes produced during processing may affect the physical properties and the bioavailability of nutrients of potato products (**Fig. 2**). Microstructure-properties relationships could help to modify or design new processes to fulfill the new consumers needs.

Global consumption of potato as food is shifting from fresh potatoes to added-value, processed food products. The major food uses of potatoes include products such as fresh potatoes (27%), which are consumed mainly as cooked potatoes, French fries (29%), chips (10%), and dehydrated potatoes (11%) (Lin *et al.* 2001). It is worth to mention that blanching, a pretreatment widely used in the food industry, produces several changes in the structure of raw potatoes, affecting their physical properties. Hence, the blanching treatment and its effects will be considered in this review.

Blanching

Blanching is a mild heat treatment (50-85°C) used to inactivate the oxidative enzymes in fruits and vegetables prior to further processing (e.g. dehydration or frying). The main objectives of blanching in potato processing are the inactivation of enzymes and the regulation of reducing sugars content in the superficial layers of the tissue that play a predominant role in color development (Andersson *et al*. 1994). Of the oxidative enzyme systems, the enzyme peroxidase is considered to be the most heat resistant; therefore, peroxidase inactivation has been traditionally used as an index of blanching adequacy (Ramaswamy and Chen 2002).

Steam and hot water blanching are the two most commonly used blanching techniques. Conventional water blanching has lower capital cost and better energy efficiency than steam blanching but results in larger losses of water-soluble components, including vitamins, minerals and sugars (Ramaswamy and Chen 2002). A high loss of ascorbic acid after the blanching procedure was reported by Haase and Weber (2003). Potassium, calcium, and magnesium concentrations in potato tissue changed during hot water blanching, and ions were better retained than glucose, fructose, and citric acid (Gekas *et al.* 1993). A significant loss of glucose was found by Maté *et al.* (1998). However, leaching of reducing sugars in the superficial layers of the potato tissue decreases the extent of Maillard reaction during subsequent drying or frying.

Apart from enzyme inactivation, blanching also serves several additional functions: removes the tissue gases, increases the bulk temperature of the tissue and cleanses the tissue (Fellows 2000). Other reasons for blanching, especially for fried potato products, are the improvement in texture and the reduction of oil uptake due to gelatinization of surface starch (Andersson *et al.* 1994).

The published observations on the effect of blanching on potato microscopic structure show that starch is gelatinized, cell walls are intact, and the integrity of cells is preserved. Some weakening of middle lamella occurs and is accompanied by swelling of cells leads to separation and rounding off cells. In consequence, blanched tissue is less mechanically resistant in comparison to raw potato; hence it is more vulnerable to further changes due to processing (Lewicki and Pawlak 2005).

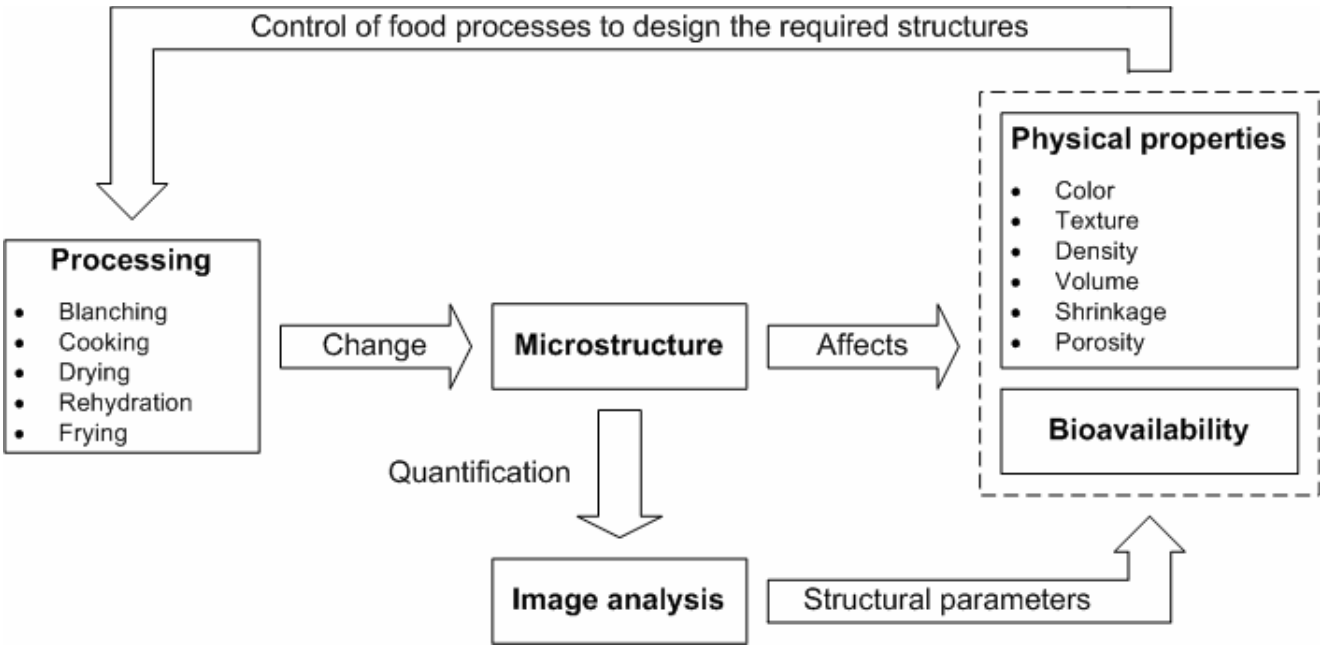

Fig. 2 Microstructure of potato products is modified by processing and has an effect over physical and nutritional properties.

Cooking

Cooking is a heat-processing technique and its primary objective is to improve the palatability of the food. Cooking can be considered a preservation technique because many cooked foods can be stored longer under proper refrigerated conditions than their uncooked counterparts, if recontamination can be minimized. Cooking results in the destruction or reduction of microbial load and inactivation of undesirable enzymes, two important requirements of most preservation techniques (Fellows 2000). It can also improve digestibility and alter color, flavor and texture to suit the consumer's need. As well as hot water blanching, cooking will also result in loss of certain soluble solids and heat-labile nutrients.

Quantitative instrumental data on the degree of cooking are essential to determine the optimum cooking time. Although cooking was traditionally accomplished almost exclusively by boiling water, nowadays oven and microwave cooking are used in the food industry, catering institutions and domestic households (Alvarez and Canet 2002).

Many of the structural changes produced by cooking are similar to those produced by blanching. The softening of cooked potatoes is the result of changes (degradation) in the structure of cell walls and middle lamella and starch gelatinization as a result of heating (Jarvis *et al.* 1992b; Andersson *et al.* 1994; van Merle *et al.* 1997; Thybo *et al.* 1998).

Drying

Drying is perhaps the oldest, most common and most diverse of food engineering unit operations used to preserve foods. Drying is defined as the evaporation of the majority of the water normally present in a food into a vapor phase via application of heat under controlled conditions (Mujumdar and Devahastin 2000). The basic objective of food drying is the removal of the water, thus reducing the water activity, to a level at which microbial spoilage is minimized and the product is relatively chemically stable, extending their shelf life (Vega-Mercado *et al.* 2001). Preservation, by means of drying processes inhibits adverse chemical and biological changes occurring in plant tissues even after the cellular structure has been damaged by its own enzymes and microbes (Lisińska and Leszczyński 1989).

