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Dietary Fiber and the Glycemic Response[1] (42199)

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Abstract. Addition of purified fiber to carbohydrate test meals has been shown to flatten the glycemic response in both normal and diabetic volunteers, reduce the insulin requirement in patients on the artificial pancreas and in the longer term reduce urinary glucose loss and improve diabetes control. In the context of high fiber–high carbohydrate diets these findings have had a major impact in influencing recommendations for the dietary management of diabetes internationally. The mechanism of action appears in part to be due to the effect of fiber in slowing absorption rather than by increasing colonic losses of carbohydrate. Consequently postprandial GIP and insulin levels are reduced and the more viscous purified fibers (e.g., guar and pectin) appear most effective. In addition it has been suggested that colonic fermentation products of fiber may enhance glucose utilization. More recently it has become clear that many aspects of carbohydrate foods (food form, antinutrients, etc.) in addition to fiber may influence the rate of digestion and has led to a classification especially of starchy foods in terms of glycemic index to define the degree to which equicarbohydrate portions of different foods raise the blood glucose. Use of such data may maximize the effectiveness of high carbohydrate and high fiber diets in the management of diabetes and related disorders.

Studies on dietary fiber and fiber rich foods in the treatment of diabetes have had considerable impact on recommendations for the dietary management of diabetes. The emergence of the fiber hypothesis of Denis Burkitt and Hugh Trowell at the beginning of the 1970s with its emphasis on increasing the consumption of unrefined carbohydrate foods was indeed opportune (1). It came at a time when increasing evidence pointed to a reduction in fat intake in the diabetic diet. It was feared that if this caloric void was filled with carbohydrate, then raised postprandial blood glucose levels and poor diabetic control would result. Fiber appeared to provide a means by which increased carbohydrate intakes would be possible without compromising the postprandial glycemia. Within half a decade of the end of the 1970s the major English-speaking diabetes associations had all recommended that together with increased carbohydrate consumption diabetics should increase their intakes of fiber (2–4).

There is much support for these recommendations in terms of experimental evidence. However, this aspect of the fiber hypothesis is perhaps even more notable in emphasizing hitherto largely unnoticed aspects of food form and composition in relation to human gastrointestinal physiology and metabolism.

Mechanisms of Action of Fiber. The dietary fiber hypothesis suggested that the beneficial effect of increased fiber consumption in diabetes might result from its ability to reduce the rate of carbohydrate absorption (1). Subsequently studies suggested that this might be achieved by reducing the rate of gastric emptying (5–9) and the rate of digestion of foods (10–12) and increasing the effective thickness of the so-called unstirred water layer (13, 14). With high fiber foods, absorption would therefore be expected to continue for longer and utilize a greater length of the small intestine (Fig. 1). On the other hand it would also be predicted that low fiber or refined foods would be rapidly digested and liberate their products of carbohydrate digestion at a much greater rate (Fig. 1). In this situation absorption would occur higher in the small intestine and would be likely to stimulate a gut hormone response different from that seen after a high fiber meal.

As a consequence, the high fiber meal would give rise to a flattened blood glucose and endocrine response (Fig. 2). On the other hand

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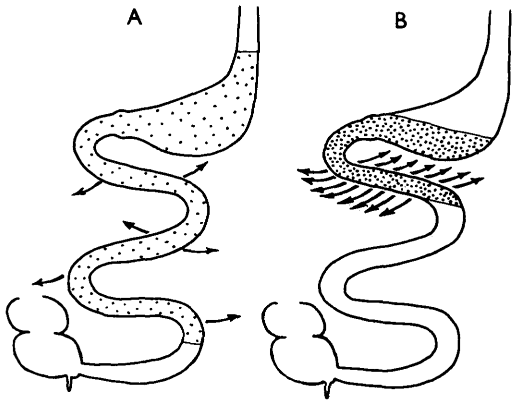

FIG. 1. Stomach and small intestine showing (A) slow absorption of energy-dilute nutrient in a fiber-rich "primitive" diet, and (B) rapid absorption of energy-dense nutrient from low-fiber modern Western foods. Modified from Ref. (49).

with the refined meal a high rise and a lag component to the glucose curve would be predicted (Fig. 2).

Viscous Fiber and Sustained Release Carbohydrate. Initially studies with certain types of purified dietary fiber served to illustrate the possible effects of those food constituents in slowing carbohydrate absorption (10, 13, 15–17).

