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Glycemic Index of Sweet Potato as Affected by Cooking Methods

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Abstract: Understanding the effect of cooking on glucose availability will aid in the recommendation for including sweet potatoes as a regular component in American diets. Heating breaks down starch granules to allow amylopectin and amylose to be more readily digested by pancreatic amylase, which theoretically should increase the glycemic index of sweet potato. Twelve volunteers consumed 25 g of available carbohydrate from Beauregard sweet potato skin and flesh separately that were subjected to conventional cooking methods: baking at 163 °C for 1 hour; microwaving for five minutes in a 1000 watt microwave; dehydrating at 60°C for 16 hours; and steaming at 100°C for 45 minutes. Available carbohydrate was determined by difference from proximate analysis of protein, lipid, total dietary fiber, moisture, and ash. Fasted participants measured blood glucose levels at 0, 30, 60, 90, and 120 minutes after consuming 25 g of carbohydrate from test foods or glucose. Glycemic indices calculated from these methods for steamed, baked and microwaved sweet potato flesh were 63 ± 3.6, 64 ± 4.3 and 66 ± 5.7, respectively, indicative of a moderate glycemic index food. However, dehydrated and raw sweet potato flesh had a low glycemic index (41 ± 4.0 and 32 ± 3.0, respectively). Steamed skin, baked skin, and dehydrated flesh did not have a statistically different glycemic index ($P > 0.05$) from that of raw sweet potatoes. A second experiment confirmed the low glycemic index of raw sweet potato, especially the skin, and showed that a commercial extract of the sweet potato cortex, Caiapo, tended to lower the glycemic index of white potato to a level that was not different from the raw sweet potato peel. The physiological mechanism for the lower glycemic index was not due to a greater release or a greater clearance of insulin during the glycemic response. Depending on cooking methods, "Beauregard" sweet potato flesh and skin may be considered low and medium glycemic index foods, which may prove beneficial for diabetic or insulin-resistant consumers.

Keywords: Sweet potato, glycemic index, cooking, insulin.

INTRODUCTION

Glycemic index (GI), which is a ranking of carbohydrate-containing foods according to their immediate effects on blood sugar levels, has significant public interest and scrutiny [1]. Pure glucose is usually used as the standard to which other foods are compared and is given the glycemic index of 100. Although all dietary carbohydrates provide the same amount of energy, they are not all handled with equal efficiency by the body [2]. The glucose absorbed from any given food is affected by physiological and nutritional factors, which include the digestibility of the starch, interactions of starch with proteins, amounts and kinds of fat, sugar and fiber in the presence of constituents, and the level and type of food processing [3-5]. Changes in the physiological state of the food, from green to ripe, increases its glycemic index [3]. Several other factors influencing glycemic index are the source and class of carbohydrate, resistant starches, amylose and amylopectin levels, fiber content, and cooking.

The starch in raw food is stored in compact granules that are difficult to digest [6]. The cooking process causes hydrogen-bonding sites involved in intermolecular bonds of starch molecules to engage more water, releasing individual molecules [7]. Gelatinization occurs when starch molecules enter the aqueous solution followed by total disruption of the granules in a sequential process [8]. Starch is gelatinized at 60-90°C and becomes susceptible to hydrolysis by alpha and beta amylase. Incomplete cooking processes followed by cooling results in starch becoming resistant to digestion [9] leading to slow digestion and lower glycemic response.

Starch hydrolysis varies from quite rapid to very slow. Small intestinal starch digestion may be so retarded that starch can escape into the large bowel without being digested [10]. This fraction is termed *resistant starch,* which is likely formed during cooling after the starch has been gelatinized during cooking with heat and excess water. Disruption of the crystalline structure takes place at temperatures of 60 to 70 °C [11]. Above 90 °C, fragments of amylopectin and amylose are suspended in water due to the significant loss of granular structure [12]. Granules high in amylose swell more slowly than those rich in amylopectin due to amylopectin's increased branching.

Cooked food is almost always stored for variable lengths of time under moderate or low temperatures before con-

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sumption. Amylose and amylopectin molecules can associate to form a gel [13]. The exact nature of the gel depends on amylose:amylopectin ratio, amount of water, and time and temperature of storage [14]. The gel network is created by glucan chains that retrograde (recrystallize) in a helical structure [11]. It may take hours or days to form this gel. Retrogradation may also be increased by replicated heated and cooling [15]. The change in structure of starches during heating and cooling has a significant influence on starch digestibility in the gastrointestinal tract. Some evidence from intubated humans indicates that free glucose may pass to the colon from traces found in the terminal ileum [16]. This too is termed resistant starch since it escapes digestion. Englyst, *et al*., [17] classified resistant starches according to the cause that allows them to pass to the large bowel: chemically resistant starch (i.e. enzyme resistant starch) and physiologically resistant starch (i.e. starch that passes undegraded through the small intestine and into the large bowel). Raw starches are highly resistant to enzymatic hydrolysis compared with gelatinized starches [14].

Soh and Brand-Miller [18] found no significant difference in GI of potatoes prepared by boiling, oven-baking, microwaving, or mashing. Conversely, Crimi, *et al*., [19] found that baked potatoes produced a significantly lower incremental glycemic response compared with boiled potatoes. Wolever, *et al*., [20] also found no differences in baking, boiling, and canned potatoes, but found that mashing significantly increased the glycemic response (by 15-20%). The variability noted in potatoes, although of a different species than sweet potatoes, leads to questions surrounding the effect of cooking methods on glycemic index with sweet potatoes.

Baked sweet potato elicited a high GI of 94 when studied with 14 West Indian carbohydrate rich foods [3]. This study found boiled sweet potatoes to have a low GI of 46 ± 5. Likewise, the roasted tubers were all high (82 for sweet yam). Blood glucose response curves for low (≤ 55), intermediate (56 – 69), and high (≥70) GI foods were similar to the relationship shown in the response curves of boiled, roasted, and fried sweet potato. These results suggest the different processing methods used (boiling, roasting, baking, or frying) may influence the GI of sweet potatoes.

