Role of the Waxy Skin Layer in Moisture Loss during Dehydration of Prunes

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Permeability studies of water through the skin and flesh of d'Agen plums have been carried out by radiotracer and PGSE NMR techniques as a function of moisture content. The results have shown that the diffusion coefficient of water through the skin layer increases as the fruit is dried at 70 °C or above. By contrast, the water diffusion through the fruit becomes more hindered as moisture is lost and structural collapse of the cell layers takes place. Values for diffusion coefficients of water at 21 °C through the fruit of 1×10^{-9} m^2 s^{-1} for fresh plums and 2.0×10^{-10} m^2 s^{-1} for fruit dried to 50% moisture content (wet basis) were found. Structural studies using scanning electron microscopy techniques were also performed. These showed that drying induces marked changes to the waxy skin layer of the fruit as well as the fruit flesh. These results are discussed in terms of the important role that the plum skin has in modulating the moisture loss process during dehydration, particularly at early stages of drying.

Keywords: *Dehydration; prunes; waxy skin layer; microscopy*

INTRODUCTION

Dehydration is an important postharvest operation for a number of fruit. Dried fruit have many advantages including extended shelf life, due to low water activity, and reduced transportation costs. Some fruit are generally dried in the sun while dehydration tunnels are utilized for others, particularly stone and tree fruit. For example, d'Ente and d'Agen varieties of plum (*Prunus domestica*) are grown mainly for the production of dried prunes. The energy costs expended during the drying process account for a major portion of the total production costs.

Thermal drying involves mass transfer of moisture by diffusion through the food matrix to the evaporation surface and evaporation from the fruit surface. Evaporation of moisture from the product surface is usually influenced by process parameters including temperature, humidity, and velocity of the drying air. Transfer of water vapor from the fruit surface will also depend on the thickness and resistance of the boundary layer surrounding the fruit. Water movement (volume flux density) within the food matrix is determined by the gradient of water activity and the hydraulic conductances/resistances of the water pathway that are dependent on the characteristics of the product. (Perry et al., 1984).

In previous work (Newman et al., 1996; Sabarez and Price, 1996; Price et al., 1997; Sabarez et al., 1997; Wilford et al., 1997), it was found that mass transfer of water through the fruit matrix was the rate-limiting factor for the majority of the drying period. This was particularly true at high drying temperatures such as 80 °C. This could be rationalized thus: the major resistances are situated across the cuticle and boundary layer at ambient temperatures and therefore these will be the major rate-limiting resistances. However, at 80 °C the vapor pressure deficit across the cuticle−boundary layer will increase water flux that in turn will increase the water potential difference across the flesh as mass transfer of water increases. It was therefore found that at lower drying temperatures such as 60 or 70 °C an initial period of drying was present where the rate is controlled by the evaporation rate of moisture transfer from the surface of the fruit, resulting in a constant rate period of drying.

A constant rate of drying signifies a process mainly controlled by the external resistance to moisture transfer—the driving force being the vapor pressure deficit between the turbulent air and the evaporation surface and the major resistance being the boundary layer. Initially the supply of moisture from the interior to the fruit surface may be adequate for surface evaporation, but the rate may be much lower compared to the maximum evaporation potential of free water. In a previous paper (Sabarez and Price, 1999), it was shown that the initial rate of drying at 70 °C of plums that had their skin removed was over 5 times that for plums with skin intact. This leads one to ask the question as to the importance of the waxy skin layer of a plum in modulating the transfer of moisture to the surface. This is of particular significance as there are several possible ways of pretreating the fruit prior to drying. For example, grapes are often sprayed with an emulsion of fatty acid esters in an aqueous matrix before drying in the sun. This has the effect of increasing the drying rate substantially, by disrupting the skin layer of the grape (Uhlig, 1993).

The aim of this paper is to investigate further the role the waxy skin of the prune plays in the moisture loss process by studying the water permeability of the skin

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and fruit flesh as a function of drying and drying conditions. The results are correlated with changes in the structure of the waxy skin and the fruit as observed by scanning electron microscopy (SEM).