Loss of water results in major structural changes in materials that lead to textural and sensory characteristics different from the fresh product (Ramos *et al.* 2003). The specific drying method as well as the physicochemical changes that occur during drying seems to affect the quality of dehydrated products. More specifically, the particular drying method applied, affects properties such as color, texture, density, porosity and sorption characteristics of materials.

The main changes to dried foods are related to texture and loss of flavor or aroma, but changes in color and nutritional value are also significant in potato. Specifically, a reduction in vitamin C content has been reported for dried potato (Mclaughlin and Magee 1998; Khraisheh *et al.* 2004). Also, drying causes physical and structural modifications of potato tissue. Shrinkage, porosity, collapse, case hardening and cracks (internal and external) are among the most important structural features induced by drying (Aguilera 2003; Lewicki and Pawlak 2005).

Drying processes lead to changes of foods at microstructural level, consequently it affects their macroscopic characteristics. Loss of water and segregation of components occurring during drying, result in rigidity of cell walls. Damage and disruption of the cellular walls may happen, and even collapse of the cellular tissue may occur. These changes are associated with volume reduction of the product (Ramos *et al.* 2003).

Rehydration

Many dried products are consumed or further industrially used after rehydration. Therefore, concerns on the quality of dried foods should be extended to their characteristics after rehydration. Most dried foods should undergo a full and fast rehydration in order to improve their characteristics before cooking (Oliveira and Illincanu 1999).

The reduction in potato water content can be achieved by many ways, but the problem is to obtain a final product which, after rehydration, still maintains high quality and acceptable organoleptic properties (Lisińska and Leszczyński 1989). The wide variety of dehydrated potato products available today (potato slices, granules, flakes and flour) and the concern for meeting quality specifications and conserving energy, emphasize the need for a thorough understanding of the rehydration process (Cunningham *et al.* 2008a).

Many studies have been published on drying of fruits and vegetables, but literature on rehydration is relatively scarce. Much of the progress in this field has been made by analogy with dehydration processes, but several aspects of rehydration cannot be satisfactorily addressed by simply "reversing" the phenomena that occur during drying. Rehydration of dried plant tissues is essentially a sorption process and is highly dependent on the food microstructure developed during drying (Oliveira and Illincanu 1999). During rehydration three processes can be distinguished: the imbibing of water by the dried material, the swelling of biopolymers and leaching of soluble solids into surrounding medium (Witrowa-Rajchert and Lewicki 2006).

Water removed during dehydration cannot be replaced in the same way when the food is rehydrated. Loss of cellular osmotic pressure, changes in cell membrane permeability, solute migration, crystallization of polysaccharides and coagulation of cellular proteins all contribute to texture changes and volatile losses, which are irreversible (Fellows 2000). Heat reduces the degree of hydration of starch and the elasticity of cell walls, and coagulates proteins reducing their water-holding capacity. The extent and kinetics of rehydration can be considered as a measure of the damage (related to food quality) done to the tissue caused by drying and the treatments preceding dehydration (Krokida and Marinos-Kouris 2003; Witrowa-Rajchert and Lewicki 2006).

It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption produced during drying. Foods that are dried under optimum conditions suffer less damage and rehydrate more rapidly and completely than poorly dried foods (Krokida and Maroulis 2001; Krokida and Marinos-Kouris 2003). Also, higher rehydration temperatures induce structural changes that may hinder rehydration (Cunningham *et al.* 2008a).

Finally, dehydration and rehydration processes lead to changes of potato products at microstructural level, and consequently affect their macroscopic characteristics. Shrinkage of cells, loss of rehydration ability, wettability, migration of solids, case hardening, and loss of volatile aroma components are important factors (Bruin and Luyben 1980). For example, hot air drying results in a dense product with a hard outer crust and slower water adsorption properties (Aguilera *et al.* 2003). Loss of water and segregation of components occurring during drying result in rigidity of cell walls. These changes are associated with volume reduction of the product (Ramos *et al.* 2003). Thus, functionality and final use determines the appropriate drying or dehydration method and conditions.

Frying

Frying is a unit operation involving the immersion and cooking of foods in hot oil. It involves heat and mass transfer and includes complex interactions between the food and the frying medium (Saguy and Dana 2003; Dana and Saguy 2006). The high temperature causes partial evaporation of the water, which moves away from the food and

through the surrounding oil. Oil is absorbed by the food, replacing some of the lost water (Moyano and Pedreschi 2007). As the food is fried for a longer period of time the moisture content in the food surface slowly diminishes forming a crust. Water deep inside the food will become heated and the food will be cooked (Mellema 2003). The purpose of frying is a fast cooking with formation of unique flavors and texture that improves the overall palatability.

Basically, frying is a dehydration process with three distinctive characteristics (Saguy and Dana 2003): (i) high oil temperature (160-180°C) enables rapid heat transfer and a short cooking time; (ii) product temperature (except for the crust region) does not exceed 100°C; and (iii) water-soluble compound leaching is minimal.

The term "fried potato products" refers mainly to chips and French fries. French fries are made from potato strips of approximately 1 × 1 cm^2 in cross section and 6–7 cm in length and the deep-fat frying process gives them a crispy crust and a well-cooked center (Lisińska and Leszczyński 1989). On the other hand, potato chips are very thin pieces (1.27–1.78 mm thick) of sliced raw potatoes that are fried to a final oil content of ~2% wet basis (Moyano and Pedreschi 2007). The high temperature of the frying oil typically leads to the appreciated textural dichotomy of the French fries: dry, porous, oily and crispy outside (crust), and tender inside (cooked core). Potato chips constitute a good model of the crust of the French fries.

Frying affects potato properties such as starch gelatinization, cellular changes, protein denaturation, Maillard reaction and degradation of pectin substances. At cellular level frying induces cell separation, shrinkage, wrinkling, and cell wall convolution around dehydrated gelatinized starch without cell wall rupture, starting at the potato surface and progress toward the center during frying (Aguilera *et al.* 2001; Costa *et al.* 2001). Exact starch gelatinization degree will depend on the frying time and the amount of water locally available. At the outer surface a very fast evaporation of water will occur, which will limit starch gelatinization. Therefore the starch gelatinization depends on the distance from the surface (Luyten *et al.* 2004).

The heat treatments above mentioned generate structural changes in potato tuber, which modify the raw material and produce different properties of final products. These structural changes can be evaluated by several methods. However, microscopy is the main technique to quantify these changes and to improve the understanding of the underlying mechanisms of food processes and changes on food properties.

STRUCTURAL CHANGES DURING POTATO PROCESSING

Potatoes tubers are the raw materials of many processed food, such as cooked potatoes in hot water, dehydrated potatoes and the most popular fried potatoes. The microstructural characteristics of each one of these food products will depend of the type and process conditions.

Cooked potatoes in hot water

During cooking of potatoes in hot water the typical changes at microstructural level are the weakening of the binding between cells and gelatinization and swelling of the intracellular starch (Ormerod *et al.* 2002). Thybo *et al.* (1998) follow the microscopic changes produced in cooked potatoes, they found that when exposed to water cooking for 5 min the starch granules hydrate and swell forming a reticulum of amylose and amylopectin completely filling the cell lumen. This structure persisted throughout the cooking period. Cell separation proceeds with cooking time leading to disintegration after 20-30 min. After about 50 min the cells collapsed, accompanied by pasting of gelatinized starch to the surface of the samples. Starch granules absorb cellular water and gelatinize to form a sponge-like matrix. Swollen starch within cells exerts a strong swelling pressure on the cell wall and the middle lamella degradation cause the expansion of the cells.