Extrusion cooking, explosion puffing, and instantization appear to make the starch of rice, potato, and corn products more readily digested [21]. Hydration of granules (gelatinization) and disruption of organized granule structure increase the availability of starch to amylase digestion and are more likely to occur in processing factory cooking conditions when higher temperatures and pressures are utilized. The more processed a food is, the higher the glycemic response it will produce [22]. Conventionally cooked starches may be recommended for diabetics to achieve glycemic indices lower than those processed in factories.

Boiling may cause leaching of glucose monomers from amylose-amylopectin degradation. Loss of the readily digestible sugars due to leaching did not impact the amount of carbohydrate used to calculate the GI of boiled or steamed foods [3]. Using wet heat to cook a potato can increase resistant starches. Baking foods uses dry heat, causing loss of water and concentrating free sugars. The degradation of starches further increases the sugar content and glycemic index. Cutting sweet potatoes into strips and cooking rapidly retained significant amounts of starch, whereas the cooking of whole roots allowed more complete conversion of starch into sugars and dextrins [23]. Conversely, sugar concentrations were similar in roots cooked in microwave and convection ovens [24].

The recrystallization of dispersed starches results in stronger hydrogen bonds [25]. The cook-cool-re-warming of the potatoes affected about 7% of the starch and allowed it to escape digestion in the small intestine compared to about 3% in freshly cooked potato [26]. Earlier studies on potatoes *in vitro* showed cooling, freezing, or drying produces starches partially resistant to α-amylase. Digestibility of starch made resistant to α-amylase by cooling improves on reheating. The increased resistance to amylase on cooling appeared to relate to changes in crystalline structure of starch rather than overall physical form [26]. The resistant starches do significantly affect the glycemic index.

Protein within sweet potato also exhibited high amylase activity with an average of 480 units/mg protein and a range of 274-758 units/mg protein [27]. After heating the extract for 10 minutes at 80°C to destroy native amylase activity, amylase inhibitory activity was assayed *via* the dinitrosalycylic acid method. No amylase inhibitors were found in the sweetpotato extract. Rekha, *et al.,* [28] found that native amylase activity remained after heating for 10 minutes at 80°C and thus used trichloroacetic acid to selectively precipitate the amylases before assaying the extract for amylase inhibitory activity *via* the iodine binding method. Of the 100 cultivars studied, amylase inhibitors were found in 79.

Cultivar also can play a significant role in the stability of the amylase inhibitors [29]. Boiling sweetpotato pieces in water for 30 minutes resulted in residual amylase inhibitor activities of 29.3 ± 1.1% (cultivar RS III), 29.1 ± 1.1% (cultivar S 62), 44.6 ± 1.9% (cultivar S 56-2), and 58.9 ± 0.7% (cultivar S 1195). Microwave baking resulted in complete amylase inhibitor inactivation in the S 62 cultivar after 120 seconds and the S 1195 cultivar after 180 seconds. Residual amylase inhibitor activities of 29.1 ± 1.1% and 19.2 ± 0.6% remained after 180 seconds in the cultivars RS III and S 56-2, respectively. Grating or blending, oven drying at 70°C for 24 hours, and then powdering to obtain flour resulted in complete inactivation of amylase inhibitors in all cultivars tested [29].

Sweetpotatoes contain multiple proteins that exhibit trypsin inhibitor activity. Trypsin inhibitors have been identified with molecular weights of 23 and 24 kDa [30, 31], molecular weights of 73, 38, and 22 kDa [32], and 10 different trypsin inhibitors with the most active inhibitors having molecular weights of 12, 10, and 9.3 kDa [33]. Trypsin inhibitors had no effect on chymotrypsin and pepsin activity [30]. Processing of sweetpotatoes can greatly affect the activity of trypsin inhibitors. Boiling sweetpotatoes for 40 minutes resulted in complete inactivation of trypsin inhibitors [33]. Microwave baking was the most effective method for inactivating trypsin inhibitors in sweetpotatoes followed by boiling and then oven-drying [34]. Microwave baking for 180 seconds resulted in complete inactivation of trypsin inhibitors while boiling for 30 minutes resulted in 17-31% residual activity. Trypsin inhibitors in oven-dried sweetpotato chips were relatively stable for 2 hours at 70°C, with 80-90% residual activ-

ity. After 2 hours, however, inactivation progressed at a more rapid rate, with less than 20% activity remaining after 24 hours. Higher temperatures also led to more rapid inactivation, with inactivation complete after 4 hours at 100°C. Minor variations in thermostability were seen for different cultivars. Moist heat treatment provided better inactivation of trypsin inhibitors than dry heat treatment [35]. Dry heat treatment at 60, 80, and 100°C for 15 minutes resulted in average residual activities of 92, 84, and 71%, respectively, where as moist heat treatment at 60, 80, and 100°C for 15 minutes resulted in average residual activities of 71, 26, and 5%, respectively. Similarly to Kiran and others [34], Zhang and Corke [35] found that the trypsin inhibitors of some cultivars were more heat resistant than others. Protease inhibitors that are not degraded could impact the degradation of amylase and thereby affect starch digestion and glycemic index.

The glycemic index of sweet potato reported by various researchers ranges from 44 to 94 [36]. These studies vary in cultivar, growing location, and preparation methods. Although generally considered sweet by definition, there is a large range of perceived sweetness, depending on sugar components and starch conversion during cooking of sweet potatoes [37]. Collins and Walter [23] estimated available sugar values between 30-35% on a dry-weight basis. Raw sweet potato tissue contains sucrose, glucose, and fructose. The principal change in sugar composition with cooking is the production of maltose from hydrolyzed starch. Much of the starch is converted into dextrins and maltose by alpha amylase and beta-amylase; however the degree of starch conversion can differ across cultivars [38].