EXPERIMENTAL PROCEDURES

Materials. Fresh d'Agen plums for drying studies were obtained from the Young district of New South Wales, Australia. The fruit were sorted according to size to obtain an approximately homogeneous sample. Plums weighing between 10 and 20 g, which represented the average size, were used. Samples were kept in sealed plastic bags purged with nitrogen. These were then stored in a refrigerator at 4 (± 1) °C prior to the drying experiments. Fresh d'Agen plums for observation by SEM were collected from a commercial orchard near Loxton in South Australia, Australia. The plums were stored at 4 (± 1) °C.

Experimental Dehydration System. An automated laboratory drier was used to dry the fruit in preparation for the permeability and SEM studies. This system, previously described (Sabarez and Price, 1996), allows online monitoring and data logging of sample mass and the experimental conditions during dehydration. The air flow was laminar and the velocity was 1 ± 0.25 m s^{-1} and the relative humidity (RH %) was 3% ± 2%. The mass loss was determined to an accuracy of better than ± 0.05%. Drying took place at a range of temperatures (40−90 °C) and was controlled to better than ±0.5 °C. Prior to each drying run, the samples were washed with water and allowed to equilibrate under room conditions. The fruit, 800−1000 g (about 50 fresh plums), was uniformly spread on a steel mesh in a single layer and loaded into the drying chamber after the desired drying conditions had stabilized.

Measurement of Fruit Temperature Profiles during Drying. The fruit surface and center temperatures were monitored with two iron−constantan thermocouples of 0.5 mm diameter inserted into the sample, one into the flesh adjacent to the stone and the other as close to the fruit surface as possible without exposing the thermocouple. The cold junction used was ice (0 °C) and the resultant potential difference was measured with a six-figure digital multimeter (Hewlett-Packard 3468 A) and converted to temperature by use of standard tables. The estimated deviation of measurement of fruit temperature, based on two replicates, ranged from 0.1 to 1.5 °C.

Determination of Water Permeability of Skin by Use of Tritiated Water. Fresh plums were dried by use of the experimental setup described above. A plum sample was cut into halves along the longitudinal axis in order to obtain maximum surface area. The pulp was then manually scraped and removed from the waxy skin layer. The thickness of the skin layer was determined with a hand-held micrometer. The average thickness of the excised plum skin was found to be 0.53 (± 0.01) mm.

A custom-made diffusion cell was used for the skin permeability experiments. It consisted of two compartments separated by a membrane (in this case a plum skin). One side of the cell was used as the compartment for the source solution where the tracer was introduced. The other side acted as the compartment where the concentration of the diffusing tracer was constantly monitored. The effective membrane surface area was about 3.14 cm^2. The compartments were made of cylindrical glass mounted into a Teflon block and clamped together with four screws. The skin sample held between the two blocks was positioned in such a way that its waxy surface was facing toward the receiver side of the cell to emulate the actual movement of moisture in plums during drying. The tightness between the two compartments was achieved without damaging the skin sample via a rubber O-ring. The diffusion cell was mounted on a magnetic stirrer unit and a magnetic stirring bar was placed on each side of the cell to provide thorough mixing. An open wire mesh was placed just before the skin sample on both sides to prevent damage due to the rotating action of the stirring bar. The permeability measurements were carried out at ambient temperature, 21 °C, because of the difficulties of trying to perform them at elevated temperatures.

Prior to each experiment, both sides of the cell were filled with Milli-Q water (10 MΩ cm^{-1}) of about the same volume (15 mL) and allowed to equilibrate overnight. Radiolabeled water (^{3}HHO) tracer (20 μL) (equivalent to about 20 μCi) was then added into the source side of the cell. The radioactivity in the receiving solution was monitored by taking 50 μL samples at predetermined time intervals. Each sample was transferred into the vial containing 16 mL of scintillant. BCS scintillant and ^{3}HHO were obtained from Amersham Australia Ltd. The reproducibility was found to be about ±1%.