The presence of starch in cells and the size of the starch granules have been reported to be important for the final texture of potato (Martens and Thybo 2000). For instance, Kaur *et al.* (2002b) founded that the size and shape of granules have an effect on the textural, thermal and rheological properties. Large-size starch granules present lowest glass transition temperatures (Tg') and highest values for the storage (G') and loss (G'') modulus, and small-size starch granules present highest Tg' and lowest values for G' and G''.

Jarvis and Duncan (1992a) associated the structural changes produced during cooking, with textural parameters. These parameters were softness and dryness, softness resulting from cell cleavage and cell separation, and dryness resulting on the ratio of cell separation to cell cleavage. They established that cell wall softening was due to the disintegration of the calcium-pectic gel in the wall matrix by thermal β-eliminative cleavage of the pectic chain. This allows to the teeth or knifes to slice through the cells releasing their contents so that the texture is perceived as moist and the cut surface appears smooth. On the other hand, cell separation, is due to dissolution of the calcium pectic gel of the middle lamella, by the same mechanism but also by chelation of calcium ion with citrate released from within the cell. Biting or cutting then separates the cell without breaking them open. Since the cell contents are not released, texture feels dry and the surface looks powdery.

Dehydrated potatoes

Drying is a process that causes many irreversible changes in plant tissue. Transient thermal and moisture gradients develop a tensional and compressional stresses. The stresses cause breakage and fracturing of the tissue undergoing drying. In potato, fractures are very small and occur during the final stages of dehydration. The surface layer of potato slabs dried by convection is severely damage after a short time, while inner structure is apparently intact. Further drying induces formation of cracks, the inner tissue is pulled and numerous holes are produced (Aguilera 2003; Lewicki and Pawlak 2005).

Lewicki and Pawlak (2005) quantified the changes produced in the potato structure during drying. They found that the most frequent cross-sectional area of cell was 5.75 μm^2 during convective drying and that the small cells shrinked much less than the large ones. The shape factor of the cross-sectional area of cells in dry tissue was smaller than in raw tissue. This implies that cells were elongated and stretched in one direction. The most frequent perimeter and Feret diameters values did not present high differences between raw and dry structures. This suggests that most of cells were intact and cell walls were not broken during convective drying. The calculation of the cross-sectional area of 700 objects seen under the microscope showed that in convective air drying of potatoes, there were 12% fewer cells than in raw potato tissue. This means that during convective drying some cell walls are broken and large cavities are formed.

Iyota *et al.* (2001) evaluated structural changes during drying with hot air. The cross sectional views of the materials before drying had starch granules spreading throughout with their visible cellular structure. After 120 s of drying at 240°C, their entire cross sections showed starch granules, and the material thickness reduced down to 2.5 mm, approximately. After 300 s, the material thickness decreased down 1.3 mm approximately. At this time, uniform cell sizes and cavities in the cross sections could not be recognized. Starch granules were only observed in the region near the surface due to the presence of starch granules still not gelatinized. This was because in the surface moisture evaporates around the wet-bulb temperature (45 to 55°C), and thus the drying process at the surface do not satisfy the temperature condition for starch granule gelatinization (i.e. ~65°C).

Fried potatoes

Deep-fat frying is essentially a cooking and dehydration process in which the starch content of the cells is gelled and dehydrated and some of the water in the tissue is replaced by oil (Miranda and Aguilera 2006; Moyano and Pedreschi 2007). In addition, changes at the cellular and sub-cellular levels in the outermost layers of the product are developed during this process. However, prior to frying, different pretreatments (e.g. blanching, drying, freezing, osmotic dehydration, among others) can generate changes occur in the cell membranes, which play a key role in the changes that occur within the tissue during further processing. During French fries processing, the structure of potato tissue is markedly and irreversible changed (Lisińska and Golubowska 2005; Miranda and Aguilera 2006). This product has two well defined regions with distinctive characteristics: the crust composed of shrunken cell with very low water content, and the core, that consist of cooked and slightly dried cells (Costa *et al.* 2001). The crust structure of fried potato products is the result of several alterations, most of which occur at the cellular and subcellular levels. These alterations they take place in the outer cell layers of the product and the major changes include physical damage owing the cutting (slicing), release of contents of broken cells, gelatinization of starch granules, softening of cell walls, and fast dehydration of tissue (Bouchon and Aguilera 2001). As the crust becomes thicker as the frying proceeds, the resistance to the vapor release is increased. This leads to a pressure build-up below the crust with the consequent formation of swollen pockets. The water vapor is released by the bursting of a few localized sites that break under stresses caused by pressure. There are round holes in the swollen areas and elongated cracks in the areas of crust still attached to the flesh (Costa *et al.* 2001). As frying proceeded, samples showed a great extension of tissue disruption/separation just below the surface, due to pressure caused by the expanding water vapor entrapped by the crust. As the middle lamella pectic substances between adjacent cell walls becomes softened and partially solubilized by the cook treatment, the cells are forced apart. In turn, microstructural changes in the core are much milder and similar to those occurring during the cooking of potatoes, the major ones being hydration and swelling of starch granules and softening of middle lamella (Bouchon and Aguilera 2001).

Thus, potatoes are processed in many different ways, which generate specific physical and nutritional properties in potato products due to the microstructural changes developed during potato processing, which can be visualized using microscopy techniques. The possibility to follow changes (e.g. shrinkage, cell wall disintegration and collapse) directly under the microscope opens new opportunities to get an insight into the kinetics of structure breakdown (and structure formation). It is possible to quantify these structural changes using image analysis methods and extracting different features from the images such as area, perimeter, form factor, Feret diameters of cells, crack or pores, which can be used for establish relationships between microstructure and the mechanical/physical properties of foods.

OBSERVATION AND QUANTIFICATION OF MICROSTRUCTURAL CHANGES DURING POTATO PROCESSING

Visual changes due to processing of raw materials can be attributed to changes at the microscopic and molecular levels. Many tools are available to observe the microstructure formation or breakdown during processing. Imaging techniques can be used to evaluate these changes in terms of morphology and composition. The microscopy techniques allows the visualization of food structures, such as fruit and vegetables structures, and can offer valuable information leading to a better understanding of texture and other quality properties (Hu *et al.* 2006).

Microscopy and imaging techniques are the most appropriate techniques for evaluating food microstructure, being among the most widely used different types light microscopy (LM) and electron microscopy (EM) methods. In LM, the most common applications involve bright field illumination and confocal laser scanning microscopy (CLSM). In the EM, the most used techniques are scanning electron microscopy (SEM), cryogenic scanning electron microscopy (Cryo-SEM) and environmental scanning electron microscopy (ESEM). Some of these techniques used in potato structure analysis are shown in **Table 1**.

Extracting quantitative data from image analysis

The analysis of digital images has become in the last years a relevant tool in food science and technology. Today, food microstructure can be easily evaluated by many different imaging techniques, and their importance in improving our understanding about how foods behave is unquestionable. However, the real value of images relies on the quantitative information and numerical data that can be extracted from them. The extraction of quantitative data from an image is often the main goal if structure-property relationships will be evaluated. The most direct measurements on individual object are related to size and shape (**Table 2**). Russ (2004) has proposed that the object characterization (equivalent diameters, shape, compactness, etc.) and advanced microstructural descriptors, derived from Fourier, fractal and image texture analysis, are the main parameters extracted from image analysis.

