

CHAPTER 6

DISCUSSION

The word “hardness” is often used loosely to describe the endosperm texture of cereal grains. In the following discussion, if the word “hard” is used to describe maize endosperm, it will refer to endosperm with a vitreous texture, like that of flint maize. In maize, hard endosperm is translucent, unlike wheat endosperm where it is possible to get hard endosperm that is opaque (Hoseney, 1994). If the word “soft” is used, it will refer to endosperm with a floury texture, like that of floury maize. The floury endosperm is opaque due to air holes that refract light. A maize cultivar will be classified as a hard cultivar if the mean percentage of translucent endosperm was high and similar to that of the hard standard. A soft maize cultivar was a cultivar with a low mean percentage of translucent endosperm and similar to that of the soft standard. Taking into consideration the fact that cultivar B had a significantly higher percentage translucency than A and that B was not significantly lower than C and D, A was classified as a soft cultivar, B, C, and D as intermediate and E and F as hard

The composition of the maize meal used in this study was typical (compared to literature values reported by Peterson & Johnson, 1979) and similar to the standard for commercial “Super” maize meal (South Africa, 1984) in terms of fat content and particle size distribution. The starch digestibility of highly refined maize meal and not unrefined maize meal was determined, because the popularity of highly refined maize meal seems to be increasing.

Unlike Björck and co-workers (Granfeldt & Björck, 1991; Granfeldt *et al.*, 1992; Liljeberg *et al.*, 1992; Liljeberg & Björck, 1994) who used volunteers to chew the samples, in this study the researcher did the chewing herself. There were two reasons for this decision; firstly that there were not enough trustworthy volunteers available on a regular basis to do the chewing and secondly that differences between the way that

people chew would be eliminated.

Based on personal experience and conversation with other people who eat porridge regularly, a stiff maize porridge sample containing 1 g of starch (about 5 g porridge) was chewed about five times in five seconds before being swallowed. A bread sample containing 1 g of starch weighed about 2.4 g. Using the same approach as with porridge, it was found that such a sample was chewed about seven times in seven seconds. Considering this, all porridge samples were chewed five times in five seconds and all bread samples seven times in seven seconds.

During digestion with α -amylase, the sample was inside a dialysis tube and suspended in a beaker with buffer that was placed in water bath. The water in the water bath was circulated. The buffer solution in the beaker was stirred before samples of the dialysate were taken (every 30 minutes). The lack of constant agitation in the form of a shaking water bath or magnetic stirrer bar inside the beaker with buffer could be thought to have an effect on the rate of starch digestibility. Because the maltose had to diffuse from inside to outside the dialysis tube, the unstirred buffer solution surrounding the dialysis tube could have slowed down diffusion to the outside as the concentration of maltose in that surrounding layer increased. This has been found not to be the case (Wong *et al.*, 1985). Increasing the shaking rate of a shaking water bath from 1 to 120 oscillations per minute did not increase the starch digestibility of red kidney beans.

When the *in vitro* starch digestibility determinations were done initially, very low absorbancy values were obtained. The volume of dialysate was increased in order to try to increase the absorbancy values. The absorbancy values did not increase. It was suspected that the absorbancy was not only dependent on the volume of the dialysate, but also the volume ratio of dialysate to dinitrosalysilic acid reagent. The results shown in Figure 14 confirm this. The relationship between absorbance and maltose (mg) weakened when the volume of maltose solution was increased, even though the mg maltose in the solution was kept constant. When the volume ratio of reagent and maltose solution was kept constant, however, the relationship between absorbance and maltose

(mg) remained constant, even if the actual volumes were 2 ml in the one case and 5 ml in the other. It appears that concentration of the reagent is very important and that if the sample volume is increased without increasing the reagent volume accordingly, it dilutes the reagent to such an extent that the colour development is decreased.

The dinitrosalicylic acid method determines reducing power (Granfeldt *et al.*, 1992). Even though a maltose standard curve was used to convert absorbance to maltose concentration, it really measures reducing equivalents and not maltose concentration. Faulks & Bailey (1990) determined the relative percentages of the products of maize starch digestion by HPLC (high performance liquid chromatography). The results are shown in Figure 27.