Four calibration solutions were prepared of different tracer concentrations. A 1 mL sample taken from a 100 mL aqueous solution containing 10 μL of tracer was added to 100, 250, 500, 1000 mL portions of Milli-Q water. Fifty microliters of sample from each solution was taken and filled into the sampling vials containing 16 mL of BCS scintillant and were analyzed. These calibrations confirmed a linear response with scintillant counts over the entire range of tracer concentrations used.

Diffusion of Water Measurements in Plum Flesh by Spin−Echo NMR Methods. Thin sections of plum flesh, both fresh and partially dried, were placed in thin-walled glass tubes with Teflon stoppers. For each moisture content, three plums were examined by use of cubic sections 8 mm^3 cut from both the superficial and central part of the fruit flesh. No significant difference in diffusion coefficient was found between the two regions. The diffusion coefficient of water in the samples was measured at room temperature (21 °C) by standard spin−echo NMR techniques with either a Hahn spin−echo or a stimulated spin−echo pulse sequence (Price and Lüdemann, 1997). The magnetic gradients were produced by a custom-made generator and the time delay between gradients was varied up to 100 ms. Measurements were carried out on a Unity 300 MHz NMR spectrometer.

Scanning Electron Microscopy. Fully hydrated frozen skin samples were examined in a Philips 500 scanning electron microscope as described by Storey and Price (1999). To examine the surface structure of plum skin epicuticular wax, skin samples were attached to aluminum stubs with conductive carbon cement, frozen in liquid nitrogen and transferred to a Balzers SCU 102 preparation chamber and sputter-coated with gold prior to examination in the SEM. Freeze fractures were prepared in the Balzers chamber, lightly etched, and sputter-coated with gold.

RESULTS AND DISCUSSION

The resistance to the transfer of water across the skin will depend on the hydraulic conductance of the cell layers that make up the skin, the water permeability of the cuticle, and the degree of disruption of the cell and cuticular membranes by thermal heating during drying. Like most fruits, the epicuticular wax layer of the cuticle of d'Agen plum is well developed and is more than 5 μm thick (Storey and Price, 1999) and therefore confers high resistance to water movement across the cuticle. There is some ambiguity in the literature about the mode of cuticular transpiration. Nobel (1991) suggests that transfer of water probably involves liquid water as well as water vapor movement whereas Kerstiens (1996) considers that cuticles act as solution-diffusion membranes. Elevated temperatures during drying might increase the transport of water as vapor across the cuticle, change the diffusion properties of the cuticular waxes, and modify the boundary layer properties of the cuticle. A SEM study of d'Agen plum showed (Figure 1) that there is a clear phase transition from a crystalline form to a more amorphous phase occurring between 55 and 60 °C. At 55 °C there is some evidence

