LOW-CARBOHYDRATE BREAD

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FORMULATION OF HIGH-PROTEIN, HIGH-FIBER (LOW-CARBOHYDRATE), REDUCED CALORIE BREADS

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INTRODUCTION

A great deal of attention has recently focused on low-carbohydrate foods and beverages (1–4). Because of overwhelming consumer interest in these types of products, traditional mainstays of the American dinner table such as bread, pizza, pasta, and potatoes are losing favor due to their high carbohydrate content. This topic initiated considerable discussion and debate in the food industry among sales and marketing professionals, product developers, nutritionists, dietitians, and research and development scientists (5–6). Trade magazines and scientific journals picked up on the subject and reported the connection of low-carbohydrate foods with the Atkins Diet (7). This brought the pros and cons of the various diets for losing weight and/or improving overall health and wellness into the limelight (3–4, 7–13). In addition, high carbohydrate intake was linked to the prevalence of overweight condition, obesity, and diabetes among the population (1–4).

The quick rise in popularity of low-carbohydrate products challenged the abilities of both ingredient suppliers and food manufacturers to respond appropriately to heightened consumer interest. Overwhelming industry demand led to a shortage of production capacity, placing a considerable burden on ingredient suppliers. From the food manufacturing side, most food designers accelerated their market introduction of low-carbohydrate products to keep up with consumer demand. The race to offer low-carbohydrate versions created some crowded supermarket shelves in just a few months. Then, surprisingly, sales declined recently, casting doubt on the staying power of low-carbohydrate products (14). Factors contributing to the decline of consumer interest included price, taste, texture, product positioning, and potential health issues of newly introduced low-carbohydrate foods when compared to traditional versions (4, 11). The question now is whether this low-carbohydrate phenomenon will perish, slow down, or remain viable and evolve into a solid, niche category.

This Bulletin will discuss the popular diet plans for weight control, the role of carbohydrates in obesity and diabetes, government regulations on carbohydrate labeling, ingredients for low-carbohydrate formulations, and food processing adjustments in the production of low-carbohydrate foods. In addition, a study to evaluate breads formulated with high-protein, high-fiber (low-carbohydrate) ingredients will be reported.

POPULAR DIET PLANS FOR WEIGHT CONTROL

In the 1970s, Dr. Robert Atkins, now deceased, popularized the low-carbohydrate, high-protein diet that bears his name. There are four phases in the **Atkins Diet** (7). Induction, the first phase of this program, initiates weight loss. Its purpose is to induce a change in the body chemistry that leads to lipolysis and a secondary process known as ketosis. During ketosis, the body switches from using glucose for energy to using fats. Foods that are consumed liberally during the Induction Phase are poultry, fish, shellfish, eggs, and red meat, as well as pure, natural fats in the form of butter, mayonnaise, and olive, safflower, sunflower, and other vegetable oils. Fruit, bread, pasta, grains, starchy vegetables, and dairy products other than cheese, cream, or butter are forbidden. Carbohydrate consumption is limited to 20 grams per day, and these must come in the form of salad greens and other vegetables (e.g., two to three cups per day of escarole, fennel, radicchio, cucumber, lettuce, or mushrooms). Salads can be garnished with bacon bits, grated cheese, and hard-boiled eggs. Eight glasses of water per day are to be consumed and can be in the form of tap water, spring water, mineral water, or filtered water. Other allowed beverages include herbal tea and decaffeinated coffee. The Induction Phase serves to stabilize blood sugar, curb food cravings, break food addictions, control fatigue, and result in weight loss. Ongoing Weight Loss is the second phase of the Atkins Diet. It follows the same diet regimen as the Induction Phase, except that the carbohydrate intake is increased by 5 grams each week until the Critical Carbohydrate Level for Losing Weight is attained. Next is the Pre-Maintenance Phase, which bridges losing weight and maintaining weight. Carbohydrate intake is increased by 10 grams each week until a Critical Carbohydrate Level for Maintenance is reached. The fourth phase is Lifetime Maintenance, involving a diet that adheres strictly to the Critical Carbohydrate Level for Maintenance.