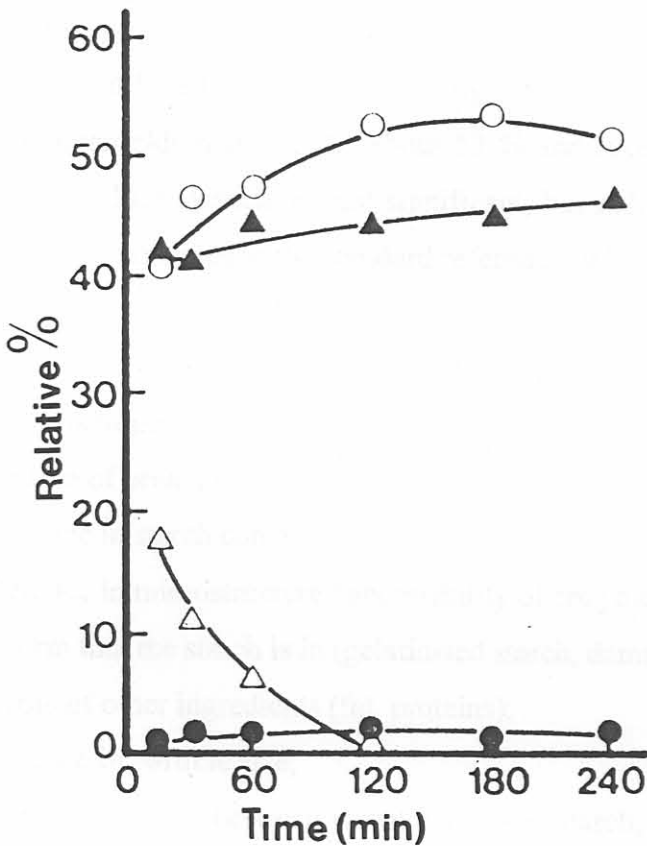


Figure 27: Relative percentage composition of the hydrolysate from maize starch treated with α -amylase. Glucose (●); maltose (○); maltotriose (▲); maltotetraose (Δ). (Faulks & Bailey, 1990)

The digestion products of maize starch consisted of about 50 % maltose, 40% maltotriose and a small amount of glucose after 180 min. Since the amylose content and glucose chain length of starch from different origin may differ, the relative percentages of the products of digestion may differ. This might have had an effect on the results obtained, because only the reducing power of the products of digestion and not the products themselves are determined. On the positive side, maltose is the largest component of the digestion products and the relative proportion of maltose remains relatively constant over the period of digestion.

Considering the effect that sample preparation, enzymes used, incubation conditions, and method of measuring the end products have on the results of *in vitro* starch digestibility experiments, it is important to interpret the results accordingly. In this study the starch in white wheat bread was about 33 % digestible, while Granfeldt & Björck reported about 46 %, Granfeldt *et al.* (1992) about 53 % and Åkerberg *et al.* (1998) about 50 %. The absolute values as such are not significant, but rather the relation of the values obtained for different samples to the standard reference (white wheat bread).

The rate of starch digestibility of white bread was significantly higher than that of all the maize porridge samples. There could be several possible reasons for the higher rate of digestion of bread, including:

- difference in starch content;
- difference in microstructure / accessibility of enzymes to substrate;
- the form that the starch is in (gelatinised starch, damaged starch, retrograded starch);
- the role of other ingredients (fat, proteins);
- difference in particle size;
- intrinsic difference between wheat and maize starch; and
- difference in preparation and type of heat treatment.

When substrate and not enzyme is limited, the velocity of an enzyme reaction is increased with increased substrate concentration (Mathews & Van Holde, 1990). In the current study the enzyme was not limited. The difference in starch content between bread and

maize porridge could not have affected the starch digestibility, because all the analyses were done on samples containing approximately 1 g of starch.

The microstructure of white bread and maize porridge differed. White bread had an open structure with many air holes. Other researchers who studied the microstructure of bread using SEM also observed an open structure (Freeman & Shelton, 1991; Brennan, Blake, Ellis & Schofield, 1996). This porous structure would greatly increase the surface area of the bread sample. Maize porridge, on the other hand, had a dense structure that consisted of maize endosperm grit particles suspended in a matrix of gelatinised starch granules and free starch. The endosperm grit particles consisted of cells with starch granules inside that were generally still intact. Figure 28 is a simplified diagram of a lump of porridge showing endosperm grit particles in the porridge matrix.