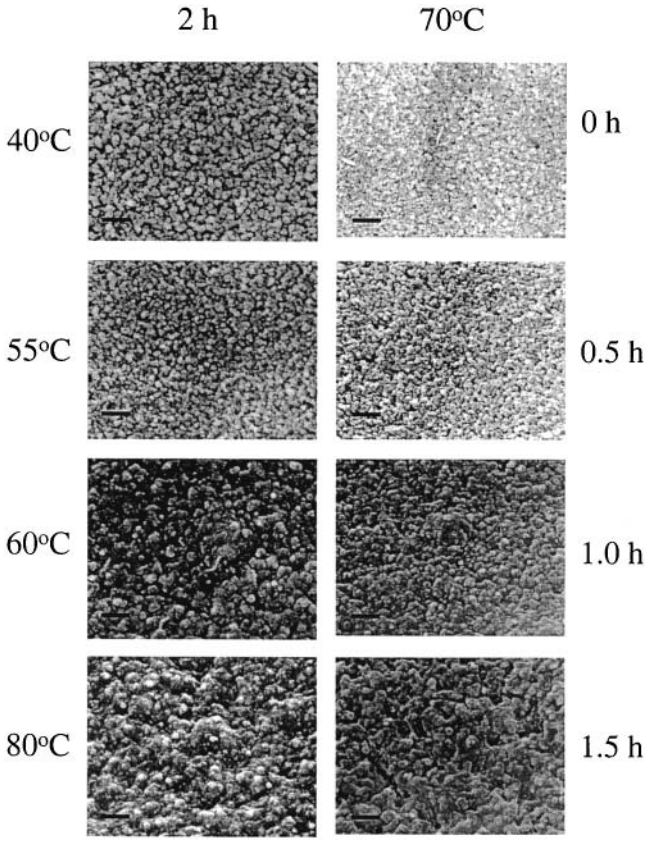

Figure 1. Effect of temperature (left) and time (right) on the crystalline structure of the epicuticular wax of d'Agen plum during drying (bar = 2.5 μm).

of thinning of the bloom after 4 h, but the transition is more rapid (2 h) and substantial at 60 °C. At 70 °C, which is approaching the conditions used commercially to dry prunes, the phase transition is most apparent between 0.5 and 1 h. This is consistent with the drying studies, where the constant drying period was confined to only the early part of drying, decreasing with both temperature and air-flow velocity. At 70 °C and 1 m s^{-1} air-flow, it was on the order of 1 h. (Sabarez and Price, 1999; Sabarez et al., 1997). McBean and co-workers (McBean et al., 1966; Bain and McBean, 1967, 1969; McBean, 1976) studied the prune wax coating on the skin and concluded that it does not melt or become disrupted as a whole until about 65 °C. An interpretation of these results is not conclusive, but the phase change of the cuticle wax might be expected to change the solution-diffusion properties of the cuticle. Also, the protruding crystalline granules of the outer epicuticular wax layer (Storey and Price, 1999) would create a substantial boundary layer to the movement of water vapor from the site of evaporation to the turbulent drying air. The melting of the wax is likely to substantially reduce the thickness of the boundary layer. The resistances across the cuticle and boundary layer are likely to be large in fresh fruit and any modulation of their conductance will probably increase water transfer.

The temperature of the surface of the fruit was measured in order to ascertain what temperature the fruit skin attained during drying. The surface temperature of the plum increased quite rapidly in the first 30 min of drying to about 5−8 °C below the set drying air temperature, as shown in Figure 2. After this the temperature changed much more slowly. For example, at 70 °C, the surface temperature of the fruit rapidly

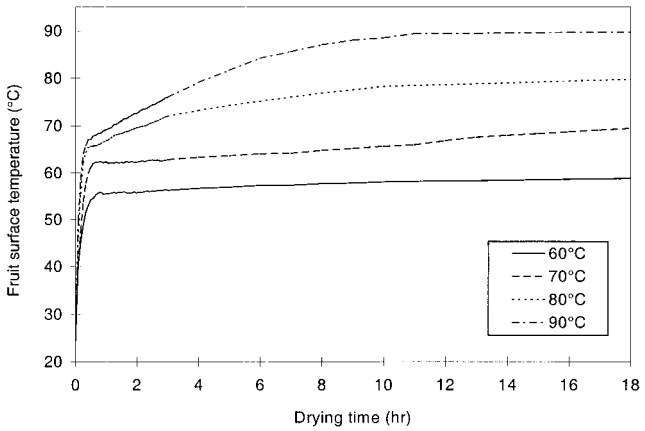

Figure 2. Surface temperature profile of plums during drying at various air temperatures (RH = 3%; V = 1 m s^{-1}).