Using an *in vitro* dialysis system, it was noted that the rates at which glucose diffused out of dialysis bags containing fiber varied greatly. The least viscous fiber, bran, allowed the most rapid glucose diffusion being similar to the control, while the most viscous, guar and tragacanth, impeded glucose diffusion the most. These studies confirmed earlier work where guar alone had been used (18).

A similar relationship was seen in terms of blood glucose and indeed insulin responses when these fibers were taken by groups of five or six healthy volunteers (10). In each case after taking fiber the blood glucose and insulin response curve lay below the control. As in the *in vitro* system the greatest flattening was seen by the most viscous, guar and tragancanth (Fig. 3). Subsequent studies have confirmed this action of viscous fibers (5–7, 13, 19–21) and confirmed the relationship between viscosity and the flattening of the glycemic response.

It was most likely that the effect of viscous fiber was due to slower absorption rather than malabsorption. This is illustrated by studies where 25 g of xylose was added to test meals containing guar (10). The xylose output, which was then measured in two hourly aliquots over an 8-hr period, reflected a slower rate of absorption after guar with significantly more xylose excreted in the latter half of the experimental period by comparison with the control study. Nevertheless the total amount of xylose excreted was the same in both situations and so argued against carbohydrate malabsorption as the reason for the flatter blood glucose responses seen.

In addition when glucose was mixed with guar no breath hydrogen was evolved as a marker of colonic fermentation of malabsorbed carbohydrate at a time when lactulose mixed with guar would have produced substantial quantities of hydrogen. Further studies attesting to the fact that viscous fiber did not appear to induce malabsorption have involved the use of paracetamol (acetominophen) and digoxin as markers (22, 23). Again the absorption was merely delayed.

There has been considerable debate whether the observed slowing of the rate of absorption was due to delayed gastric emptying, delayed small intestinal absorption, or both. The latter seems a more satisfactory explanation. Studies with postgastrectomy patients and normal volunteers have demonstrated flatter glucose, insulin, GIP, and enteroglucagon responses with pectin and an amelioration of the hypoglycemia of delayed dumping (6–8, 16). Early gamma camera studies of gastric emptying indicated that this was delayed in the presence of viscous fibers. However, subsequently more recent studies have confirmed that there is no clear relationship between the

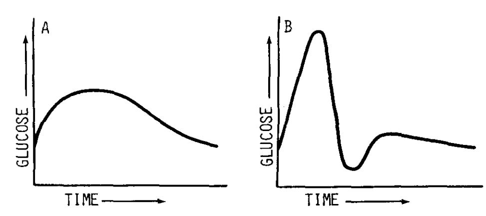

FIG. 2. Postprandial glycemia following (A) slow absorption from starchy, fiber-rich meals, and (B) rapid absorption with undershoot due to excessive insulin release following refined fiber-depleted carbohydrate foods. Modified from Ref. (49).