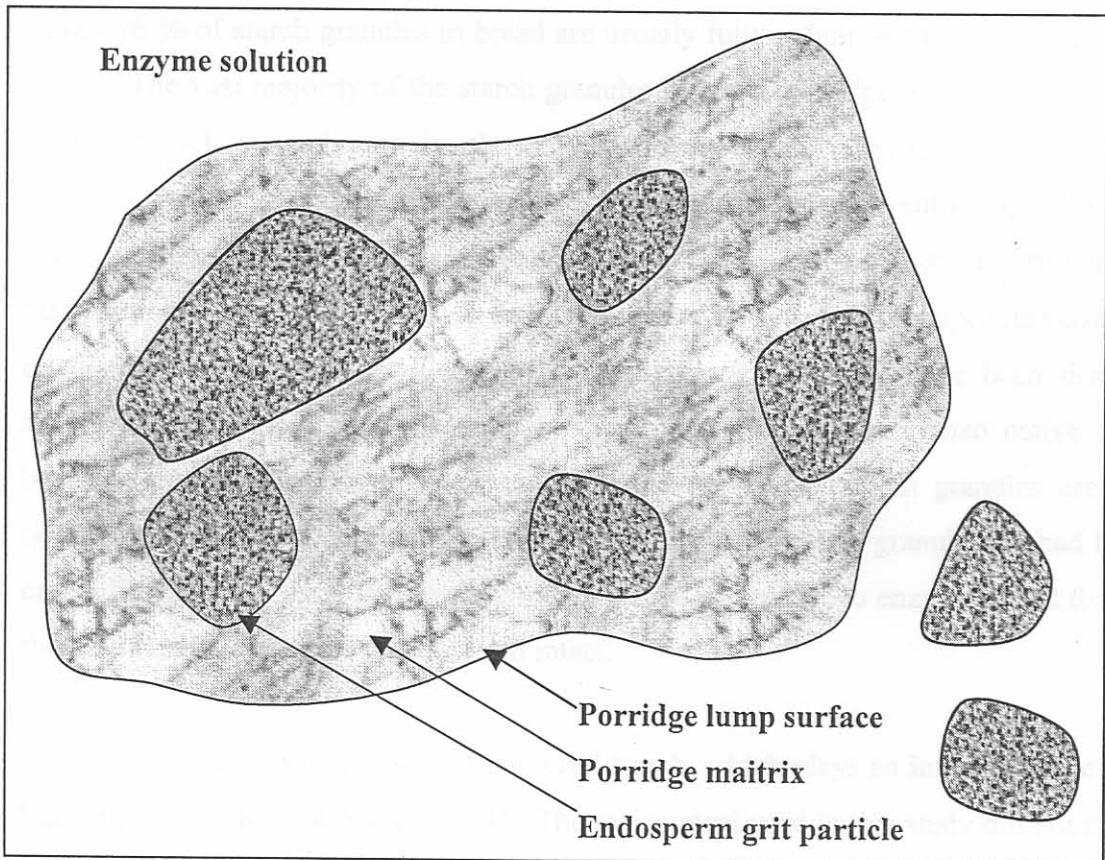


Figure 28: Simplified schematic representation of a porridge lump showing porridge matrix and endosperm grit particles

In the case of bread, the enzyme solution would fill the pores and have a large contact surface area with the substrates. With maize porridge, the enzymes would be in contact with the surface of the porridge lumps and the endosperm grit particles. Initially the surface area would be very small, but as the porridge matrix was digested, more endosperm grit particles would be released and the contact surface area of the enzymes with the substrate would increase. Much of the starch in the porridge particles was however still enclosed in cells. Physically enclosed starch is type 1 enzyme resistant starch (Englyst *et al*, 1992). This was in contrast to starch granules in bread, which could not even be seen as intact entities in the white bread (using light microscopy). The fact that starch in white bread was physically more accessible to the enzymes than the starch in maize porridge, could have contributed to the higher rate of starch digestibility of white bread compared to maize porridge.

About 96 % of starch granules in bread are usually fully gelatinised (Whistler & Daniel, 1985). The vast majority of the starch granules in maize porridge were also gelatinised, because very few starch granules showed birefringence under polarised light. The extent to which the starch granules were distorted or disrupted was different though. In maize porridge, the starch granules were swollen, but especially in the endosperm grit particles, many granules were still intact. In the bread the starch and gluten components could not be distinguished, which implied that the starch granules must have been disrupted severely. Gelatinised starch is more susceptible to enzyme attack than native starch, because gelatinisation destroys crystallinity and gelatinised starch granules are more porous than native starch granules (Holm *et al.*, 1985). A starch granule that had lost its crystallinity and is disrupted severely may be more susceptible to enzyme attack than one that had lost its crystallinity, but is still intact.

Bread flour contains an amount of damaged starch, which plays an important role in the baking process (Kent & Evers, 1994). The maize meal used in this study did not contain measurable amounts of damaged starch. Damaged starch is more susceptible to digestion by enzymes than intact native starch granules (Tester & Morrison, 1994). The fact that the starch in bread is gelatinised fully during the baking (Whistler & Daniel, 1985) may, however, cause the effect of damaged starch to be insignificant.

After cooking, the porridge was allowed to cool to 50 °C at room temperature. During this period retrogradation of amylose would take place (Whistler & BeMiller, 1997), thus forming type 3 enzyme resistant starch (Englyst *et al.*, 1992). Starch retrogradation also takes place in bread after baking (Coultate, 1996). Because the maize porridge and bread were analysed shortly after they were prepared, mainly amylose retrogradation and not amylopectin retrogradation would have taken place, as according to Whistler & BeMiller (1997) amylose retrogradation takes place in minutes or hours, but amylopectin retrogradation in hours or days.