Table 1. Effect of Drying on Water Permeability of Plum Skin at 21 °C by Radiolabeled Water

drying time (h)	0	1	2	3	4	5
relative permeability of water[a]	1.0	1.0	1.1	1.9	2.6	3.0

[a] Calculated as rate of passage of labeled water through partially dried skin relative to that for the fresh sample. Uncertainty in values estimated to be 5% or better. [b] Drying method used: 70 °C at RH = 3% and air velocity of 5 m s^{-1}.

reached a temperature of about 63 °C. At 60 °C drying, the fruit surface temperature only reached about 55 °C and then maintained this level throughout the 18-h drying period, with no further significant increases observed. There is, though, a marked difference in the drying rate and total drying time to 20% moisture between 60 and 70 °C, (Sabarez et al., 1997). In particular, the initial drying rate was found to be over 3 times higher at 70 °C and the total drying time was 1200 min compared with 2800 min at 60 °C. The results are consistent with modulation of the diffusion properties of the cuticle and a decrease in the boundary layer formed by the protruding granular crystalline layer of the epicuticular wax layer. It implies that the phase transition of the waxy layer at higher temperatures may be partly responsible for the increased drying rates. However, as previously highlighted, other influences are present, such as the vapor pressure deficit between the drying air and the fruit that increases with drying temperature. Thus, to substantiate whether changes in the waxy skin layer are important in controlling the rate of moisture loss, an investigation of the permeability of water in both the skin and flesh was carried out.

Permeability measurements of the skin indicated that drying of plums at 70 °C for up to 2 h resulted in insignificant alteration in the skin permeability relative to the fresh plum sample (Table 1). On further drying for 3−5 h, there was substantial increase in the skin permeability. However, it was not possible to continue the experiments beyond 5 h because of the difficulty associated in extracting an intact skin sample. The change in skin permeability after thermal heating at 70 °C for more than 2 h was consistent with the time dependency of the phase change in the epicuticular wax layer. Further, during the initial heating period the plum surface temperature was ca. 7 °C below ambient temperature (Figure 2) and only increased toward the set temperature when skin permeability increased (Table 1).

SEM studies also showed that after 2 h at relatively high drying temperatures of 70 and 80 °C, three

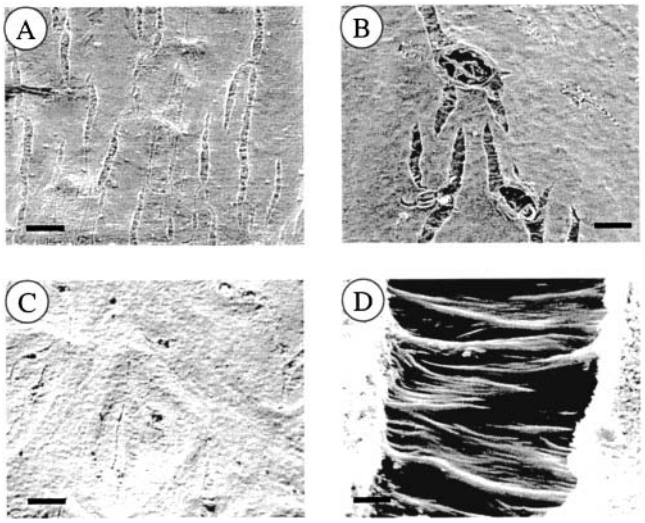

Figure 3. Surface views of skin fractures of d'Agen plum formed during drying. (A) Parallel fractures orientated along the polar axis of the fruit (bar = 320 μm). (B) Large irregular fractures initiated in the area of the stomatal pore (bar = 80 μm). (C) Backscattered image of collapsed dermal cell around stomatal pores with radiating fractures of the cuticular membrane (bar = 160 μm). (D) Parallel fracture showing splitting of the epicuticular wax layer and exposure of the cuticular layer + cuticle proper (bar = 5 μm).