We do not understand all the components associated with the low glycemic index in raw sweet potatoes [39]. Proteins, fiber, or starch are components that could be attributed to the low glycemic index of sweet potatoes. Ludvik, *et al.,* [40] reported beneficial effects of Caiapo, an extract of the white-skinned sweet potato (*Ipomoea batatas* L.), on fasting plasma glucose, total cholesterol, and low-density lipoprotein (LDL) cholesterol in type 2 diabetic patients. This sweet potato variety has been cultivated in the Kagawa Prefecture in Japan and the extract of the skin of the root is used for the treatment of type 2 diabetes in Japan. The isolated antidiabetic component of Caiapo is an acidic glycoprotein that is similar to the proteins found in Beauregard and White Star sweet potatoes (*Ipomeabatatas* L.) [40, 41]. However, sweet potatoes are rarely consumed raw in most countries due to the starchy flavor. Thus, cooking could affect sweet potato glycemic index by denaturing the Caiapo glycoprotein. In developing countries, the consumption of sweet potato appears to be inversely proportional to income level, and they are typically viewed as a food to be consumed only for survival [42].

Theoretically, an increase in simple sugars should cause higher glycemic indices due to improved sugar availability. Other compounds, such as fiber, can confound this effect by maintaining low glycemic index values [43, 44]. Consumption of dietary fiber, particularly viscous fiber, may alter the digestion and absorption of carbohydrates whereas lipids delay gastric emptying to the small intestine and retard interaction with digestive enzymes [10]. Nishimune, *et al*., [43] further explained the effect of total dietary fiber on polysaccharide absorption through five mechanisms. Fiber delays the digestion of starch in the stomach; secondly, fiber will delay the transition time of stomach contents to the duodenum; thirdly, fiber will delay the diffusion of different saccharides in the duodenum, and fourthly, fiber will delay the hydrolysis of polysaccharaides in the upper parts of the duodenum. Finally, fiber will lower the rate of absorption of monosaccharides through the microvilli of the epithelial cells in the jejunum and upper ileum. Dietary fiber, with increasing concentration, may act as a competitor for sugar uptake through a membrane because fiber may compete with sugars released during cooking for the same binding site [41].

This study aimed to investigate the change in glycemic index after cooking sweet potatoes under conventional domestic methods. Sweet potatoes are commonly cooked using various methods. Baked sweet potatoes are popular in the Americas. The North Carolina Sweet Potato Commission [45] recommends baking at a temperature of 350°F (177°C) for forty minutes. Sweet potatoes are also boiled and steamed in many countries and cultures. Dehydrated sweet potatoes are consumed as chips for snacks. The objective of this study was, first, to determine the effect of cooking by different methods on the glycemic index of sweet potato skin and flesh, and, secondly, to investigate the physiological impact and causes of low glycemic effect of raw sweet potato and its components.

MATERIALS & METHODS

Reagents

Hydrochloric acid (HCl) was purchased from Fisher Scientific (Fair Lawn, NJ) to digest dehydrated samples. Sodium sulfate (anhydrous) was used to dry lipid samples dissolved in n-hexane, also purchased from Fisher Scientific. Heat stable α-amylase, protease, and amyloglucosidase were provided in a Megazyme total dietary fiber assay procedure kit AOAC 991.43 (Bray, Co. Wicklow, Ireland). MES/TRIS buffer (2N-morpholino ethanesulfonic acid and tris(hydroxymethyl) aminomethane) (0.05 M) at pH 8.2 adjusted with 6N HCL was prepared using reagents from Sigma- Aldrich (St. Louis, MO). Celite, acid-washed, prewashed from World Minerals was also used in the total dietary fiber assay. Ethanol (95%), 78% ethanol (AAPER Alcohol, Shelbyville, Kentucky), and acetone (Fisher Scientific, St. Louis, MO) used for washing of total dietary fiber samples were reagent grade. Glucose oxidase/ peroxidase and o-dianisidine reagents were provided in the Glucose (GO) assay kit by SIGMA- Aldrich (GAGO-20) (St. Louis, MO). C-peptide (10-11136-01) and insulin (10-1113-01) ELISA assay kits were manufactured by Mercodia (Sweden, ALPCO Diagnostics, Windham, NH). Caiapo was obtained from Fuji-Sangyo Company (Japan).

Instrumentation

Sweet potato roots were skinned using a household potato peeler. Conventional ovens were used for baking. Temperature was checked by an oven thermometer. Sweet potato samples were dehydrated in a Precision Scientific economy oven (Chicago, IL) that operated by mechanical convection. A 10-cup household steamer was used to steam sweet potato slices. Sweet potato samples were microwaved at full power (750 watts) in General Electric 'Hotpoint'® (Fairfield, CT) microwave oven in food grade areas of the lab.

A Cuisinart® 14-cup food processor blended samples after cooking for freeze drying. Cooked sweet potato samples were prepared for proximate analysis using a vacuum bottle type 4.5-L benchtop freeze dryer (Labconco, Kansas City, Missouri) to ensure complete dehydration of pureed sweet potato samples. Coffee grinders were used to create a sweet potato powder suitable for analysis of macronutrients.

Digestion conditions were simulated in hot water baths made by Precision Scientific. A rotary evaporator was utilized to remove n-hexane solvent from solution in lipid extraction procedures. Fritted crucibles (Pyrex 50 mL ASTM 40-60 C) were used for filtering samples in total dietary fiber separation extraction methods. Samples were ashed at 525 °C in a muffle furnace (Barnstead/ Thermolyne, Dubuque, IA) and cooled in desicators. Therasense® Freestyle glucometers (Abbott Diabetes Care, Inc., Alameda, CA) were used to monitor changes in blood glucose levels of volunteers. The accuracy of the glucometers was confirmed by comparing readings from approximately 20 subjects with analysis of serum glucose collected from the same subjects at the same time using a glucose oxidase microtiter plate method (GAGO-20, Sigma, St. Louis, MO).