On a dry basis, bread contains approximately 3 % fat, but the maize meal used in this study contained only about 1% fat. Bread contains more fat, because fat is added as an ingredient of bread (Kent & Evers, 1994). Amylose can form complexes with lipids (Czuchajowska, Sievert & Pomeranz, 1991). These amylose-lipid complexes are digested more slowly than free amylose (Annison & Topping, 1994). Retrograded amylose, on the other hand, is resistant to digestion (Englyst *et al.*, 1992). The formation of amylose-lipid complexes competes effectively with the formation of resistant starch (type 3) (Czuchajowska *et al.*, 1991). The higher fat content of bread could thus result in lower levels of enzyme resistant starch and higher starch digestibility compared to maize porridge.

Wheat, maize and oat starch generally have the same amylose content, roughly 25 % (Hareland, 1993). The amylose content of the cultivars analysed in this study was in the region of 37 %. It is known that South African dent maize cultivars typically have high amylose contents (Mrs. C. Erasmus, Foodtek CSIR, South Africa, Personal Communication, 1999). High amylose starch is digested more slowly than normal or low amylose starch and also yields more resistant starch (type 3) in food products (Muir *et al.*, 1995). The high amylose content of the maize starch compared to the wheat starch could therefore have lead to higher levels of retrograded amylose and slower starch digestion in the maize porridge than in the bread.

Wheat flour used for baking bread has a particle size of $< 212 \mu\text{m}$ (Kent & Evers, 1994), which is much finer than the particle size of the maize meal that was used ($< 1\text{mm}$). It was seen as a possibility that the smaller particle size of the cereal in bread could cause the higher starch digestibility, because several researchers had found that decreasing particle size increased digestibility (Snow & O'Dea, 1981; Holm & Björck, 1992; Granfeldt, *et al.*, 1994). To test this hypothesis, the maize meal of cultivar C was milled down to a flour with a particle size of $< 212 \mu\text{m}$. The digestibility of this maize flour porridge was, however, not significantly different from the maize meal porridge from the same cultivar. This finding agrees with Nelles, Dewar & Taylor (1999), who attempted to increase the degree of solubilisation and enzyme susceptibility of the starch in maize grits adjunct used in the sorghum beer brewing industry. It was found that decreasing the particle size of the maize grits did not have a significant effect on the amount of starch that was solubilised after digestion with malt enzymes when the maize grits had been cooked under well-stirred conditions. The maize porridge in this study was also stirred well during cooking

It is possible that the starch digestibility of the porridge was not so much related to the particle size of the endosperm grit particles in the porridge, but more to the size of the porridge lumps after chewing. In the porridge lumps the surface area of the individual endosperm grit particles could be less important than the surface area of the lump itself (refer to Figure 28).

Another possible explanation is that the particle size of the maize meal was already reasonably small compared to the maize flour. Snow & O'Dea (1981) compared the *in vitro* starch digestibility of raw oats, wheat, barley and rye in the rolled and ground forms. The ground cereals were significantly more digestible than the rolled cereals. Cooked ground rice was also significantly more digestible than cooked whole rice. Holm & Björck (1992) found that substituting 80% of the wheat flour in a white wheat bread recipe with intact wheat kernels decreased the GI significantly. Granfeldt *et al.* (1994) compared the metabolic response of boiled whole barley kernels with barley flour porridge. The barley flour porridge had a significantly higher GI and *in vitro* starch

digestibility than cooked whole barley kernels. In all these studies the particle size of the cereal was reduced dramatically, whereas the reduction in particle size from maize meal to maize flour is not that dramatic.

The difference between the digestibility of bread and maize porridge might be due to intrinsic differences between wheat starch and maize starch, or different preparation methods for bread and porridge (baking and wet cooking). To test the hypothesis, the starch digestibility of maize flour porridge and wheat flour porridge was compared (thus keeping the particle size and preparation method constant). Oat flour porridge was also tested to see how the digestibility of oat flour porridge would be in relation to the other two cereal flour porridges. The fact that wheat flour porridge was much less digestible than wheat bread (even less digestible than maize porridge), indicated that the preparation method had an enormous effect on starch digestibility. This result is in agreement with work done by other researchers. For example, the starch digestibility of steam-cooked and popped wheat were significantly higher than that of flaked wheat (Holm *et al.*, 1985); bread baked from spaghetti ingredients was significantly more digestible than spaghetti mixed into a porridge and spaghetti porridge significantly more digestible than spaghetti (Granfeldt & Björck, 1991).

The starch digestibility of maize flour porridge was higher than that of wheat and oat flour porridges, but was the difference due to intrinsic differences between the starches? Faulks & Bailey (1990) studied the digestibility of isolated starch from different sources after being fully gelatinised. After 240 min incubation with α -amylase, it was found that maize starch was 77 % hydrolysed and wheat starch 72 % (no data for oat starch). The difference in the digestibility of the pure, gelatinised starches could have contributed to the higher starch digestibility of maize flour porridge compared to wheat flour porridge. Yet the cereal porridges in the present study were not made from pure starch, but from cereal endosperm flours. The non-starch components (protein, non-starch polysaccharides, cell wall remnants and lipids) in wheat and oat flour could also have contributed to the low starch digestibility.