morphologically distinct regions of the skin were present. First, there were areas where the skin was smooth containing no fractures and stomata. Second, there were regions where parallel fractures formed along the long axis of the fruit with a striated appearance (Figure 3A). These formed as the fruit swelled initially during heating. Third, there were portions of the skin where radial fractures were present. These tended to be initiated around stoma (Figure 3B) and caused the skin to take on a stippled appearance. We frequently found catastrophic rupturing of the cuticle around the stomatal pore (Figure 3B). This had the effect of causing collapse of dermal cell layers adjacent to and below the pore (Figure 3C). From the micrographs it would appear that most of the fractures were relatively superficial and the thick epicuticular wax layer was ruptured (Figure 3D). The formation of many fractures through the epicuticular/cuticle layer is likely to lead to large increases in skin permeability. This interpretation is partly corroborated by our observation of dehydration and collapse of cells around fractures radiating out from stomatal pores (Figure 3C). The rupture of the cuticle is likely to decrease resistance to water transfer significantly. For example, the extraction of the soluble lipids from cuticles of citrus leaves, pear leaves, and onion bulb scales was reported to increase permeability to water by 300−500 times (Schonherr, 1976).

Freeze fractures of drying d'Agen plum (Figure 4A) confirmed that the fractures in the skin occurring after 4 h of drying at 80 °C were relatively superficial. Figure 4B shows a section of a plum dried at 55 °C for 4 h. Here the dermal cells appear to have remained intact. This is contrasted by Figure 5C, where drying at 80 °C for 2 h has caused substantial collapse of the dermal layer. This collapsed layer is likely to increase the resistance of the skin to water loss. Also at 80 °C the cell walls of the parenchymatous cells of the fruit flesh show marked changes after only 1 h of drying (Figure 4D). The observed changes to cell walls are difficult to interpret but may represent some kind of gelling or

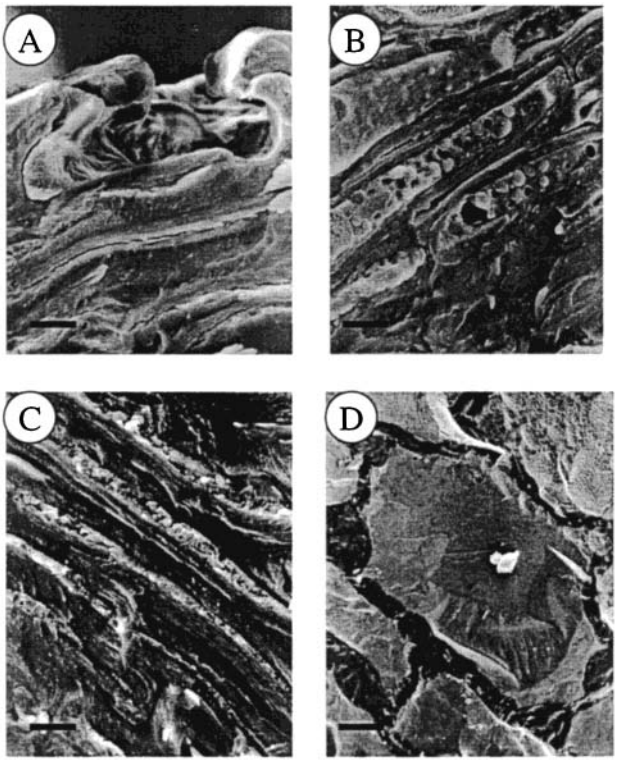

Figure 4. Transverse freeze fractures of partially dried d'Agen plum. (A) Superficial fracture of the skin after a drying treatment of 80 °C for 4 h (bar = 10 μm). (B) Intact dermal cell layers after a drying treatment of 55 °C for 4 h (bar = 10 μm). (C) Collapsed dermal cell layers after a drying treatment of 80 °C for 2 h (bar = 10 μm). (D) Parenchymatous cells of the flesh after a drying treatment of 80 °C for 1 h (bar = 40 μm).

swelling process and could possibly modulate both the pathway of water movement and the hydraulic conductance of the flesh. Figure 4D also seems to confirm that after drying at 80 °C for 1 h cell membranes no longer function as semipermeable membranes regulating water and solute flow.