In turn, different mathematical algorithms, such as those described by Russ (2004), can be applied for generating the kinetics of structural parameters. Basically, this process consists in the acquisition of digital images (e.g. 768 × 512 pixels) which are pre-processed to improve their quality using digital filters to eliminate noise and to enhance the contrast (Castleman 1996). Color images are converted to a grayscale (intensity) image and segmented to isolate important elements from the background. Thus, the region of interest within the image corresponds to the area occupied by particles (e.g. granules) and the microstructures of interest can be characterized using commercial available softwares or by a specific generated software (see **Fig. 3**).

Measurements of structural parameters can be obtained manually or by automatic methods. However, using one or other approach presents advantages and disadvantages

Table 1 Microscopy techniques used in microstructure analysis of potatoes.

Microscopy technique	Evaluation	Reference
LM	Effect heat application to potato tuber parenchyma tissue	Ormerod *et al.* 2002
	Changes of parenchymous tissue structure in the production drum-dried potato flakes	Lamberti *et al.* 2004
CLSM	Oil location in fried potatoes	Bouchon and Aguilera 2001
	Oil distribution and surface morphology during potato frying	Pedreschi *et al.* 2008
	Changes in the starch granules and tuber tissue of transgenically modified potatoes with a large spread in amylose/amylopectin ratios	Karlsson *et al.* 2007
SEM	Changes in the structure of potato tissue during French fries production	Lisińska and Golubowska 2005
	Integration of microstructural, sensory and instrumental análisis to describe potato texture	Martens and Thybo 2000
ESEM	Starch molecular structure, nano-scale crystalline arrangements and topographical-morphological features	Blennow *et al.* 2003
	Effect of different processing techniques on the microstructure of potatoes	Uwins *et al.* 1993

Table 2 Most common measurement used in the quantitative food microscopy.

Measurement	Parameter	Description
Size	Area	Determined by counting of the number of pixels that are part of the objects
	Perimeter	Determined by counting of the number of pixels that are part of border of the objects
	Diameter	Easily determined in round shape object. For other forms different strategies are used to measure
	Equivalent diameter	Used to characterize a non-perfectly circular shape-object
	Area fraction	Determined by measuring both the total area of interest and also the total area
Shape	Factor form	$= \frac{4 \cdot \pi \cdot \text{area}}{\text{perimeter}^2}$ Ratio between the area of an object and that of a circle with the same perimeter. Value varies between 0 and 1 (perfect circle)
	Elongation	$= \frac{\text{major axis length}}{\text{minor axis length}}$ Ratio of the major axis length to the minor axis length. Object is more elongated as the value increases
	Compactness	$= \frac{\sqrt{\frac{4}{\pi} \cdot \text{area}}}{\text{max perimeter}}$ Ratio between the diameter of the circle (with the same area of the object) and the object major axis length
	Feret diameter	$= \sqrt{\frac{4 \cdot \text{area}}{\pi}}$ Diameter of the circle with the same area of the object

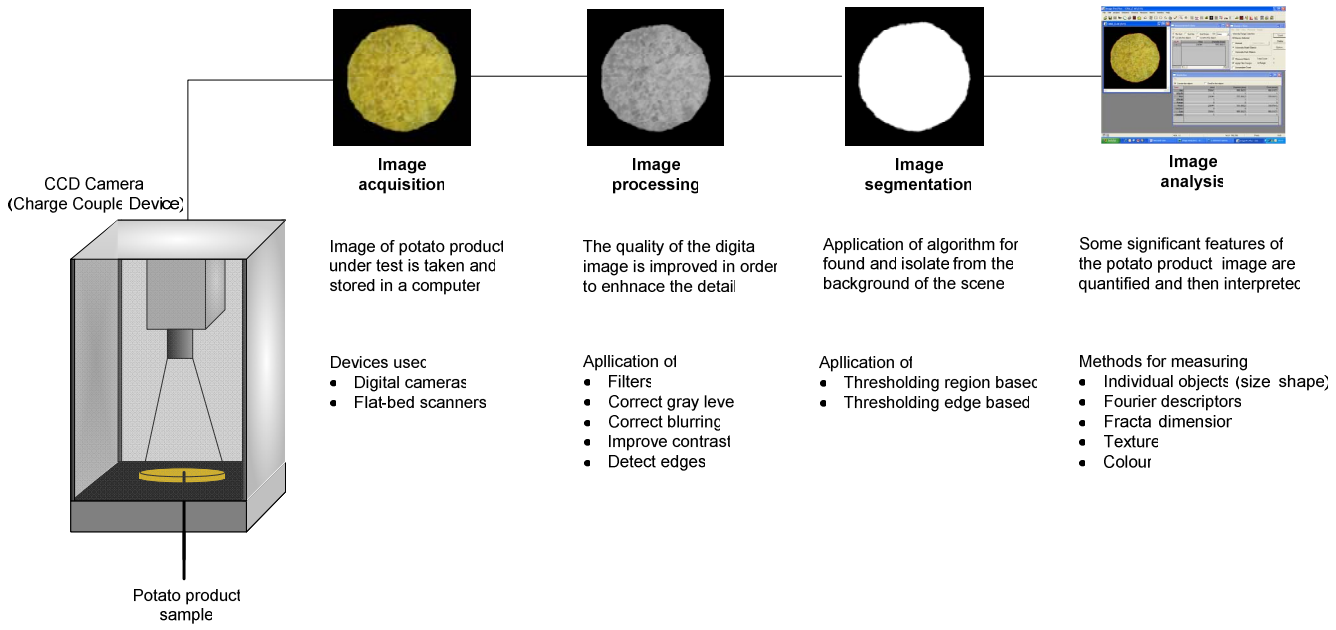

Fig. 3 Schematic representation for potato products image analysis.

because food microstructure is very complex, it can present large variations in gray tones and also, because of the incorporation of instrumental artifacts during sample preparation. Manual measurements have the advantage of being more precise than automatic process, because a human operator is far better trained to discriminate objects on an image based on visual information than a machine. However the process is slower and subject to stronger biases. In contrast, automatic measurements are better suited to give quantitative data without introducing biases. They are also faster if there are a large number of images to be analyzed (Aguilera and Germain 2007). For instance, measurements done in a light microscope can provide accurate data, but results are limited by the equipment resolution and affected by the operator. Also, dimensional distortion and shrinkage are unavoidable consequences of chemical fixation that can have direct influence on the measurements (Aguilera and Stanley 1999).

Finally, global structural changes generated during the different potato processing will determine diverse characteristics of potato products which will affect their quality, which can be measured by diverse physical properties.

INFLUENCE OF MICROSTRUCTURE ON PHYSICAL PROPERTIES OF POTATO PRODUCTS

The majority of potatoes are used as table foods these days, frequently consumed in the different forms of processed potato products. Apart from use of fresh potatoes, they are mainly dehydrated in different processing (for example, cooking, drying, frying, etc) and forms (for example, slices, strips, cubes, cylinders or flakes) to impart better physical properties, related with sensory attributes, and shelf life. Different operation conditions generate chemical, physical and biological changes that affect the integrity of living tissue (raw material), and subsequently the properties of final products. Because of the complex and reactive nature of food materials, determination of physical properties is a

Table 3 Some works that have reported the effect of processing conditions on physical properties of potato products.