It is probable that the gluten in the wheat porridge covered the starch granules and by doing that reduced accessibility of the enzymes to the starch. This would make the starch less susceptible to enzyme attack (Oates, 1997) and hence reduce the rate of digestion. The wheat flour porridge had a dense and elastic texture. Of course the starch granules in bread are also covered with gluten, but because the structure of bread is porous the starch in bread could be more accessible to enzymes than the starch in wheat flour porridge. Wheat flour porridge is not a food that is usually consumed in the form that it was prepared in this study. The wheat flour porridge studied here had an unpalatable elastic texture. According to the author's knowledge, wheat flour or meal is only used to prepare porridge after being toasted. Porridge made from toasted wheat flour has a pleasant consistency (not elastic at all). This change in consistency is probably caused by a breakdown of glutenin and gliadin during the toasting, which will then prevent the formation of gluten during the cooking. Without the gluten, the texture will not be elastic and rubbery. The starch in the porridge will most probably be more easily digestible too, because the starch would not be covered by protein.

The starch digestibility of oat flour porridge was also lower than that of maize flour porridge, but oat flour does not contain gluten (Kent & Evers, 1994). However, the fat content of oat flour is very high (8.1 %, Kent & Evers, 1994; 11.0 %, Langenhoven *et al.*, 1991) compared to wheat flour (1.6 %, manufacturer) and maize flour (1.1 %, this study). The fat content of oat starch itself is also known to be higher than other cereal starches (Paton, 1986). These lipids could reduce the surface accessibility of starch to enzymes, and thereby reduce starch digestibility (Oates, 1997).

Oats are also rich in β -glucans (Hareland, 1993). β -glucans are gums and responsible for the high viscosity of oat porridge (Hareland, 1993). The increased viscosity could reduce the rate of diffusion of the digestion products out of the dialysis tube and in that way reduce the measured starch digestibility.

The oat flour used in this study was milled from rolled oats. Whole oats has to be steamed to plasticise it before it can be rolled (Kent & Evers, 1994). During steaming,

some starch gelatinisation will take place. According to Kent & Evers (1994) about 30 % of the starch in commercial rolled oats is gelatinised. This pre-gelatinised starch could cause an increase in starch digestibility, because gelatinised starch is more susceptible to enzymes than raw starch (Holm *et al.*, 1985). Upon storage, gelatinised starch retrogrades (Whistler & BeMiller, 1997). This implies that there would also be some enzyme resistant starch (type 3) in rolled oats before cooking porridge. To minimise the effect of pre-gelatinised starch, the rolled oats chosen for this study was a product made from whole oat groats and hence had received minimum processing.

Bread baking involves the mixing of ingredients (wheat flour, water, yeast, salt, fat, etc.) to form an elastic dough (Kent & Evers, 1994). The dough is aerated by carbon dioxide formed by yeast fermentation and then baked at 220-230 °C for 30 min (Kent & Evers, 1994). To cook stiff maize porridge, maize meal is added to boiling water. After cooking it for a few minutes, more water is added and the porridge is simmered for about six minutes before being served. Cooking porridge takes less than eleven minutes in total and because it is a wet heat process, the temperature will not exceed the boiling point of water. During bread baking the temperature of the crust will exceed the boiling point of water when all the water in the crust had evaporated. The starch granules in bread flour would have had time take up water during the dough formation, whereas the starch in maize porridge would not have been hydrated before the heat treatment. Baking bread takes longer than cooking porridge and together with the fact that bread baking is a dry heat process and porridge cooking a wet heat process, this could cause the starch granules in bread to be more disrupted than the starch granules in maize porridge.

To summarise, white bread had a higher rate and extent of starch digestibility than traditional stiff maize porridge. This difference is probably due to the difference in microstructure, the higher fat content of bread and the higher amylose content of maize porridge and the less distorted starch granules in maize porridge. The difference in starch content, particle size and levels of damaged starch probably did not play an important role. The intrinsic difference in digestibility between maize and wheat starch could play a small role, but the most important reasons were probably extrinsic, namely the

difference in the ingredients of bread and porridge recipes, the difference in the preparation (mixing, proofing) and the difference in the heat treatments.

The average predicted GI of 44 (glucose reference) for hotplate cooked maize porridge definitely fell into the slow carbohydrate release group (GI less than 55) if the classification of Perlstein *et al.* (1997) is used. This predicted GI of stiff maize porridge is only an estimation making use of the *in vitro* starch digestibility results obtained in this study, combined with correlations between *in vitro* and *in vivo* results obtained in studies done by other researchers who used the same *in vitro* method. Björck and co-workers obtained close correlations between GI and hydrolysis index for various starchy food products, e.g. pasta, bread and legumes (Granfeldt *et al.*, 1992) and wheat, rye, oats and barley bread products (Liljeberg, Granfeldt & Björck, 1992); Other researchers using different *in vitro* methods also found close correlations between GI and starch digestibility (O'Dea *et al.*, 1981 for rice, Bornet *et al.*, 1989 for wheat, tapioca, manioc, smooth pea and mung bean starches), therefore it is valid to use the hydrolysis index to predict GI.