The above discussion is consistent with suggestions that for fruits having waxy coatings on the skin surface (i.e., apples, grapes, plums, etc.) the skin layer is resistant to the passage of water or water vapor and represents a significant barrier to water transfer from the fruit to the drying air. This has been hypothesized in the studies of several authors (McBean et al., 1966; Bain and McBean, 1967; Ponting and McBean, 1970). The magnitude to which the rate-controlling properties of the skin affect the drying process seems to depend on the drying conditions. When all the free water is depleted, the diffusion rate-controlling mechanism within the flesh is assumed to dominate the drying process and the effect of skin layer becomes less significant. Aguilera and Stanley (1990) stated that as the moisture content decreases, the waxy cuticle plays a smaller role as a rate-controlling factor of the drying process. In order for this to be true, drying must cause a very large decrease in the resistance of the cuticle. Vascular plants developed cuticles to protect against desiccation (Kerstiens, 1996); the low permeance of cuticles to water reduces water loss from plant cells such as those making up the flesh of fruits. To reach a point where the flesh is rate-limiting, the resistance of the flesh must increase substantially and the resistance of the cuticle must decrease substantially. This is consistent with our

Table 2. Diffusion Coefficients for Water at 21 °C in Sections of Skin and Flesh of Fresh and Partially Dried Plums by Tracer and NMR Techniques, Respectively

moisture content of plums (kg of H_2O/kg of dry matter)	2.3	1.6	1.1	0.65
10^9 $D(H_2O)_{flesh}$[a] (m^2 s^{-1})	1.0 (± 0.2)	0.8 (± 0.1)	0.41 (± 0.2)	0.22 (± 0.15)
10^9 $D(H_2O)_{skin}$[b] (m^2 s^{-1})	0.028	0.032	0.071	0.14

[a] Mean values of three determinations; uncertainties given as standard deviation. [b] Estimated from tracer experiments using application of Fick's law for a plane sheet.

results showing disruption of the cuticle leading to localized collapse of cells. On the other hand, the destruction of cell membranes and the matrix effect of gelling proteins and cell walls would tend to imbibe water and increase the resistance to water transfer in the flesh of fruits. The disruption of the cell-to-cell pathway of water transport in the flesh could also lead to an increase in resistance. Thus resistance to water movement in the flesh may increase because of a change in the pathway from intracellular to extracellular and the matrix effects of gelling proteins and cell wall components. It is therefore interesting to consider further the characteristics of water transport within the flesh, particularly in the light of the conclusions from Figure 6 about the collapse of dermal cells and the changes to the cell walls of the fruit flesh.

Table 2 shows the diffusion coefficient of water in the flesh of the plum as a function of moisture content at 21 °C measured by NMR spin−echo techniques. The results indicate high moisture mobility within the flesh of fresh plums (equivalent to a moisture content of about 2.23 kg of H_2O/kg of dry matter) compared to the dried plums (0.65 kg of H_2O/kg of dry matter). It shows that as plums were dried the hydraulic conductance of the flesh decreased. The diffusion coefficient of fresh plums was found to be about 1×10^{-9} m^2 s^{-1}. The self-diffusion coefficient (Mills, 1973) of water at 21 °C is 2.0×10^{-9} m^2 s^{-1}. Plums dried to a moisture content of around 50% (dry basis) were observed to have a diffusion coefficient of 2×10^{-10} m^2 s^{-1}. The diffusivities for plums compare well with work on other foodstuffs. Fukuoka (1994) estimated a water diffusion coefficient of 4.3×10^{-10} m^2 s^{-1} in a dry soybean seed with a moisture content of about 14% (dry basis). By use of NMR imaging, the D_{eff} values for potato during drying were found (Ruan 1991) to be $(1.04-7.28) \times 10^{-10}$ m^2 s^{-1} for moisture contents between 40% and 55% (wet basis) at 40 °C. In addition, Callaghan et al. (1979) measured water diffusion in wheat grains by pulsed field gradient NMR with a short diffusion time (<10 ms). They found the diffusion coefficient varied from 1.8×10^{-10} m^2 s^{-1} at 25% moisture content (dry basis) to 1.2×10^{-9} m^2 s^{-1} at 50% moisture content.