Cooking Methods

Sweet potatoes were grown at the NCSU Research Farm in Clinton, North Carolina, cured at 30 °C, 85% relative humidity, and held in a temperature controlled cooler (13 °C, 85% relative humidity) in NC State University's Horticulture Department after harvest. Samples were retrieved from storage coolers, washed and allowed to dry at room temperature (22°C) for 10 minutes. Inedible portions were removed and not used in cooking. Samples were then skinned for flesh and skin fractions to be separated and weighed to 25-g available carbohydrate quantities determined from proximate analysis. The conventional cooking methods investigated in this study were baking, dehydrating, steaming, and microwaving. These cooking methods were intended to be representative of common sweet potato preparations.

Raw sweet potato samples were sliced and baked to 163 °C (325 °F) for one hour in sealed aluminium foil packets. Peeled raw sweet potatoes were thinly sliced using a Cuisinart® food processor with a 4 mm blade. The slices were then placed on baking sheets in a dehydrator at 60 °C for 16 hours. Other slices were placed in a home steamer for 45 minutes and in a domestic microwave at 750 watts for 5 minutes.

If sweet potato roots are cut into strips and cooked rapidly, significant amounts of starch remain, whereas the cooking of whole roots allows a more complete conversion of starch into dextrins and sugars [38]. Since processing of sweet potato into pieces before cooking is standard method used in both household and industrial sweet potato preparation [45], it was used in this study.

After cooking, samples were placed in a refrigerator (4-6 °C) for a maximum of one week until needed and then warmed for one minute in a microwave oven for volunteer consumption. Thereafter, any unused samples were discarded.

Proximate Analysis

Carbohydrate content was quantified in raw, baked, steamed, and dehydrated sweet potatoes. Analysis was conducted on duplicate samples after cooking to observe the possible change in macronutrient levels through leaching or other manner. The proximate compositions of total dietary fiber, ash, lipid, and moisture contents for the different cooking methods of sweet potatoes were determined using a standard method [46] and available carbohydrate content was calculated by difference [6, 47].

Total Dietary Fiber

The AOAC 991.43 Megazyme kit method required samples to be cooked at 100 °C with heat stable alpha amylase to give gelatinization, hydrolysis and depolymerization of starch. Incubation at 60°C with protease followed to solubilize and depolymerise proteins and amyloglucosidase to hydrolyze starch fragments to glucose. Treatment with ethanol precipitated the soluble fiber and removed depolymerized protein and glucose from starch. The residue was then filtered and washed with 78% ethanol, 95% ethanol, and acetone. One duplicate was analyzed for protein and another for ash. Total dietary fiber was then calculated by difference from filtered and dried residues.

Lipid

Acid hydrolysis was used to release bound lipids, polar and non-polar, by dissociating lipid-starch and lipid-protein intermolecular forces. Samples were hydrolyzed with hydrochloric acid under heat. Extraction of lipids using hexane retained lipid in the organic solvent. The organic layer was filtered through sodium sulfate and evaporated at 40°C under reduced pressure using a rotary evaporator. The resulting weight was subtracted revealing the amount of lipid present.

Moisture

Sweet potatoes were placed in a moisture determination dehydrator. The sample was automatically weighed, dehydrated to a constant weight, and the percentage of moisture was then calculated and displayed.

Protein

The NC State University Analytical Spectroscopy Services Laboratory determined dry matter nitrogen levels as a part of the analysis using a C-H-N 2400 CO_2 Elemental Analyzer (Perkin Elmer, Norwalk, CT). The amount of protein was determined from N content x 6.25 (16% N in sweet potato protein).

Ash

Ash was measured by placing samples in a muffle furnace for five hours at 525°C. The high constant temperature destroyed all compounds other than minerals found in the sweet potato. An analytical error in some of the cooked samples required that we use the ash content of the raw material in the calculation of carbohydrate content.

Human Subject Panel: Experiment 1, Cooking Methods

The experimental procedure was approved by the NCSU Institutional Review Board. All subjects signed informed consent documents. Once 25 g of carbohydrate was deter-

mined by proximate analysis of other macronutrients and components, 12 volunteers were recruited to participate in the feeding trial. All volunteers were healthy participants, free of chronic carbohydrate metabolism disease, who consented to the approved protocol of the research. The study required two months for completion. Participants were financially compensated for each completed day of the panel. Questionnaires were provided to the volunteers for age, gender, medical history, and normal daily carbohydrate consumption information. Anthropometric data measured were for weight and height for subjects at the commencement of the study. Body mass index (BMI) was calculated from the measured data.

Samples were warmed for one minute in a microwave oven on the day they were needed for each volunteer [3]. Three hundred µL of blood was collected on the first day of the study to be analyzed for fasting insulin levels to remove participants with hyperinsulemia. Volunteers began between 7 a.m. and 9 a.m. after fasting for at least 7 hours. A fasting blood glucose level was taken using Therasense® Freestyle glucometers (Alameda, CA) and followed by participants consuming their samples in 15 to 20 minutes. Previous research [48] showed no difference between venous and capillary blood samples using continuous glucose monitoring systems for determining the blood glucose response to food. The time when participants completed each sample was recorded and blood glucose levels were taken in thirty-minute increments thereafter, stopping at two hours.

Human Subject Panel: Experiment 2, Raw Sweet Potato and Potato

Beauregard sweet potato roots grown in Clinton, North Carolina were washed, skinned, and prepared by grating using a Cuisinart® food processor (East Windsor, NJ). All 200-g portions of sweet potato (skin, flesh, or whole) were weighed, placed in Ziplock bags, and stored in food grade freezers for a maximum of one week until needed for participants. White potatoes (*Solanum tuberosum*) were purchased at a local supermarket. The treatments consumed for this study were T1= Glucose drink, T2= whole sweet potato, T3= sweet potato flesh, T4= sweet potato skin, T5= white potato, T6= white potato plus Caiapo (4 g). All sweet potato samples were consumed raw, unexposed to any cooking heat. White potato samples were microwaved in the food grade lab for 3 minutes at 750 watts to reduce potential solanine toxicity. Frozen samples were thawed each morning for 1.5 hours at room temperature (22 °C) before consumption. Approximately 4 grams of Caiapo was added to white potato and mixed prior to eating. Each treatment was consumed on two different days by each subject to determine glycemic index.