Process	Processing conditions	Product	Physical properties measured	Reference
Blanching	Immersion in boiling solutions	Potato slices	Color	Severini *et al.* 2003
	Immersion in water at different temperatures and times	Potato slices	Texture	Maté *et al.* 1999; Abu-Ghannan and Crowley 2006
Cooking	Forced convection and steaming	Potato cylinders	Color and texture	Chiavaro *et al.* 2006
	Immersion in water	Potato cylinders	Color and texture	Nourian *et al.* 2003; Singh *et al.* 2005
			Texture	Martens and Thybo 2000; Kaur *et al.* 2002a
	Immersion in water and steaming	Potato cylinders	Texture	Rahardjo and Sastry 1993
Blanching and cooking	Immersion in water at different temperatures and times	Potato cylinders	Texture	Verlinden *et al.* 2000
Drying	Freeze	Potato cylinders	Color	Krokida *et al.* 2001a
			Density and porosity	Sablani and Rahman 2002
		Potato strips	Density and porosity	Sablani and Rahman 2002
	Hot air	Potato cylinders	Density, porosity, shrinkage and volume	McMinn and Magee 1997
			Texture	Krokida *et al.* 2000a
		Potato slabs	Density, porosity, shrinkage and volume	Wang and Brennan 1995
		Potato slices	Color	Iyota *et al.* 2001
	Hot air, microwave, osmotic and vacuum pressure	Potato cylinders	Color	Krokida *et al.* 2001a
	Hot air and superheated steam	Potato slices	Color and texture	Leeratanarak *et al.* 2006
	Microwave and convective	Potato cylinders	Shrinkage and volume	Khraisheh *et al.* 2004
	Superheated steam	Potato slices	Color	Iyota *et al.* 2001
Blanching and drying	Different conditions of blanching and drying	Potato cubes	Color	Severini *et al.* 2005
Frying	Atmospheric pressure	Potato cubes	Texture	Sundara *et al.* 2001
		Potato slabs	Texture	Ross and Scanlon 2004
		Potato slices	Color	Mitchell and Rutledge 1973; Sahin 2000
			Color and texture	Pedreschi *et al.* 2007a
			Color, shrinkage and volume	Mai Tran *et al.* 2007
			Density, shrinkage and volume	Costa *et al.* 2001
			Density, porosity, shrinkage and texture	Taiwo and Baik 2007
			Shrinkage	Yamsaengsung and Moreira 2002
			Texture	Pedreschi and Moyano 2005a, 2005b; Kita *et al.* 2007; Moyano *et al.* 2007
		Potato strips	Color	Agblor and Scanlon 2000; Krokida *et al.* 2001b; Moyano *et al.* 2002; Tajner-Czopek *et al.* 2007
			Density, porosity, shrinkage and volume	Krokida *et al.* 2000b, 2001c
			Density, shrinkage and volume	Costa *et al.* 2001
			Texture	Agblor and Scanlon 2000; Pedreschi *et al.* 2001; Moyano and Berna 2002; Golubowska 2005; Lisińska and Golubowska 2005; Moyano *et al.* 2007; Tajner-Czopek *et al.* 2007; van Loon *et al.* 2007
	Vacuum pressure	Potato slices	Color and texture	da Silva and Moreira 2008; Song *et al.* 2007a; Troncoso *et al.* 2008
			Color, shrinkage, texture and volume	Garayo and Moreira 2002
			Texture	Song *et al.* 2007b
Rehydration	Air drying prior to the immersion in water at different temperatures	Potato cylinders	Density, porosity, shrinkage and volume	Krokida and Maroulis 2001
		Potato slices	Texture	Maté *et al.* 1999
	Different drying techniques, prior to the immersion in water at different temperatures	Potato slices	Texture	Cunningham *et al.* 2008b

challenging task. Likewise, recent scientific evidence shows that the way in which a food is structured, rather than solely its composition, influences the major sensory, nutritional and physical characteristics. Thus, components that meet the criteria of nutritional adequacy, safety, and other quality tests can be restructured to yield foods that are attractive to consumers (Aguilera and Stanley 1999). In this way, physical properties of foods are the upmost importance for product development, process design, shelf life and quality. Accurate and reliable measurements of physical properties of foods are required for process simulation and optimization.

Understanding the relationship between food microstructure and food perceived characteristics is of increasing importance to produce attractive food products (Wilkinson *et al.* 2000) and the knowledge of food properties will provide qualitative and quantitative data suitable to modeling. Several works have been developed to study the effect of different processing conditions on physical properties of potato products (**Table 3**). However, is necessary to describe what physical properties are of major importance in each one processing applied to the potato products, considering the main quality parameters in food processing, such as color, texture, volume/density, shrinkage and porosity (structure).

Color

Color is an important parameter for the consumer acceptance as well as being an indicator of the brown pigments formed during non-enzymatic browning and caramelization process generated during thermal processing.

In elementary physiology of vision, color is the result of

light (400 to 700 nm wavelengths) reaching the retina of the eye. Humans see color by means of three types of cones (or receptors) in the retina, each of which has different wavelenght sensivity. The response of the cones was found to be linear with light intensity, and thus, the physical basis of color vision can be described by three numbers, each giving the integral of [incoming light intensity × cone sensivity] over the incoming light frequency spectrum (Clydescale 1978; Hunt 1991).

Colors could be described visually or mathematically by a combination of three independent attributes, which can be specified in 3D-space that has become known as a *color solid*. The three-color attributes were described as (Clydescale 1978; Hunt 1991):

***Lightness*:** The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting (adjectives: *light* and *dark*).

***Hue*:** Attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green, and blue.

***Chroma or intensity*:** The colorfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting (adjectives: *strong* and *weak*).

Generally, color has been measured usually in L*a*b* units, which is an international standard for color measurements adopted by the Commission Internationale d'Eclairage (CIE) in 1976. L* is the lightness component, which ranges from 0 to 100, and parameters a* (from green to red) and b* (from blue to yellow) are the two chromatic components, which range from -120 to +120 (Papadakis *et al.* 2000). In the L*a*b* space, the color perception is uniform which means that the Euclidean distance between two colors corresponds approximately to the color difference perceived by the human eye (Hunt 1991).

Color of a food could be measured visually or instrumentally. The visual measurements are usually done by comparison with standard photographs (e.g. Munsell color system), but this technique produces considerable variability due to the influence of the surrounding light, and the objective reaction of different observers, or the reaction of the same observer at different times (Kent and Porreta 1992). Instrumental measurements of color can be done using conventional colorimeters. In the last years, some simple computer vision systems (CVS) have been used to measure objectively the color of foods since they provide some obvious advantages over a conventional colorimeter, namely, the possibility analyzing the whole surface of the product, and quantifying local characteristics (e.g. defects).

Many studies have been conducted on the color changes of potato products during thermal processing (**Table 3**). Modeling of color changes may be useful in monitoring the quality of the final product. Kineticists usually measured color changes focusing on surface color as consumers evaluate color quality of food practically from the surface color and inner color change tends to follow surface color.