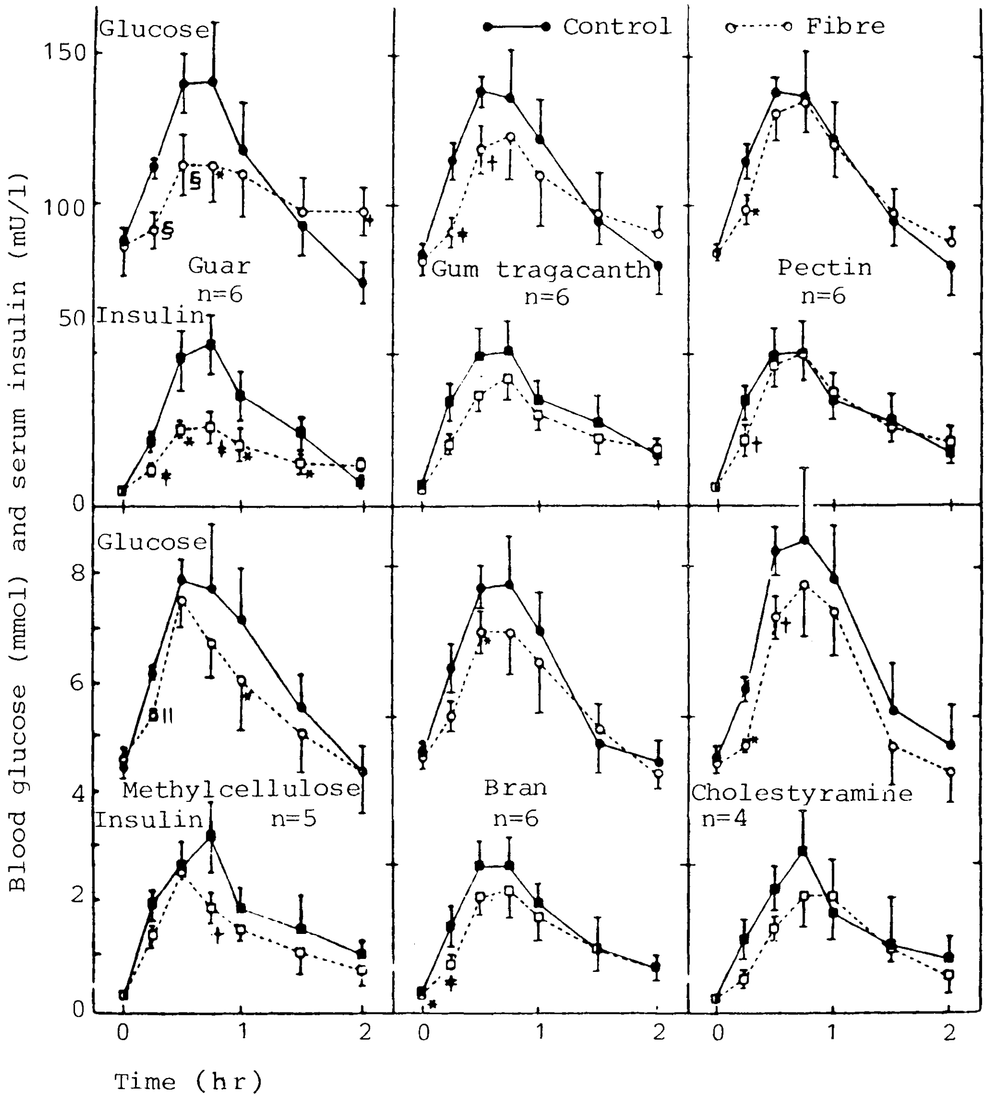

FIG. 3. Mean blood glucose and serum insulin levels of volunteers after taking 50-g glucose tolerance tests (control) to which had also been added the equivalent of 12 g of a range of dietary fibers and fiber analogs (test). Modified from Ref. (10).

slowing of gastric emptying and the flattening in blood glucose (8). Indeed this same flattening is seen in a totally gastrectomized individual on taking viscous fiber test meal (14). Similar conclusions have been arrived at by Reed using direct intubation (24).

It is likely therefore that both gastric emptying and small intestinal events play a part in the reduced rate of absorption observed with viscous fibers.

In terms of application to the treatment of diabetes, when guar was added to bread and pectin to marmalade, and given as a bread and marmalade test breakfast to insulin-dependent diabetics, it was noted that after the fiber enriched meal both the glycemic and the insulin responses were markedly flattened (15). A similar effect was noted in insulin dependent diabetics who took their normal prebreakfast insulin dose before each meal (15).

The Second Meal Effect. Fiber in one meal also appears to improve glucose tolerance to the next. This effect on the subsequent meal was assessed in healthy volunteers who took an 80-g glucose tolerance test as "lunch" on three separate occasions (25). On one occasion this was preceded by a breakfast consisting of 80 g of glucose taken alone, on another occasion "breakfast" consisted of 80 g of glucose mixed with 25 g guar, and on a further occasion 80 g of glucose was sipped at an even rate over the 4-hr "prelunch" period. After guar had been taken at breakfast a much reduced glucose response was seen at lunch. A proportionately lower insulin response was also seen but there was no significant change in the GIP (25). This was in keeping with a lack of residual effect on the gastrointestinal tract of guar from the preceding meal. It is likely, therefore, that the metabolic changes induced by the first meal, e.g., lower FFA and ketone body levels, also seen, were responsible for the flatter blood glucose profile. In addition the guar effect on the second meal was mimicked when glucose was sipped continuously over the prelunch period (25). This added further support to the concept that fiber (guar) was transforming the first glucose load into a source of slow release or "lente carbohydrate."