Volunteers arriving at the test site were asked to recall the last meal consumed prior to the required 8-hr fast. Fisher® HealthCare Brand (ArtaPlast AB, Fisher HealthCare, Houston, TX) self-retracting safety lancets were provided to prick the tips of their fingers for fasting glucose level determination by Therasense® Freestyle glucometers. Participants were then asked to consume 50-g of Fisherbrand Sun-Dex Glucose Tolerance Test Beverages (Houston, TX) to obtain the standard glycemic response against which sweet potato samples were measured. Blood glucose levels were subsequently measured by glucometer at times 30, 60, 90, and 120 minutes after consuming the sample. An additional 400 µL of blood were collected in BD Microtainer serum separator tubes, centrifuged ten minutes, and frozen for further analysis of C-peptide and insulin concentrations. Participants consumed each treatment twice over the course of a month and a half. Serum insulin and C-peptide concentrations from times 0, 60, and 120 minutes were measured from thawed blood samples using the Mercodia Insulin ELISA assay and Mercodia C-peptide ELISA.

Glycemic Index Analysis

Each subject consumed each food sample on two separate days for improved statistical accuracy. The incremental areas under the curve, excluding the area beneath the fasting level, were calculated by weighing geometrically [49]. Glucose responses were graphed for each individual using Microsoft Excel and printed on 8.5” x 11” acid-free paper. The area under the curve, not considering regions below the time zero baseline glucose concentration, was cut and weighed on Denver Instruments and Sartorius Analytical balances. The glycemic index was calculated by expressing the glucose response area for the test foods as a percentage of the mean response area of the reference food (glucose drink) taken by the same subjects [20, 49]. The geometric weighing technique compared favorably with area-under-the-curve data obtained with a polar planimeter.

Statistical Analysis

A *t* test (LSD) using SAS 9.1 compared glycemic index means for each treatment to calculate statistical differences [2]. A program considering the interaction of treatment (baking, steaming, and raw) and part (skin vs. flesh) was used to analyze their effect on the glycemic index, followed by Duncan’s Multiple range test to determine differences between treatment means. In Experiment 2, the slopes of trend lines from 0 – 60 minutes and 60 – 120 minutes for insulin and C-peptide concentrations were graphed and analyzed by ANOVA. If there were significant main effects, Tukey’s HSD procedure was used to identify any treatments with significantly different insulin or C-peptide release or clearance rates.

RESULTS

Anthropometric and Demographic Description of Subjects

Participants completed questionnaires regarding age, date of birth, weight, height, carbohydrate metabolism deficiencies, smoking habits, carbohydrate source, physical activity, and medical history. Twelve volunteers began and ended the study, seven female and five male. Volunteers were not screened for high or low carbohydrate intake or source. All were non-diabetic and considered normal for the purposes of the study. The average age was 32 ± 12 yr. Ages ranged from twenty-two to sixty-three. BMI was calculated from the weights and heights. The mean BMI among participants was 24.63 ± 3.62 kg/m^2, which is considered a healthy BMI [50]. The average weight among volunteers was 73.1 ± 12.2 kg (161.14 ± 26.87 lb) and height was 1.701 ± .095 M (5’7” ± 3.74”). No participants reported that they currently smoked.

Proximate Composition of Sweet Potatoes

Variability was noted in proximate analysis results. Calculations were on dry matter basis due to dehydration requirements for assay procedures. The various samples averaged 3.9 ± 1.7% ash, 31 ± 14% total dietary fiber, 1.0 ± 0.7% fat and 7.6 ± 0.9% protein (means ± S.D.). Dry matter content ranged from 12.8% for the baked flesh to 75.3% for the dehydrated skin. The serving sizes providing 25 g of carbohydrate in each treatment were calculated to be 264 g of Raw Skin, 189 g of Raw Flesh, 445 g of Steamed Skin, 148 g of Steamed Flesh, 146 g of Baked Skin, 261 g of Baked Flesh, 64 g of Dehydrated Skin, and 53 g of Dehydrated Flesh. Lanza, *et al*., [51] found that sweet potatoes have an average dietary fiber content of 2.4 g/100g fresh weight using the neutral detergent fiber plus water soluble fraction and Southgate procedure for extracting the fiber. The value was an average taken from compiled literature sources. Our data show values on a dry weight basis that are substantially higher in fiber content (3.3 to 5.6% for flesh) than the average sweet potato in the earlier study [51], possibly because the Megazyme fiber assay could include resistant starch, or that it extracts non-fiber components and calculates fiber by difference, as opposed to a harsher fiber extraction method [52]. In Experiment 2, the proximate analyses determined the carbohydrate content (percent nitrogen-free extract, dry-matter basis) to be 90.1, 79.6, and 95.4% for whole sweet potato, sweet potato skin, and whole white potato; the dry matter content was 17.57,18.61 and 17.86%, respectively.

Blood Glucose Response to Cooking (Experiment 1)

A fasting blood sample was collected before any food intake and additional blood samples were drawn and analyzed in 30-min increments after participants completed consuming samples. Fig. (**1**) shows the mean glucose response levels and standard errors. The glycemic response to each food preparation method was determined in all twelve subjects on two separate occasions, except that dehydrated skin was not consumed by all subjects due to severe gastrointestinal difficulty by three volunteers. Symptoms included cramping, nausea, vomiting, and constipation. These symptoms were reported to only last for a maximum of six hours. An analysis of interaction between cooking method (steamed, baked, raw) and part (skin vs. flesh) using a comparison of means revealed that glycemic index values for part were dependent on the method of cooking and vice versa ($P \leq 0.001$). Furthermore, there were significant differences in glycemic indices based on cooking method ($P \leq 0.001$) and part ($P \leq 0.001$). No significant differences ($P>0.05$) were observed among subjects or between replications.