Pedreschi *et al.* (2007b) studied the development of color formation of pre-dried potato chips. Color measurement were done by using of CVS, quantifying representatively and precisely the color of complex surfaces such as those of potato chips in L*a*b* units from RGB images. Color values in L*a*b* units were recorded at different sampling times during frying using the total color difference parameter (ΔE) between raw (L^*_0, a^*_0, b^*_0) and fried potato slices (L*, a*, b*), which was defined as:

$$\Delta E = \sqrt{\left(L^*_0 - L^*\right)^2 + \left(a^*_0 - a^*\right)^2 + \left(b^*_0 - b^*\right)^2} \quad (1)$$

They reported that luminosity (L*) diminished with frying time for pre-dried potato samples since some parts of slice surface tend to get darker as a result of non-enzymatic browning during frying, and the luminosity decreased more as the frying temperature increased. In addition, the chromatic parameteras a* and b* increased considerably during frying and with frying temperature due to browning reactions that takes place during process. In turn, potato slices tend to get darker as frying proceeds as indicating by the progressive linear increasing of ΔE values with frying time.

On the other hand, Krokida *et al.* (2001a) tested different methods of drying (conventional, vacuum, microwave, freeze and osmotic drying) to analize the color changes during thermal processing of potatoes. Colour characteristics were studied by measuring lightness (L*), redness (a*) and yellowness (b*) using a Hunter Lab chromatometer. They determined that the method used to dry the product affected significantly the three colour parameters. Air-, vacuum- and microwave-dried caused extensive browning in the potatoes, which was manifested by a significant drop of the L* parameter and an increase of the a* and b* parameters. Osmotically pretreated samples did not brown as much as the untreated samples and the value for lightness (L*) decreased only slightly while a* and b* increased slightly. Freeze drying seems to prevent colour changes, resulting in products with improved colour characteristics. Thus, properties such as color, among others, of dehydrated materials can be affected by the drying method.

Texture

Texture is a sensory perception, which means that only humans can perceive, describe and quantify it. It is generally described as a multi-parameter attribute, usually associated with mechanical, geometrical and acoustic parameters (Szczesniak 1987). The accepted definition of texture was proposed by Szczesniak (1963), where texture is the sensory and functional manifestation of the structural and mechanical properties of foods, detected through the senses of vision, hearing, touch, and kinesthetic.

Texture is defined by the structural properties of food (Aguilera and Stanley 1999). Interactions between perceived texture and physical structure are complex, particularly for fruits and vegetables. In both cases, the cellular structure is the primary influence on texture and plant cell walls are mainly responsible for the visco-elastic behaviour of foods. In products with relatively high content of starch, such as potatoes, the major influence on texture could be related to the gelatinization of starch during heating (Jarvis and Duncan 1992a). In turn, the removal of moisture during thermal processing of potato products has detrimental effects on the physical attributes of the material, which can be measured by textural properties of the material.

Textural or rheological properties may be defined as those having to do with the behavior of the material under applied forces. Following this broad definition, such properties as stress-strain behavior of a material under static and dynamic loading as well as flow characteristics of a material can be classified as textural or rheological properties. The texture of potatoes thermally treated is often described in terms of mealiness, waxiness, sloughing, and firmness. Sloughing and firmness can be masured by objective measurements, while mealiness/waxiness has to be measured by subjective tests (sensory panel) (Andersson *et al.* 1994).

Firmness, compressibility, shear, elasticity, adhesiveness, cohesiveness, chewiness, gumminess, or combinations of these are some of the physical characteristics that can be quantified by objective tests. Instrumental analysis can be used to imitate the human masticatory process or to measure some fundamental mechanical properties of the food. In this way, have been developed instruments such as texturometers, designed to simulate mastication by means of a mechanical chewing device (Andersson *et al.* 1994).

Many studies in the field of food science have been carried out to assess different textural properties of potato products (see **Table 3**). For example, Singh *et al.* (2005) studied the cooking and textural characteristics of tubers from different potato cultivars using sensory analysis and Instron universal testing machine. They found that potatoes tubers with lower mealiness scores, amylose content, loosely packed cell arrangement, and with comparatively larger cells, showed lower hardness, cohesiveness, springiness,

chewiness, gumminess and longer cooking time. On the other hand, Nourian and Ramaswamy (2003) measured the hardness, stiffness, and firmness of fried cylindrical potatoes using compression test. The maximum force decreased more than 80% during the first 5 min of frying (160-190°C). The minimum frying time of potato was 282 s to decrease about 95% of the initial maximum force. Higher oil temperature produced the faster changes of hardness, stiffness, and firmness.

Moyano *et al.* (2007) studied the texture kinetics of potato products during thermal processing, using a texturometer to determine the maximum breaking force (F_{max}). The kinetics of textural changes in French fries during frying at 160, 170, and 180°C was studied using the dimensionless maximum force F^*_{max}, described by:

$$F^*_{max} = \frac{F_{max\ at\ t}}{F_{max\ at\ t=0}} \quad (2)$$

which allowed studying not only the softening of the tissue during the first period of the frying ($t \leq 80$ s) but also the crust development for longer times ($t > 80$ s). In adittion, they studied the textural changes during frying of potato chips at 120, 150, and 180°C, where frying processes were faster and the change from softening to hardening was very sharp, with respect to the frying of potato strips. This fact was explained by the dimensions of the chips that produce a higher heat transfer determining faster tissue textural changes.

Volume and density

During thermal processing the volume of a product expands or shrinks, depending of processing conditions and structural characteristics of the product. There are two types of density, bulk density and true density. Bulk density or apparent density is defined as the mass of the material divided by its apparent volume (including pores). Bulk density is important for the processing of snack, granular products, and powder products. Basically, foods are considered as porous media. Without pores, the density is called true density, solid density or particle density. These properties should be concerned especially for structural quality, packaging and production yield. Determining kinetics of the volume/density change is also important for mathematical modeling and computer simulation of the food processing. The experimental data of volume/density changes on potato products are provided in **Table 3**.

Wang and Brennan (1995) determined bulk density of air-dried potato products by toluene displacement. They reported that in the early stage of drying the density increased as the moisture content decreased, reaching a peak and then decreased with further decrease in moisture content. The density at a given moisture content decreased with increasing drying temperature. This was supported by microscopic observations. When potato was dried at the highest air temperature, the outer layers of the material become rigid and their final volume was fixed early in the drying. As a result, there was a lower density at high temperature than that at low temperature for a given moisture content.

Physical and chemical changes take place during drying affect the quality of the dehydrated product, and by a simple addition of water (rehydration) the properties of the raw material cannot be restored. It has been shown that the volume changes (swelling) of biological materials are often proportional to the amount of absorbed water (Steffe and Singh 1980). It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption. During drying, irreversible cellular rupture and dislocation, resulting in loss of integrity and, hence, a dense structure of collapsed, greatly shrunken capillaries with reduced hydrophilic properties, as reflected by the inability to imbibe sufficient water to rehydrate fully is observed (Jayaraman *et al.* 1990). The ability of food products to reconstitute in piece form, such as sliced or diced vegetables, primarily depends on the internal structure of the dried pieces and the extent to which the water-holding components (e.g. proteins and starch) have been damaged during drying (Brennan *et al*. 1990).