Additional studies were therefore undertaken in diabetics which were aimed at controlling the rate of delivery of carbohydrate. A diabetic treated on diet alone took 240 g glucose in a lemon-flavored drink over a 12-hr period either as three 80-g loads or sipped continuously to simulate meals of "rapidly released" as opposed to "slowly released" carbohydrate (26). This demonstrated that sipping (or "slow release" carbohydrate) resulted in a progressive fall in blood glucose, a rise in RQ, without meal induced oscillations seen in the meal study, a reduction in urinary glucose loss of 89%, and a 25% reduction in 12-hr insulin response area (Fig. 4).

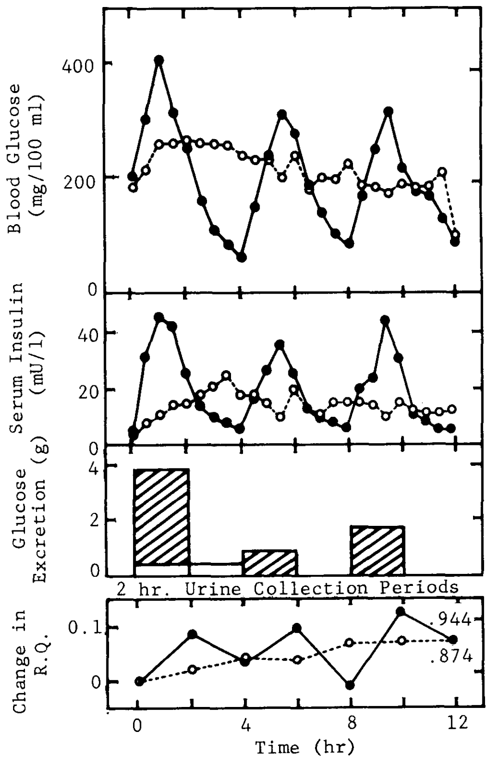

FIG. 4. Blood glucose, insulin and RQ response, and two-hourly urinary glucose loss, measured over 12 h, are shown in a diabetic controlled on diet. On one occasion 80-g glucose drinks were taken at 0, 4, and 8 h (● —;▨) and on another 5 g glucose in solution was taken every 15 min by continuous sipping (○---;□). Reproduced, with permission, from Ref. (26).

Fiber in Diabetes. *Viscous fiber.* Extending this approach further, guar has been added to the metabolic ward diet of diabetics to prolong carbohydrate absorption time and so produce lente carbohydrate (27). At a dose of 20–25 g a day with no change in available carbohydrate intake (28), this resulted in a reduction, during the last 2 days of a 5-day period, of 40% in urinary ketone body outputs (29). In addition urinary glucose losses were reduced over the last days by 38%. On an outpatient basis a reduction of 50% was maintained over a 1-year period, and at the same time there was also a corresponding 20% lowering in insulin requirement over this period (30) (Fig. 5).

A number of studies have now confirmed and extended the range of effects of guar in diabetes (19, 20, 31, 32) including a modest reduction in insulin requirement in patients on the "artificial pancreas" (32). The effect appears to have been most consistent on higher carbohydrate diets (33).

However, a major problem has been the lack of suitable fiber preparations. With guar, for example it was found necessary to mix it well with the carbohydrate load in order to ensure its effectiveness. Thus guar given be-

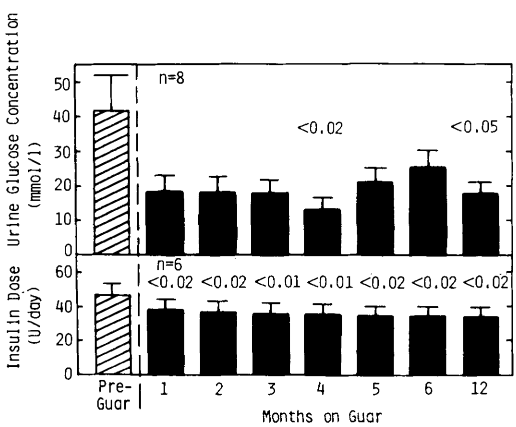

FIG. 5. Urine glucose concentration and insulin dose of eight diabetics (seven taking insulin) both before and during the first year of taking guar crispbread (containing 14–26 g guar depending on the individual). Modified from Ref. (30).

fore, as opposed to with, a glucose load no longer modified the subsequent blood glucose response (34). This failure to mix adequately with the carbohydrate portion of the diet is likely to be responsible for the lack of effect recorded in a number of trials of viscous fiber (35, 36). For this reason there has been interest in the possible use of various foods as sources of "sustained release" carbohydrate (36, 37).