Table **1** shows the calculated glycemic index for each sample. Glucose was given the value of 100. The Type III Sum of Squares analysis of subjects indicated no differences in glycemic indices calculated from subjects for each treatment ($P = 0.573$). Significant differences were observed by treatment ($P \leq 0.0001$). A t-test on least squares (LSD) of glycemic index means determined that some samples had values significantly different from others. Microwave-cooked flesh samples had a medium glycemic index of 66 followed by baked flesh (64), and steamed flesh (63). These values were statistically similar to one another. Dehydrated flesh had a glycemic index of 41, which was grouped with baked skin (32), raw flesh (28), and steamed skin (25). The final group consisted of baked (32), steamed (25), and raw skin (19) and raw flesh (28).

Blood Glucose, Insulin and C-peptide Responses to Raw Sweet Potato Components and Controls (Experiment 2)

A second glycemic response experiment was conducted to further investigate possible mechanisms for the low glycemic index of raw sweet potato. Fig. (**2**) shows the mean glycemic response for the treatments studied, compared to a standard control trial of 50 g of glucose drink. The sweetpotato treatments were also compared to a control dose of white potato (*Solanum tuberosum*) and white potato to which was added a 4-g portion of Caiapo. Using the methods de-

Fig. (1). Mean Glucose Response from Participants consuming cooked Beauregard Sweet Potato Samples containing 25 g of carbohydrate. Vertical bars are the standard error of duplicate analyses for 12 subjects.

Table 1. Calculated Glycemic Indices of Cooked Beauregard Sweet Potato[1]

Cooking Method	Flesh	Skin
Raw	32 ± 3.0[B,C]	19 ± 3.6[C]
Steamed	63 ± 3.6[A]	30 ± 3.0[B,C]
Baked	64 ± 4.3[A]	34 ± 2.3[B,C]
Microwaved	66 ± 5.7[A]	N.D.[2]
Dehydrated	41 ± 4.0[B]	N.D

[1]Values are mean ± SEM of duplicate analyses of 12 subjects. Values not followed by the same superscript letter are significantly different (P<0.05).
[2]N.D. = not determined.

scribed above, glycemic index was calculated with the following mean and S.E.M.: T1 Glucose drink, 100; T5=white potato, 52 ± 14[a]; T3 sweet potato flesh, 49 ± 12[a]; T2 whole sweet potato, 39 ± 15[ab]; T6 white potato plus Caiapo, 30 ± 8[ab]; T4 sweet potato skin, 26 ± 7[b].Treatments with glycemic indices of zero were not excluded from the data because previous data from Zakir [53] revealed the possibility of obtaining a decrease in blood glucose levels after sweet potato consumption, especially in skin fractions. The glycemic index for sweet potato skin was significantly lower than for sweet potato flesh and white potato, but was not lower than the other treatments. The GI of white potato was reduced from 52 to 30 when 4 g of Caiapo was added. This difference was not significant overall due to individual variability, but when one subject with a possible case of metabolic syndrome due to elevated insulin concentration was excluded, a paired *t*-test for this treatment indicated a significant difference ($P< 0.01$). Caiapo is an extract of the skin, or cortex, of a Japanese white sweet potato. Its effectiveness in lowering blood glucose in diabetic subjects has been documented in clinical trials [54-57]. Therefore, it seems that substances that lower the blood glycemic response in the sweet potato skin may be extracted and transferred to other foods.

Insulin and C-peptide, a post-processing fragment of the insulin gene product that is not cleared from the blood by interaction with insulin receptors, were measured in this experiment to better understand the metabolic reaction to these carbohydrate meals. Table **2** shows the mean (± S.E.M.) insulin and C-peptide responses to sweet potato and white potato samples. Insulin response to the sweet potato and white potato samples in the first hour were overall 64.7 ± 9.4 pmol/L less than the glucose standard. The slopes of insulin response levels for the first and second hours were analyzed using ANOVA and Tukey's HSD test to approximate the differences in the rate of net insulin release from the first hour data and rate of insulin uptake or apparent clearance from the second hour data. There were no significant differences in mean insulin concentration by treatment over the two-hour period ($P= 0.319$). The glucose drink (T1) gave the fastest rate of insulin concentration increase among samples (110 pmol/L/hr). Sweet potato peel gave significantly less insulin release than did glucose, but the insulin release from the other treatments were not significantly different from either glucose or sweet potato peel. The significantly greater insulin release with glucose treatment (T1) than the other treatments suggests that the greater rise in blood glucose caused greater rise in insulin. In other words, for all treatments serum insulin responded to changes in serum glucose concentration, rather than some other component of the dietary treatments that could accelerate insulin release to keep blood glucose low.

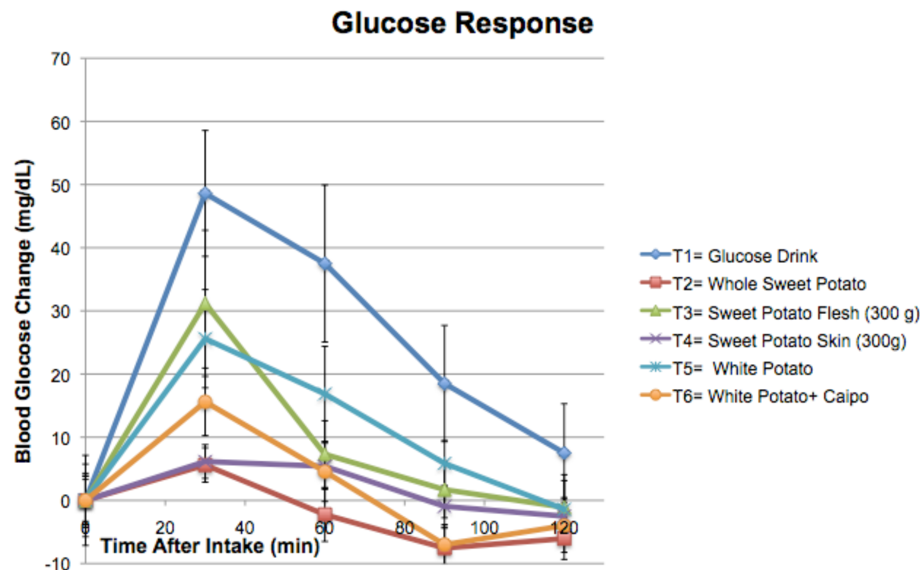

Fig. (2). Average glucose response curve relative to fasting blood glucose concentrations for treatments containing 50 g of carbohydrate consumed immediately after time 0.