Krokida and Philippopoulos (2005) have established that the true density of dehydrated and rehydrated food was a function of water content and type of solid. They reported that the true density is not affected by the drying method and it is the same during dehydration and rehydration for the same moisture content. This means that only material moisture content affected true density. Thus, as water was removed during dehydration, true density reached the value of the dry solid density, while as water was gained during rehydration, true density decreased again following the same route. On the other hand, they determined that the apparent density of potato, for different drying methods, increased and decreased with moisture content, depending on the drying method. In addition, apparent density was significantly lower during rehydration than during dehydration, for all the drying methods.

In turn, Krokida *et al.* (2000b) determined bulk density, true density and specific volume by measurements of true volume and total volume of fried potatoes. True volume was determined by a stereopycnometer using helium for pressure measurement, and total volume was obtained by immersing the samples in *n*-heptane and determining the volume displacement. All the examined structural properties were greatly affected by oil temperature, sample thickness and oil type. Apparent density and specific volume decreased during frying, while true density and porosity increased.

Shrinkage and porosity

Shrinkage of biological materials during thermal processing takes place simultaneously with moisture diffusion and thus may affect the moisture removal rate. Hence, a study of the shrinkage phenomena is of importance for better understanding of thermal processing. Loss of water during a drying process originates a reduction in the size of the cellular tissue, which is usually referred as shrinkage phenomenon. The shrinkage could be very intensive, depending of the drying method applied and drying conditions. Shrinkage affects mass and heat transfer parameters and it is a relevant factor to be accounted for establishing drying models (Ramos *et al.* 2003).

Taiwo and Baik (2007) studied the effects of various pre-treatments (blanching, freezing, air drying, osmotic dehydration and control) on the shrinkage of fried sweet potatoes. They determined that the control samples exhibited less shrinkage than pre-treated samples. Maximum change in diameter of samples ranged between 6.7 and 10.2% depending on pre-treatment and the maximum change in sample thickness was observed by 120 s of frying and the highest value was 18.3%. In turn, Wang and Brennan (1995) reported that the degree of shrinkage of potato during low-temperature drying is greater that at high-temperature drying. In adittion, they indicated that the shrinkage also affected the physical properties of materials, such as density and porosity. Thus, relating microscopic with macroscopic shrinkage, and generally, microstructure with physical properties, is an interesting field of research.

In turn, porosity is a physical property that characterizes the overall open structure of a material (Krokida and Philippopoulos 2005). Porosity is defined as the ratio between volume of pores and the total volume of the product (Lewis 1990).

During drying, the product porosity increases as the water and volatiles are removed. However, Krokida and Maroulis (1997) stated that the porosity of the final product could be controlled, if an appropriate drying method is chosen. Air-dried products have low porosity when compared to freeze, microwave and vacuum drying. Likewise, porosity is directly dependent on initial water content, com-

position and volume (Krokida *et al*. 1997).

Besides porosity, pore size and pore size distribution of a food are important structural characteristics. In some researches the porosity has been divided between total and open pore porosity. Total porosity includes pores connected to the outside and locked-in or closed pores, and open pore porosity accounts just for externally connected pores (Lozano *et al*. 1980).

Thus, evaluation of the physical properties of food is necessary to understand structure-property relationships and their effects on chemical stability, physical properties and bioavailability of potato products, improving the quality of existing foods and to create new products that satisfy consumer's demands of healthy foods.

EFFECT OF MICROSTRUCTURE ON BIOAVAILABILITY OF POTATO STARCH

The food microstructure affects the glycemic response of potato products, and this glycemic response can be considered a reflex of the nutritive effect of the food. Commonly, the postprandial blood glucose concentration (i.e. the concentration of glucose in the blood after ingestion), also called glycemic response, is a way to know the bioavailability of starch and the nutritive effect of starchy foods. In this way, the effect of microstructure can be treated in two principal areas: the degree of gelatinization of starch, and the effect of the food matrix (non starchy). These microstructural factors change from a food to another, therefore changing the digestibility of starch, and thus the glycemic response (Fernandes *et al.* 2005). For example, there has been showed that after the ingestion of different foods with equivalent energy or carbohydrate content, healthy subjects can show different glycemic responses (see **Table 4**) (Najjar *et al*. 2004; Fernandes *et al.* 2005; Tahvonene *et al*. 2006; Leeman *et al.* 2008). Also, potatoes and other moist-heated starchy foods are incompletely digested when they are cooled because of the retrogradation of the dispersed starch molecules, hence cooling may lead to resistance to enzyme hydrolysis (Najjar *et al*. 2004; Tahvonene *et al*. 2006).

Starch within potato

Potatoes are an important source of energy, which is in carbohydrate form, mainly constituted by starch. Starch is the main carbohydrate derived from foods around the world (Karamanlis *et al.* 2007). Starch is a complex carbohydrate formed by monomers of glucose linked by digestible glycoside bonds. Glucose units form two chain types, amylose (lineal structure) and amylopectin (branched structure), and those structures form the granule of starch (Lisińska and Leszczyński 1989). Upon heating, in the presence of water starch granules swell and partly disintegrate, facilitating the action of degrading enzymes that transform them progressively to maltose and glucose.

Starch digestion: from starch to glucose

In humans there are several enzymes that hydrolyze starch. In the mouth, saliva contains α-amylase, enzyme that hydrolyses accessible starch, but since this starch remains in the mouth for a short period, the level of digestion is rather small. Once the food is partly digested in the mouth it is transported to the stomach, where there is no starch digestion, but breakdown of food matrix will facilitate the access of hydrolytic enzymes to active sites for starch degradation in the small intestine (Riccardi *et al.* 2003). In the small intestine, the food receives pancreatic juice that contains pancreatic α-amylase, which hydrolyzes glycoside bonds, producing glucose, oligosaccharides and dextrins (Tester *et al.* 2004).

The main characteristic of starch, compared with simple carbohydrates, is its slow digestion in the small intestine, producing moderated glycemic responses. Food microstructure affects the kinetics of starch hydrolysis, thus, the glycemic response of starchy products, which can be considered a reflection of the final nutritive effect of the food (Parada and Aguilera 2007). **Fig. 4** shows a scheme of the main food properties related to glucose bioavailability and changes occurring during food processing and digestion.