Cereal fiber. Although in test meal studies nonviscous cereal fiber has not been shown to have any effect on meal carbohydrate tolerance, in longer term studies chronic effects have been observed with improved glucose tolerance in nondiabetics and better overall blood glucose control in diabetics (38–41). The reason for this remains to be elucidated.

Lente Carbohydrate Foods. *In vitro studies: Digestibility.* In order to determine whether foods with differing endogenous fiber contents were likely to release their carbohydrates at differing ratios, *in vitro* digestibility studies were carried out in which 2-g carbohydrate portions of 14 foods were placed in dialysis bags containing human pancreatic and salivary enzymes. These bags were in turn placed in water baths of 37°C, and the rate at which the carbohydrate products of digestion—glucose, maltose, maltotriose, and maltotetrose—were liberated was measured over a period of 3 hr (11, 12).

The results demonstrated great differences between the responses of individual foods, with bread, rice, and instant mashed potatoes liberating their products of digestion far more rapidly than kidney beans, red lentils, or soya beans which were also at the lower end of the glycemic index scale (12). The relationship between glycemic index and food fiber content though present was not strong (12) and other factors are therefore likely to be involved.

In vivo studies: The glycemic index of foods. At the same time evidence was mounting that equally large differences were observed between the glycemic responses to different foods (42–44). Limited studies had ascribed these differences to the nature of the starch (42, 43), the degree of cooking (45), or the particle size (46, 47). We therefore tested under standardized conditions the effect on the blood glucose of healthy volunteers of feeding 50-g carbohydrate portions of a wide variety of foods and sugars (48).

Each volunteer was therefore standardized against a reference carbohydrate (50 g glucose in the early studies and now 50 g carbohydrate as bread). The glycemic index (GI) for each food eaten by the volunteer was expressed as a percentage of the blood glucose response to the reference food:

$$\mathrm{GI} = \frac{\text{food blood glucose area}}{\begin{array}{c}\text{blood glucose area following an}\\ \text{equivalent amount of carbohydrate}\\ \text{as the reference food}\end{array}} \times 100.$$

In Fig. 6 the glycemic indices of some of the foods tested (48) are given with each block representing a single food. As can be seen there is a very great difference between the root vegetables at the upper end of the scale and nuts at the lower end of the scale. Comparisons of the results of over 60 foods and sugars demonstrated differences which ranged from almost 100% of the glucose equivalent down to 15%. In addition there were large differences between foods in each particular food group (e.g., root vegetables, cereals, biscuits, breads and pasta, beans, etc.). A similar pattern was also seen in diabetics where comparison of the GI of 15 foods tested in both normal and diabetic volunteers showed a significant relationship ($r = 0.76$, $P < 0.01$) (49).

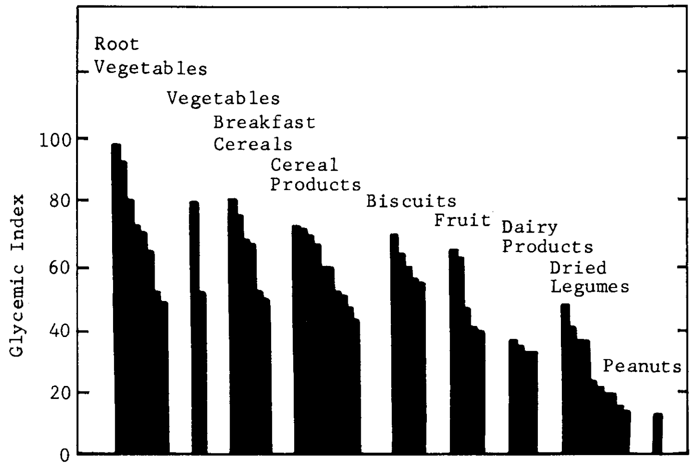

FIG. 6. Glycemic index of foods (i.e., area under the 2-h blood glucose response curve of 50-g carbohydrate food portions, 50 g glucose itself being 100%). Each bar in each block represents the mean result for one food tested by 5–10 individuals. Modified from Ref. (48).