The present results show that water transfer mobility within the flesh of plums dried to 50% moisture content is about 5 times slower compared to that of fresh plums. The slower diffusion of water in the latter part of drying may be partly explained by a changed, more tortuous water path. This is consistent with the restrictions imposed by the collapse of cells and changes to cell walls in the fruit flesh, shown in the micrographs in Figure 5. It is also consistent with the observed initial rapid moisture loss during drying and the subsequent decreasing rate in the later stages.

In an attempt to elucidate the rate-controlling mechanism of moisture loss during drying, the mobility of water within the flesh and across the skin was compared. Permeability of water across the skin layer was estimated by use of the data in Table 1 and was expressed in terms of the diffusion coefficient (Crank, 1975) (Table 2). Comparisons between these values and those for the skin layer indicate significant differences in diffusivity of water in the two regions. It can be seen that the water diffusivity within the flesh is generally higher than at the skin layer. For fresh plums, it was found that the diffusion coefficient within the flesh was around 35 times higher compared to that at skin layer.

The results may be partly explained by the length of the diffusion path in which the water is diffusing. In NMR measurements, molecular diffusion may take place in a short time interval between the two gradient pulses. Depending on the length of time of observation, the average path distance in which a molecule travels during this period may be comparable to the size of the cells. Hence the moisture diffusion coefficient obtained from NMR measurements might correspond only to the movement of water molecules within the cell. It should be noted that water molecules might diffuse not only within the cell but also through cell walls, membranes, etc., in which the diffusivity may be different (Fukuoka, 1994). Usually, the boundaries of the cells would impose a greater barrier to water movement than within the cell.

It is also interesting to observe that as drying progresses, movement of water within the flesh is increasingly restricted while at the skin layer the restriction of water transport is decreasing. This results in a decreasing difference in water movement between the skin and the flesh in the later stages of drying. For example, for plums dried to a moisture content of about 0.65 kg of H_2O/kg of dry matter it was found that the skin diffusion coefficient was about 9.7×10^{-11} m^2 s^{-1} compared to around 2×10^{-10} m^2 s^{-1} for the flesh. Thus at the last stages of drying the mobility of water within the flesh becomes the important factor. The above results further suggest a significant role for the skin layer in the moisture loss process, particularly at the early stages of drying.

CONCLUSIONS

These results confirm that the skin of d'Agen plums plays a significant role in modulating the moisture loss process. In particular, the skin represents a very significant barrier to water transfer in the initial stages of the drying of plums. However, with disruption of the waxy layer and other surfaces changes during the first few hours of drying at 70 °C or above, the permeability of the skin increases. With concomitant decreases in the permeability of water through the flesh of the fruit, this contributes to the development of internal resistance quickly becoming the major controlling mechanism for moisture loss during the drying process. This is of significance to the dried fruits industry because pretreatments such as fatty-acid ester emulsions to disrupt the waxy skin layer have been tried for fruit such as

grapes (Uhlig, 1993) and plums (McBean, 1976). It has been successful in accelerating the drying of sultana grapes but is not adopted in prune drying. This is due to the higher temperatures used for the latter fruit. As shown here, although the skin is initially a significant barrier, because of the disruption of the structure of the waxy layer early in the drying (and the rapid depletion of water near the surface at elevated temperatures), use of a pretreatment to alter the wax prior to drying is unlikely to lead to a significant reduction in total drying time. However, with increased energy costs, dehydrators of plums should remember that at lower drying temperatures (40−60 °C) the skin will remain a significant barrier to water transfer during the whole drying process and thus pretreatment becomes a viable tool for enhancing the drying rate. The effect of pretreatments on drying rates and on the microstructure of the epicuticular wax is currently under further study.

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