Participants consuming white potato with 4 g of Caiapo had a mean fasting insulin level of 21.8 ± 17.3 pmol/L. Their mean post-prandial insulin level rose to 45.6 ± 32.5 pmol/L at 60 minutes and decreased to 21.8 ± 19.9 pmol/L at 120 minutes. A difference of 23.8 pmol/L was observed between fasting and 60 minutes. Participants consuming white potato alone had mean fasting insulin levels at 26.3 ± 25.4 pmol/L which rose to 57.6 ± 21.0 pmol/L after 60 minutes and declined to 26.7 ± 21.0 pmol/L after 120 minutes. A difference of 31.3 pmol/L was observed between fasting and 60 minutes.

The rate of apparent insulin clearance (concentration change from 60 to 120 min) indicated no significant differences among subjects or treatments (*P*= 0.0530, *P*=0.2562 respectively). The rank order of treatments for apparent insulin release in 0-1 hr (T1, Glucose > T5, Whole White Potato > T6, White Potato + Caiapo > T2, Whole Sweet Potato > T3, Sweet Potato Flesh > T4, Sweet Potato Peel) was similar to the rank order of apparent insulin clearance in 1-2 hr (T1, Glucose > T5, Whole White Potato > T6, White Potato + Caiapo > T3, Sweet Potato Flesh > T2, Whole Sweet Potato > T4, Sweet Potato Peel), suggesting that sweet potato peel or Caiapo did not directly alter either insulin release or insulin clearance due to receptor binding in this single-feeding experiment.

Table **2** also shows the mean C-peptide responses to the carbohydrate sources in treatments T1-T6. The slopes of C-peptide change from 0-60 min demonstrate that all vegetable samples elicited lower C-peptide response levels than did the glucose drink. Due to the high inter-subject variability, none of the treatments T2-T6 was significantly different from the others although the mean values were dissimilar. The mean C-peptide increase for subjects consuming sweet potato samples was 181 ± 44 pmol/L. Conversely, white potato samples increased C-peptide 365 pmol/L from fasting-to-60-minutes, while white potato plus Caiapo samples had a mean increase of 445 pmol/L during the fasting to 60 minute time interval. These mean differences could suggest that Caiapo may stimulate insulin synthesis, but no conclusion can be reached because the differences were not statistically significant.

Analysis of the decrease in C-peptide levels during the 60 to 120 minute time interval provides an apparent rate of clearance of C-peptide. There was no significant difference due to treatment in C-peptide metabolism or clearance. This result would be expected because C-peptide clearance is more likely due to plasma protein turnover and not interaction with insulin receptors. The rank order of treatments for all variables in Table **2** except C-peptide clearance were similar, with the largest values attributed to the glucose treatment and the smallest to sweet potato peel. For apparent C-peptide clearance, the mean value for T1 glucose and T4 sweet potato peel were the same.

DISCUSSION

Lipid and protein levels were unaffected by cooking methods. Total dietary fiber was higher in the skin of cooked samples; however raw sweet potato skin had dietary fiber levels similar to that of raw flesh. The amount of fiber content quantified previously [3] was 3 to 14 grams per 100 grams of sweet potato fresh weight. The amount of total dietary fiber is important because of its influence on glucose absorption, post-prandial glucose levels, and glycemic index.

High levels of total dietary fiber can cause low glycemic index levels. Leaching of sugars can occur during heat processing concentrating the fiber components of the skin [58]. The amount of lipid found in sweet potatoes has been determined to be 0.30 ± 0.02 grams per 100 gram raw sample [3], a value similar to the analysis of Beauregard sweet potatoes in this study. The proximate analysis was comparable to the previous results [3], although higher concentrations of lipids were found in the sweet potato skin.

Bahado-Singh, *et al.*, [3] determined that protein levels in sweet potatoes was 2.15 ± 0.05 g per 100-g dry matter, calculated by multiplying nitrogen content by 6.25. Similarly, this study's proximate analysis revealed protein concentrations that remained relatively constant (range= 7.4% to 9.5%). Chang and Morris [59] found no observed statistical

Table 2. Glycemic index and the effects of consuming different fractions of Beauregard sweet potato and white potato on insulin. Values are means ± S.E.M of 10 subjects' responses. Values within a column that have the same superscript letter are not significantly different (α = 0.05)

Treatment	Glycemic Index	Insulin Release (pmol/L/hr)	Insulin Clearance (pmol/L/hr)	C-peptide Release (pmol/L/hr)	C-peptide Clearance (pmol/L/hr)
1. Glucose	100	110 ± 48.3^{A}	-52.1 ± 17.0	1114 ± 178^{A}	-119 ± 432
2. Whole Sweet Potato	39 ± 15^{AB}	20.9 ± 8.3^{AB}	-17.8 ± 9.5	159 ± 97^{B}	-153 ± 89
3. Sweet Potato Flesh	49 ± 12^{A}	18.5 ± 7.0^{AB}	-22.2 ± 11.6	331 ± 66^{B}	-277 ± 54
4. Sweet Potato Peel	26 ± 7^{B}	10.6 ± 10.2^{B}	-14.3 ± 8.7	151 ± 41^{B}	-119 ± 49
5. Whole White Potato	52 ± 14^{A}	30.9 ± 7.8^{AB}	-35.0 ± 6.9	365 ± 122^{B}	-266 ± 109
6. White Potato + Caiapo	30 ± 8^{AB}	25.8 ± 8.5^{AB}	-25.3 ± 6.5	445 ± 105^{B}	-385 ± 102
P	<0.01	0.0216	0.153 (NS)	<0.0001	0.905 (NS)

differences in protein content between samples of apple, corn, oat, or soy dietary fiber sources subjected to processing treatments of autoclaving and microwaving.