Relationship of in vivo to in vitro. When the carbohydrate products of digestion liberated at both 5 and 1 hr were plotted against the glycemic index, at both time intervals a good relationship existed ($r = 0.86$, $P < 0.001$, $n = 14$). Again, legumes which are one of the richest sources of dietary fiber, when expressed per gram of carbohydrate, were at the lower end of the scale (12).

On the other hand the relationship between food fiber content and GI or rate of *in vitro* digestibility, though significant, could account at best only for a relatively small proportion of the total variability (12, 48).

We are therefore suggesting that fiber is only one constituent in food which is responsible for modifying the glycemic response to a given carbohydrate load. Other factors including the vegetable protein, perhaps through the starch–protein interaction, the proportions of readily gelatinizable starch, phytates, α-amylase, and other enzyme inhibitors are likely to be of importance and have great therapeutic potential. Similarly factors which modify gastrointestinal motility and food digestibility will also alter the glycemic response. It is possible that those foods which are the best sources of slow release or lente carbohydrate, such as the legumes, may be those which contain appreciable amounts of more than one of these constituents.

Legumes as Examples of Lente Carbohydrate Foods. Legumes have emerged from the *in vitro* and *in vivo* screening of foods as sources of lente carbohydrate and can be used as an example of the physiological effects which such foods may produce. Some of their therapeutic implications have also been explored.

Not only have the digestion rates for legumes (beans and lentils) been shown to be different from those for other common starchy foods but the proportion of glucose liberated in digestion of lentils was higher and the maltotriose lower than that seen with bread (50). This might be predicted from the higher amylose to amylopectin ratio of bean starch and suggests that the amylose content of a food may be of importance as seen in rice (51).

In this context the blood glucose response area following 50 g available carbohydrate from 5–8 varieties of legumes was lower by 50% when compared with over 20 commonly eaten cereal foods and root vegetables in normal (12) (Fig. 7) and 28% in diabetic volunteers (49).

Slowing absorption of carbohydrate may also produce marked effects in terms of the endocrine, especially the gut endocrine, responses. The effects of feeding lentils were compared with whole meal bread, in meals with similar fiber content balanced with cot-