The estimated GI is in agreement with the *in vivo* study by Venter *et al.* (1990), in which it was found that traditional stiff maize porridge was a slow to intermediate carbohydrate release food with a GI of 50-66. This confirmation that starch in maize porridge is digested slowly, opens up exciting possibilities for the treatment and prevention of diabetes in South African Black people. It seems like if the South African Black people do indeed change from a slow carbohydrate release staple food (maize porridge) to a fast carbohydrate release food (bread) when they convert from a rural to an urbanised lifestyle. South African Black people consume more brown bread than white bread (Jooste, Langenhoven, Wolmarans & Benade, 1994), but this fact is of no significance regarding starch digestibility (Würsch, 1989).

The situation of urbanising South African Black people is similar to that of the Australian Aborigines, who also changed from slow to a fast carbohydrate release foods with urbanisation. In the case of diabetic Aborigines, it was shown that returning to a traditional diet (rich in slowly digested starchy tubers, roots and seeds) and lifestyle

improved their carbohydrate and lipid metabolism (O'Dea, 1984). Returning to a diet with traditional stiff maize porridge as the main carbohydrate staple could possibly aid in preventing the development of diabetes in rapidly urbanising Black South Africans.

This slow carbohydrate release food could also be useful in the dietary treatment of people who already suffer from diabetes. It is usually very difficult to convince people to change their eating habits. For people suffering from diabetes, a diet high in complex carbohydrate and dietary fibre and low in fat is one of the most important ways of managing the illness (De Villiers, 1995). Traditional stiff maize porridge is rich in starch (a complex carbohydrate) and very low in fat. The present study indicates strongly that maize porridge is high in resistant starch (type 1 and 3). Since resistant starch is part of dietary fibre (Asp, 1995), this would imply that traditionally prepared stiff maize porridge could contain a considerable amount of dietary fibre. The advantage of promoting the consumption of traditional stiff maize porridge in South Africa, is that it is a food product that is already known and used widely. According to MacIntyre, Venter & Vorster (1999), maize meal is something that can be found in almost every Black South African household, even though upper-class urban Black people consume very little maize porridge and rural Black people consume it as their main staple.

The advantages of consuming stiff maize porridge do not only apply to South Africans or people who suffer from diabetes. The principles of a healthy diet are really the same for all people (De Villiers, 1995) and including maize porridge, which is rich in complex carbohydrates and low in fat in the diet could benefit anyone.

Although this study indicated clearly that traditional stiff maize porridge was not a fast carbohydrate release food as is bread, Walker & Walker (1984) reported a GI similar to that of bread. Possible reasons for this discrepancy between the results of Walker & Walker (1984) and the results of the present study and Venter *et al.* (1990) could be that different raw materials and preparation methods were used. To explain, the effect of maize cultivar and cooking method on the *in vitro* starch digestibility of maize porridge will now be discussed.

With standard hotplate cooked porridge, the rate of starch digestibility increased as endosperm hardness increased ($p = 0.05$). Possible reasons could include:

- differences in composition of the endosperm;
- different levels of damaged starch;
- difference in particle size distribution;
- differences in starch gelatinisation;
- differences in microstructure; and
- unidentified texture-related factors.

Some researchers attempted to relate maize kernel composition and other properties with endosperm vitreousness (Dorsey-Redding *et al.*, 1991; Dombrink-Kurtzman & Bietz, 1993; Dombrink-Kurtzman, 1994; Dombrink-Kurtzman & Knutson, 1997). Results were sometimes contradictory (see Chapter 2, Literature Review, 2.2.3). In this study protein content did not seem to increase with increased endosperm hardness. The highest protein content was found in a soft cultivar (cultivar A, 8.03 %) and the lowest protein content in a medium cultivar (cultivar D, 6.88 %). This is in contrast with the study by Dorsey-Redding *et al.* (1991) who found a significant correlation between protein content and hardness with the hard cultivars having a higher protein content. The latter study was however done on 183 maize hybrids that were tested in two consecutive years, while the present study was done on only six maize cultivars.

Muir *et al.* (1995) found that maize variety affected the amount of resistant starch escaping the small intestine with varieties high in amylose yielding more resistant starch. Dombrink-Kurtzman & Knutson (1997) dissected maize kernels by hand and found that hard endosperm fractions contained 23.0 % amylose, compared to 20.5 % amylose in soft endosperm fractions. In this study the highest % amylose (39.0) was found in the one of the soft endosperm cultivars (B), but the second lowest % amylose (36.6) was also found in a soft endosperm cultivar (A). The amylose content did not vary much and could not explain the differences in starch digestibility. Panlasigui *et al.* (1991) found that rice varieties with similar high amylose contents had different starch digestibility rates and attributed the differences to differences in physiochemical properties between rice varieties.