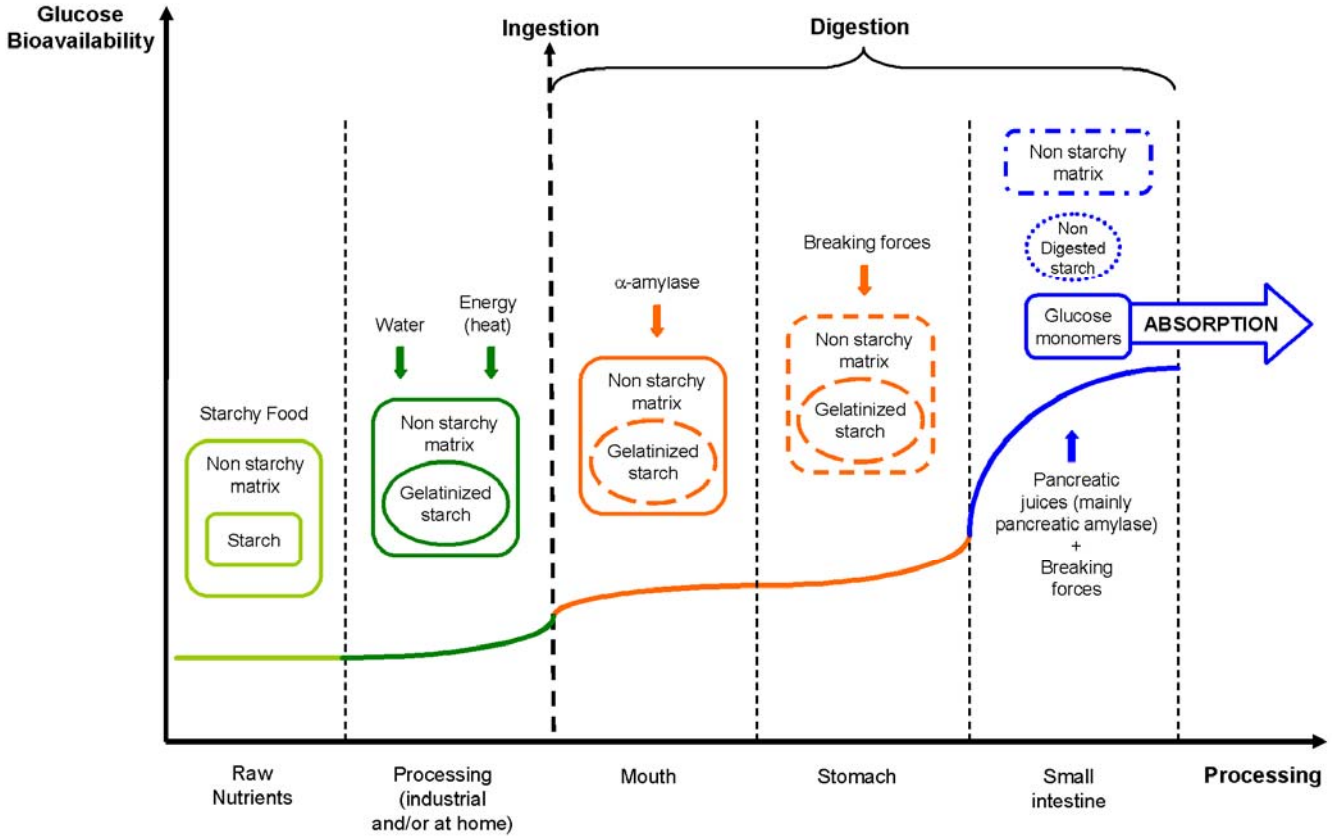

Fig. 4 Microstructural aspects that affect the bioavailability of glucose derived from starchy foods.

Microstructural factors that affect the bioavailability of starch

Bioavailability of starch involves the release of glucose monomers from starch granules during the digestive process and their use or storing in the body. The glycemic response after food ingestion is not the same for different foods with the same amount of starch (Englyst and Englyst 2005; Leeman *et al.* 2008). Different factors, as the physiological health of the person, and principally, food processing affect this response (**Table 4**). For more than a decade it has been suggested that starch gelatinization affects the glycemic response (Grandfelt *et al.* 1995). Riccardi *et al.* (2003) found that spaghetti and potato dumplings, because of their lower blood glucose response than white bread, represent a valid alternative to other starchy foods typical of the Mediterranean diet. Also, it has been shown that food microstructure affects the release of glucose (among other nutrients) in the small intestine, so affecting the glycemic response (Parada and Aguilera 2007). The main microstructural aspects of starchy products that affect its digestibility are listed below:

***Degree of starch gelatinization*:** When granules of starch are heated in water above a critical temperature (known as the gelatinization temperature, around 60-65°C), the crystalline structure of the matrix is broken down and the granules swell; this process is called gelatinization. A gelatinized granule is more digestible than a raw granule because the digestive enzymes can attack more easily the active sites, which are then exposed (the interchain structure is opened). The total amount of starch is the principal factor affected by the gelatinization process. In fully isolated amylose or amylopectin molecules the digestion rate would be basically the same and occur relatively fast (in general, less than 10 min). The change in the total amount of digestible starch in a food can be explained because in most foods starch is present as a combination of raw or partly gelatinized granules (more resistant to digestion) and gelatinized granules (more digestible) (Karlsson and Eliasson 2003). After ingestion, starch is digested in the mouth (a small fraction) and in the small intestine (mainly); during this process starch does not change further in degree of gelatinization, only in the amount broken down due to digestion (Chung *et al.* 2006).

***Non starch food matrix*:** Starch granules in a real food are not isolated but exist within a three-dimensional matrix structure formed by different components, which affects both the degree of gelatinization and the digestion of starch (Giacco *et al.* 2001). If a food matrix is relatively resistant to enzymes and the granules are not properly exposed to their action, the digestion could be limited. If the intestinal content is more viscous, the enzymatic transit is slower as well as the release of glucose from starch; in addition, if a non-starchy food matrix surrounds the gelatinized starch granules, the digestive enzymes can not access them and starch is not digested (Goñi *et al.* 2000). Nevertheless, the first point to resolve is the digestibility of starch granules depending on their gelatinization index, and then study the effect of the matrix, which is a much more complex subject (e.g. there are infinite possible matrices).

In summary, food microstructure affects the nutritive value of starchy products. The primary effect is that of the degree of gelatinization of starch granules, which should be known and considered with the aim of achieving a better management of the nutritional characteristics of starchy products.

Table 4 Effect of processing on glycemic response of potato products.

Meal	AUC[1] (mmol/ L min)	Reference
French fries	69.0[2] ± 12	Leeman *et al*. 2008[3]
Boiled potatoes	192 ± 28	
Mashed potatoes (small)	211 ± 30	
Mashed potatoes (large)	167 ± 19	
Microwave baked potatoes	178 ± 25	Fernandes *et al*. 2005[4]
Instant mashed potatoes	206 ± 23	
Boiled potatoes served hot	208 ± 20	
Boiled potatoes served cold	135 ± 18	
Steam cooked potatoes served hot	92 ± 26	Tahvonen *et al*. 2006[4]
Sliced boiled potatoes served hot	95 ± 22	
Sliced boiled potatoes cooled and served hot	74 ± 28	
Steam cooked potatoes, freezing, thawing and served hot	96 ± 28	

[1] AUC: area under the postprandial curve of blood glucose concentration
[2] Mean value ± standard deviation
[3] Energy equivalent meals (1000 kJ) and AUC were calculated from 0 min to 180 min
[4] Carbohydrate equivalent meals (50 g) and AUC were calculated from 0 min to 120 min

CONCLUSIONS

Foods are unique among materials of our daily life in sense that they are ingested and become part of our body. This immediately adds several extra dimensions to their intrinsic properties: foods have to be appealing, tasty, nutritious and safe. Understanding the microstructural changes of raw potato during processing is critical if food properties want to be controlled properly, because there is a causal connection between structure and functionality, which is central to product engineering. The search for relations between the structure and physical properties of foods started only in the 1990s. Evidence is now accumulating that structure does play a key role in controlling many others attributes important in foods beyond their basic physical or engineering properties. For example, structure is critical in texture perception and the bioavailability of some nutrients. Establishing structural changes occurring during transformation processes involved in consumption and digestion of a food will remain a further challenge in the near future. Nowadays, increasing the evidence of links between diet and some nontransmissible diseases (obesity, cardiovascular diseases, and some cancers) has opened new opportunities to tailor-made products with reduced caloric content or increased levels of beneficial nutrients that may help prevent or ameliorate the effects of these diseases.

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