Glycemic indices of zero were not omitted from the study nor were values greater than 100; negative glycemic response was given a glycemic index of zero. Individuals who had glycemic responses that created glycemic index values equal to zero indicate that breakdown of sweet potato samples could have taken longer than two hours to elicit a glucose response. Glycemic index values greater than 100 can mean that the rate at which an individual absorbed glucose from the sweet potato was faster than their response to the glucose drink standard.

The glycemic index values for raw sweet potato skin and flesh in Experiment 1 differed slightly from those in Experiment 2, in which raw sweet potato flesh was calculated to have glycemic index of 49 ± 12 and skin 26 ± 7. Experiment 1 produced values of 28 ± 7.3 and 19 ± 6.3 respectively. The variability in glycemic index could be the result of a different year's crop, time in storage, or slightdifferences in preparation method between the two studies. Experiment 2 samples were frozen and allowed to thaw or be slightly warmed in microwaves prior to eating. Minimal cooking could have taken place, or freezing may have disrupted the cell structure. The protocol in Experiment 1 required that raw samples be kept under refrigeration (4 °C) and warm slowly to room temperature without being subjected to any heat. Also, different subjects were used in the two experiments to measure glycemic index. A *t* test comparing glycemic index means from raw sweet potato skin showed statistical differences between Experiment 1 and Experiment 2. Conversely, sweet potato flesh glycemic indices were not statistically different between our two studies. The variability shown in sweet potato skin glycemic indices may be due to the microwaving done to thaw frozen samples in the second experiment. The energy from the microwave can thaw the samples of sweet potato in one minute, but some areas can become hotter than others.

The glycemic index calculated by Zakir, *et al.,* [2] for dehydrated Beauregard sweet potato was 30, which is not too different from the value of 40 determined in Experiment 1. Both values are lower than reported in U.S. Dietary Guidelines [50], and the values reported for cooked sweet potato [36]. The reproducible low values are beneficial for sweet potato consumers. The low glycemic index will allow for a slow rate of glucose absorption, thus maintaining low blood glucose levels. Zakir, *et al.,* [2] suggested the possible presence of α-amylase inhibitor protein in sweet potato skin that could cause low glycemic index values. The quantity of total dietary fiber may also have an effect on the glycemic index produced from Beauregard sweet potatoes.

The main purpose of Experiment 2 was to help elucidate such mechanisms that might be responsible for the low glycemic index in raw sweet potato and in sweet potato peel. The dietary supplement Caiapo, extracted from a white sweet potato peel, had been shown to improve glucose tolerance in several long-term clinical studies [54-56]. In the single feeding comparison of Experiment 2, we noted that Caiapo tended to lower the glycemic index of white potato, although the 22% difference was not statistically significant in this group of subjects. In contrast, Zakir, *et al.,* [53] added Caiapo to a glucose drink and found minimal or no effect on glycemic response.

The measurement of insulin and C-peptide changes in response to the sweetpotato in Experiment 2 was designed to determine whether these treatments increase insulin release, like diabetes drugs such as sulfonlyureas do, or increase insulin binding and uptake. The lack of significant difference between the reactions to different samples indicates that Caiapo did not significantly increase pancreatic insulin release in the first hour. The results from white potato + Caiapo are difficult to explain using the conclusion of Ludvik, *et al.,* [40, 54] that Caiapo increases insulin efficiency, since Caiapo tended to lower the glycemic index of white potato with no prior exposure, but did not significantly change the apparent rates of insulin release or peripheral insulin clearance.

C-peptides are the protein fraction of pro-insulin that is not metabolized immediately after release because it does not react with specific receptors. Quantifying C-peptide levels post-prandially specifies how much insulin was released from the pancreas better than does the insulin concentration because insulin has a shorter half-life. The values measured for C-peptide release (427 pmol/L/hr) were 11.7 times higher than for insulin. This ratio suggests that the insulin change between 0 and 1 hr underestimates the actual amount of insulin secretion, due to more rapid insulin turnover as it interacts with receptors on target cells. Also, the 1-hr time point in the experiment may not capture the peak insulin or C-peptide concentration because the glucose concentration reached a peak 15-30 min after consuming carbohydrate in most individuals.

Overall, the data in Table **2** suggest that insulin and C-peptide secretion by the pancreas responds to the elevation in blood glucose. These data do not strongly support hypotheses that raw sweet potato flesh or peel, or the Caiapo protein, lowers blood glucose by either stimulating insulin release or improving insulin sensitivity with consumption of these products in one dose.

Further research is needed to fully understand the mechanisms for the low glycemic index of raw sweet potato and the apparently lower values for skin or peel than flesh. Possible mechanisms include the dietary fiber content, starch granule structure, or other bioactivities of the protein components. One or more of these components could impact carbohydrate digestion or absorption, creating lower glycemic indices.

SUMMARY & SUGGESTIONS FOR FUTURE WORK

Beauregard sweet potato samples had glycemic indices that were low to medium despite different methods of cooking. This may prove beneficial for diabetic patients who consume sweet potatoes. Using the glycemic index can help diabetic patients predict their daily diets to control blood glucose levels. The total dietary fiber content of sweet potatoes is enough to affect the glycemic index elicited by these roots, and we cannot rule out a bioactive effect of the protein components.

Further research quantifying the amount of maltodextrins produced from starch after various cooking procedures using HPLC can give insight to starch breakdown by cooking.

Measuring the concentrations of the resulting sugars could help explain whether readily absorbed available carbohydrate is related to the glucose response and glycemic index [60]. Isolating the protein fractions from this or similar cultivars of sweet potato would allow for evaluation of bioactive effects.

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