Dr. Arthur Agatston, a cardiologist based in south Florida, developed the **South Beach Diet** for his chronically overweight heart patients (8). This diet focuses on glycemic index (i.e., how much a particular food raises the blood sugar level). Rapid spikes with immediate lowering of blood sugar lead to overeating because a feeling of hunger soon occurs. This diet promotes reduced consumption of "bad carbohydrates" while encouraging "good carbohydrates" and "good fats". Decreased consumption of carbohydrates from highly processed foods helps metabolize the food better and reduces insulin resistance, leading to weight loss. The South Beach Diet consists of three phases. Phase 1, lasting for two weeks, is the strictest phase of the diet. Its purpose is to resolve the insulin resistance that was brought about by eating highly processed carbohydrates prior to embarking on the diet. Phase 1 is similar to the Induction Phase of the Atkins Diet, but it provides ample portions of protein, good fats, and the lowest glycemic index carbohydrates for blood sugar control. During this period, the diet consists of normal-sized servings of meat, chicken, turkey, fish, shellfish, vegetables, eggs, cheese, nuts, and salads with olive oil in the dressing. The following foods are not allowed: rice, potatoes, pasta, baked goods, fruits, candy, ice cream, sugar, beer, or alcohol. A typical day consists of three balanced meals with midmorning and midafternoon snacks and a dessert after dinner. Drinks consist of water, coffee, or tea. Phase 2, a more liberal version of the diet, allows the introduction of healthy sources of carbohydrates such as fruits, whole grain breads, whole wheat pastas, and sweet potatoes in the diet. Phase 3 is the most liberal stage of the diet. Ideal weight is probably attained at the beginning of Phase 3. Knowledge gained in Phases 1 and 2 helps the consumer determine how to eat for the rest of his or her life. The South Beach Diet is sometimes referred to as a "kinder" or "less strict" version of the Atkins Diet.

The **North Beach Diet**, which draws its name from a San Francisco, CA, neighborhood, was created by Mauricio Mazzon, author of "Il Fornaio Pasta Book", in response to the low-carbohydrate phenomenon (15–16). This diet emphasizes whole grains, complex carbohydrates, and vegetable-based dishes, and it encourages 30 minutes of daily exercise.

Balance is the focus of the **Zone Diet**, developed by Dr. Barry Sears (9–10). The key is balancing the ratio of carbohydrate, fat, and protein in the diet. Consuming the right amounts of these components helps control the body's insulin production and promotes fat burning more effectively. The Zone Diet's food plan recommends daily caloric contributions from carbohydrate, protein, and fat of 40, 30, and 30%, respectively. The caloric content of the diet is low (typically 800–1200 calories per day), which most likely causes the weight loss.

The **Protein Power Diet** is an insulin-management eating plan devised by Drs. Michael and Mary Eades in 1995 (9–10, 17). This high-protein, low-carbohydrate diet calculates protein minimums and carbohydrate maximums based on body composition (height, weight, body fat percentage) and the activity level of the individual. The Eades couple feels that obesity is a result of insulin sensitivity rather than of overeating. When the diet restricts insulin production, it results in weight reduction as well as control of ailments such as high cholesterol, high blood pressure, and elevated blood sugar levels. High-protein foods such as meats, poultry, and fish are encouraged, as are milk, cream, and cheese, but not bread and pasta. The Protein Power Diet is very similar to the Atkins Diet as both are very restrictive to carbohydrates. The diet consists of three stages. Stage I is Intervention, which allows very low carbohydrate intake until the dieter approaches his or her target weight. Stage II is Transition, during which some additional carbohydrates are introduced until the target weight is met. Stage III is Maintenance, where carbohydrate intake is increased to maintain the target weight.

The **Fat Flush Plan** was conceived by nutritionist Ann Louise Gittleman. This fat-flushing, liver-loving, low-carbohydrate diet calls for drinking eight glasses of cranberry water a day to deter water retention and help clean up cellulite (17). In addition, drinking a glass of hot water with fresh lemon juice is recommended to aid fat metabolism and delay carbohydrate digestion.

The **Schwarzbein Principle** is a diet plan that emphasizes the need for stress management as well as metabolic healing, since stress hormones affect the food cravings of a person (17).