Generally in this study, small, but significant differences in composition between cultivars were found, but except for particle size distribution, these differences did not seem to be related directly to endosperm vitreousness. It seemed like the harder cultivars had more large particles than the softer cultivars and the softer cultivars more small particles than the hard cultivars. This was expected, because hard endosperm needs more mechanical force to be broken (Dorsey-Redding, *et al.*, 1991) and yields more grits (Kent & Evers, 1994) than soft endosperm which breaks down to flour very easily (Wu & Bergquist, 1991). This was also experienced during the milling of the maize grits when the grits from the hard endosperm cultivars (E and F) had to be put through the roller mill one extra time before the desired particle size (< 1.01 mm) was obtained.

In hard wheat, it is the starch granules that break when the kernel is fractured and not starch-protein bonds (Hoseney, 1994). If the same were true for maize (no information in this regard could be found in the literature), then one would expect that maize meal from hard endosperm would contain more damaged starch than maize meal from soft endosperm. The fact that the hard cultivars had to be milled an extra time, meaning more severe milling, could also increase the amount of damaged starch in the meal (Tester & Morrison, 1994). If the hard cultivars had contained more damaged starch, then they should have had a higher starch digestibility (Kent & Evers, 1994) than the soft cultivars in the raw form. However, none of the maize meal samples contained measurable levels of damaged starch. Phegelo (1998) found no damaged starch in maize flour with a particle size of > 150 μm , but 11.7 AACCC units in maize flour with a particle size of < 150 μm . The maize meal samples used in this study all contained 14-29% particles with a particle size of < 150 μm . The particle size of maize meal was relatively large and did not need such a severe milling as is needed to produce a flour, therefore it could be expected that the damaged starch content would be low (Jones, 1940). Considering the absence of measurable amounts of damaged starch, the effect of damaged starch on the digestibility of maize porridge from cultivars with different endosperm hardness can be ignored.

The particle size distribution of cultivars with different endosperm hardness differed, but that could not have caused the differences in starch digestibility, because reducing the particle size of the maize meal of cultivar C to maize flour (discussed earlier) did not change the starch digestibility of that cultivar as had been expected.

The initial hypothesis (Objective 4) was that starch in hard endosperm would be difficult to gelatinise because of the tight packing in the protein matrix. It is also said that the protein matrix is thicker in the hard than in the soft endosperm of maize (Pedersen *et al.*, 1989). Starch in soft endosperm would be easier to gelatinise, because of the more loose packing of the starch granules in the cells. The higher degree of starch gelatinisation would then increase the digestibility of maize porridge made from a soft cultivar compared to a hard cultivar. This hypothesis does not explain the differences in digestibility between cultivars and is not valid, because virtually all the starch in stiff maize porridge was gelatinised.

It may well be that the starch in the softer cultivars was more easily disrupted than the starch in hard cultivars where distortion and disruption could have been limited by the protein matrix. During the cooling period, however, the cultivars with more disrupted starch granules (solubilised amylose leached out) could have formed more retrograded amylose (type 3 enzyme resistant starch). Raben *et al.* (1994) found that the glycaemic response is reduced if digestible starch is replaced by resistant starch. The soft cultivar porridges could possibly have had a lower rate of starch digestion than the hard cultivar porridges because possibly more enzyme resistant retrograded amylose had formed in the soft cultivar porridges than the hard cultivar porridges.

No difference could be observed between the microstructure (as observed with light microscopy) of porridge made from hard and porridge made from soft endosperm cultivars. This means that there were probably no obvious differences in microstructure that could have affected the starch digestibility of different maize cultivars.

Maize endosperm hardness is not well defined and understood (Dombrink-Kurtzman & Bietz, 1993). The differences in starch digestibility between the cultivars could also have been caused by endosperm texture related physiochemical properties that are not identified and understood yet.

As expected, decreasing the cooking time by half decreased the starch digestibility of maize porridge. With the shorter cooking time, the starch granules were probably gelatinised to a lower extent and less disrupted than with the standard time. The ungelatinised or partially gelatinised starch is less susceptible to enzyme digestion (Holm *et al.*, 1985), which decreased the digestibility.

Surprisingly, the opposite (doubling the cooking time) did not increase the digestibility rate as was expected. In fact, it reduced digestibility. Many researchers reported that gelatinisation increased starch digestibility, for example Holm *et al.*, 1985 (raw, cooked, popped, flaked and steam cooked wheat); Holm *et al.*, 1988 (wheat starch); Bornet *et al.*, 1989 (wheat, manioc and smooth pea starch) and Eerlingen *et al.*, 1994a (waxy maize starch). The reduced digestibility of long cooked maize porridge can be explained as follows: Increasing the cooking time would increase the degree of starch granule disruption, especially because of the increased number of times that the porridge was stirred during the extended cooking time. This could have lead to more starch molecules being released from starch granules. The increased degree of starch solubilisation could have lead to the formation of more retrograded amylose (type 3 enzyme resistant starch) during the cooling period than was the case with the porridge cooked for the standard period of time. If more type 3 resistant starch had formed, then starch digestibility rate could have been decreased (Raben *et al.*, 1994).