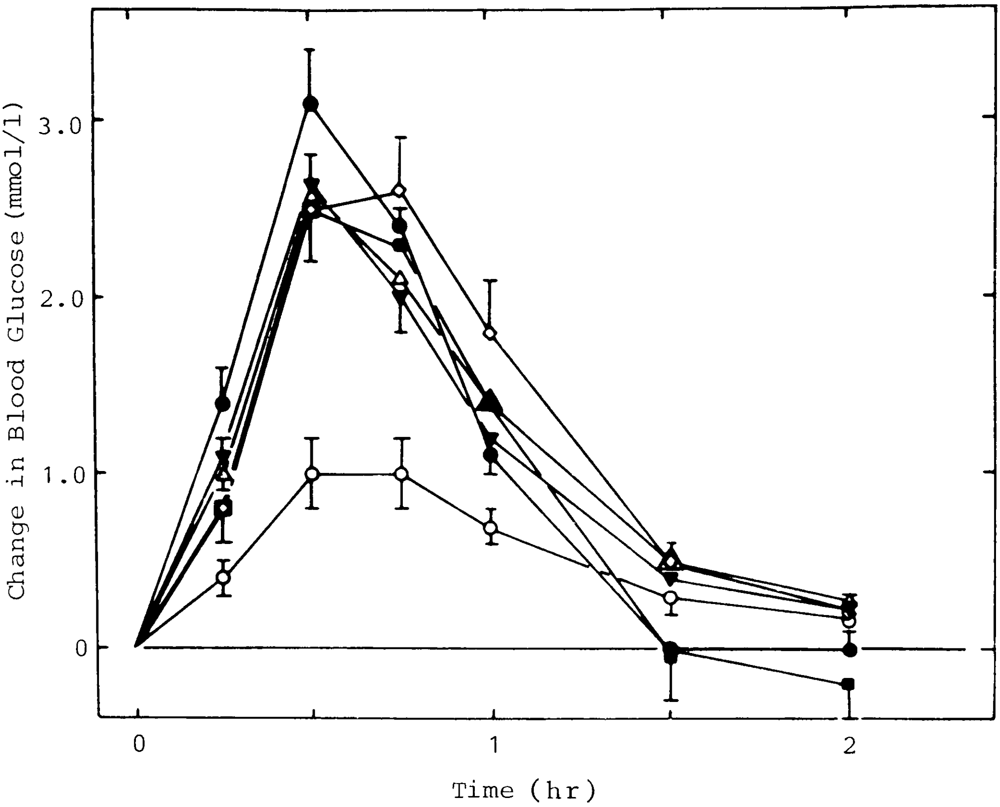

FIG. 7. Change in blood glucose concentration after eating 50-g carbohydrate portions of individual grains (●, $n = 5$), breads and pasta (△, $n = 5$), breakfast cereals (▼, $n = 6$), biscuits (◇, $n = 4$), tubers (■, $n = 4$), and dried legumes (○, $n = 8$). Reproduced, with permission, from Ref. (37).

tage cheese to ensure that the fat, protein, carbohydrate, and fiber contents were identical (52). Lentils, as a slowly digested food, produced markedly flattened blood glucose, insulin, and GIP responses. These responses were similar to those reported after feeding guar (20). This raised the question as to what metabolic effect such changes may have on the handling of the second meal.

The Second Meal Effect. As was seen when glucose absorption was slowed with guar, lentils at breakfast caused a flatter blood glucose response to the standard test meal at lunch. When bread was fed in divided portions over the 4-hr period to simulate the slow release of the digestion of lentils, a similar degree of flattening of the blood glucose response was observed. Finally, if only one-fourth of the meal were eaten to simulate malabsorption, the result was a blood glucose response far higher than that of the standard lunch. This emphasizes the possible metabolic importance of slow release foods on the subsequent meals as also demonstrated with guar and glucose (25). If fiber acts by slowing absorption then its effect on the metabolism of peripheral tissues is therefore likely to relate to slower absorption. Thus any aspect of food which slows absorption will too be of importance in this respect.

Diabetes and Lente Carbohydrate. High fiber diets have been used in the successful treatment of diabetics (53–59) (Fig. 8). These diets contained substantial amounts of such sustained release carbohydrate foods as legumes. Use of low glycemic index foods such as legumes appear to be a common feature of many of the most successful high fiber diets for diabetics. As with the guar studies (30) not only was blood glucose control improved but serum lipids were reduced.

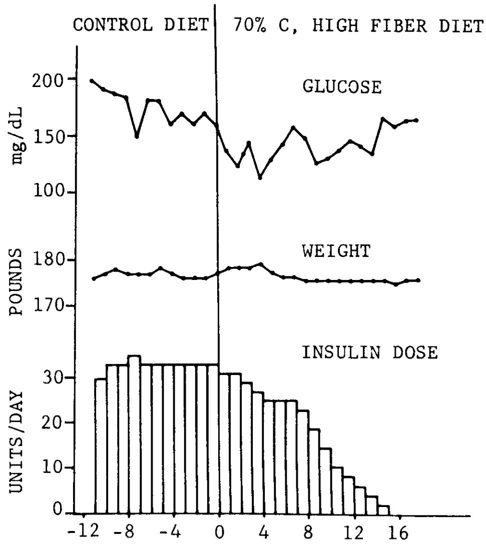

FIG. 8. Fasting blood glucose, body weight, and insulin dose in a diabetic man on control-carbohydrate (43%), low-fiber diet and high-carbohydrate (70%), high-fiber diet. Modified from Ref. (55).

Use of diet where the primary intention has been to lower the glycemic index of the diet has demonstrated reductions of both cholesterol and triglyceride levels in hyperlipidemic individuals (41, 60–62). Recently it has been shown that this can even be achieved with low GI diets where no major changes were made in the level of fiber intake (63).

Conclusion. Dietary fiber is therefore one factor which may influence the glycemic response. However, only certain types of fiber are effective and fiber as such is likely to be only one of many factors which contribute to the slow release or lente carbohydrate characteristic of certain foods. Conceptually much of the importance of the fiber studies lies in emphasizing the possible usefulness of slow release or lente carbohydrate food sources in the treatment of disease.

In this respect it is also of interest that the American (3), British (2), and Canadian (4) Diabetes Associations have all agreed on increasing their carbohydrate intakes and in advocating an increase in the intake of high fiber foods. Perhaps with more understanding of the effects of different types of fiber and high fiber foods this will be interpreted as advice to increase the consumption of "lente" carbohydrate foods.

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