It is interesting to see how people prepare the same food differently by culture. Black South Africans seem to prefer stiff maize porridge and use relatively short cooking times. The porridge studied here was a stiff porridge. Black South Africans also eat a crumbly porridge. The crumbly porridge is made by adding more dry maize meal later in the cooking process (Mr. P. Rankhumise, Tswana man aged 65, Personal Communication, 1998). In the crumbly porridge the water would be limited, which would in turn limit

starch gelatinisation at cooking temperatures (Colonna *et al.*, 1992). Mr. Rankhumise remarked that the crumbly porridge kept hunger away for longer than the stiff maize porridge. The lower degree of gelatinisation would decrease the rate of starch digestion, because native maize starch is slowly, but completely digestible (Englyst *et al.*, 1992). Because of the lower moisture content, the crumbly porridge also has a higher nutrient density, which could increase satiety.

Traditionally, White South Africans use longer cooking times in the preparation of maize porridge. De Villiers (1992), in her book on traditional South African cooking, remarked that the longer porridge is cooked, the better it tastes. This was referring to a recipe for a thin porridge with a maize meal to water ratio of about 1:10. If such porridge was cooked for an hour or more (as suggested by the author), the starch would probably be fully gelatinised. This porridge would probably be highly digestible, because the gelatinised starch granules would be disrupted during the long cooking time in the presence of excess water. Very little starch would probably retrograde before the porridge is eaten, because White South Africans eat their porridge hot. In this study the stiff maize porridge was chewed when it was lukewarm, because it is usually consumed at a lukewarm temperature (Mr. P. Rankhumise, Tswana man aged 65, Personal Communication, 1998). Black South Africans also often eat cold porridge, in which a considerable amount of retrograded starch would have formed, especially when left over night (Venter *et al.*, 1990).

The starch digestibility of microwave cooked porridge was very similar to traditional hotplate cooked porridge. This is an advantage, because it means that more affluent, urbanised people with their busy lifestyles could use this convenient way of preparing the porridge and still enjoy the benefits of slow starch digestibility. In contrast with hotplate cooked porridge, the starch digestibility of microwave cooked porridge made from different maize cultivars did not increase with increased endosperm hardness. In fact, there was no correlation between starch digestibility and endosperm hardness. Cultivars B and F had a lower rate of digestibility than the rest. Cultivar B was a soft endosperm cultivar and cultivar F a hard endosperm cultivar.

Not much research had been done on the difference in the effect of microwave and conventional heating on starch. Lewandowicz, Fornal & Walkowski (1997) reported that the changes that occur in moist tuber starches on microwave heating were similar to those brought about by conventional heat moisture treatment. According to Marsono & Topping (1993) the effects of cooking rice in a rice cooker and microwave oven were similar and generally produced similar amounts of resistant starch upon cooling. On the other hand, Huang, Hess, Weber, Purcell & Huber (1990) examined potatoes after microwave and conductive heating and found that the swelling patterns of the starch granules were different. Heated to the same temperature, the starch granules in microwave heated samples were less hydrated and disrupted than conventionally heated samples. Yui, Weisz & Wood (1991) found that the starch in microwave cooked rolled oat porridge was less dispersed than porridge prepared by the conventional method. This difference was, however, ascribed to the fact that the microwave cooked porridge was stirred less. In the present study the effect of stirring would be minimal.

The reason for this difference or absence in trend was probably related to the way that energy is transferred during conventional and microwave cooking. The kinetics of heating during conventional and microwave heating are not comparable (Tomasik & Zaranyika, 1995). During conventional cooking, energy is conducted from the surface to the inside of the food. With microwave cooking, the heat is generated within the product (Potter & Hotchkiss, 1995). Because the microwaves generated the heat very fast and inside each endosperm grit particle, the endosperm texture related properties that may have caused the differences in digestibility in the hotplate cooked porridge, may have been destroyed.

Neither Walker & Walker (1984) nor Venter *et al.* (1990) gave full details on the nature of the maize meal that they used to cook the porridge from, it was just called “refined” or “unrefined” maize meal respectively. The two groups used different cooking methods. Walker & Walker did not specify, but considering that it was done 15 years ago it was probably a form of conventional heating (e.g. stove or hotplate). Venter *et al.* (1990) used microwave cooking. Walker & Walker (1984) gave the ratio of maize meal to water, but did not say whether that was a mass or volume ratio. They gave the cooking