The **Neanderthin Diet**, which rules out grains, beans, potatoes, sugar, and virtually all processed foods, was conceived by Ray Audette (9, 17). The premise of this diet is a return to the unprocessed foods eaten by the hunter/gatherer societies of the Paleolithic Era. This caveman diet does not involve carbohydrate or calorie counting, but encourages keeping the carbohydrate intake low. No sugar is allowed on the diet, although small amounts of honey may be included. Artificial sweeteners, alcoholic beverages, and dairy products are forbidden.

A low-fat, high-fiber diet originally designed to prevent heart disease was developed by Nathan Pritikin. This **Pritikin Diet** eliminates white bread and pasta in favor of whole grains, while most fats are exchanged for fruits and vegetables (10). The diet includes regular exercise, with a minimum of a 45-minute walk per day.

Somewhat similar to the Pritikin Diet is the **Ornish Diet**, which limits fat to 10% of total calories (roughly 15–25 grams of fat) per day (18). The goal of this diet, developed by Dr. Dean Ornish, is to prevent or treat heart disease. To achieve a low level of fat intake, many foods must be avoided, including meat, fish, oils and fats, avocados, olives, nuts, cheese, whole or low-fat milk, egg yolks, and any other food product that has more than 2 grams of fat per serving. Caffeine is prohibited, but moderate intakes of alcohol, sugar, and salt are allowed. Non-fat dairy products are also allowed in moderation. The Ornish Diet primarily includes legumes, vegetables, fruits, and whole grains. In addition to a low-fat, whole-foods diet, Dr. Ornish encourages moderate exercise, stress management techniques, and social support.

Weight Watchers has been around for years (9). Participants are told how much of specific food groups should make up their daily meals and snacks. In 1997, the program began its "Points" program known as "1–2–3 Success", which is still in use today but is now called "Winning Points". Each food has a particular "Points" value. The number of Points is tracked, which allows for planning the remaining meals and snacks accordingly. Any type of food is acceptable on Weight Watchers. The key is meeting the allotted Points for the day.

The **Slim Fast Diet** is a meal replacement diet that relies on one Slim Fast shake for breakfast, another shake for lunch, and a normal or sensible meal for dinner (10). The daily caloric intake for a Slim Fast Diet is 1000–1200 calories. Weight loss experienced by followers of the diet is due to its low calorie content.

OBESITY, DIABETES, AND CARBOHYDRATES

Recent statistics indicate that more than two-thirds of Americans are either overweight or obese, and the number has been growing (19–21). Approximately 127 million adults in the U.S. are overweight, 60 million are obese, and 9 million are severely obese. This figure is a substantial increase compared to 1980, when only 47% of Americans were overweight or obese.

A variety of methods can be used to determine a person's overweight or obese status, but the most common one is Body Mass Index (BMI). This is defined as body weight (in kilograms) divided by height (in meters) squared [or as body weight (in pounds) divided by height (in inches) squared then times 703]. According to the Centers for Disease Control and Prevention (CDC), a BMI value between 25 and 30 indicates overweight status, over 30 is considered obese, and over 40 is severely obese. The primary causes of escalating obesity rates are increased per capita caloric consumption and larger portion sizes, along with a lack of adequate physical activity.

Obesity has become the second leading cause of preventable death behind smoking. Conditions that arise as a result of obesity are type II diabetes, cardiovascular disease, osteoarthritis, and certain cancers. Diabetes, the fifth deadliest disease, afflicts about 17 million people in the U.S. (22). This disease affects the body's ability to produce or respond to insulin, a hormone that allows blood glucose to enter the cells for energy production. Of the 17 million people with diabetes, about 10% have type I diabetes, in which the body's immune system attacks and destroys the insulin-producing cells of the pancreas. As a result, the body cannot produce insulin. The remaining 90% have type II diabetes, which results from the body's failure to make enough or properly use insulin.

A related condition called pre-diabetes affects an additional 16 million Americans. Pre-diabetes is characterized by blood glucose levels being higher than normal but not yet above diabetic levels. Most people with this condition have a high risk of eventually developing type II diabetes. Pre-diabetes and type II diabetes can often be controlled through weight loss, improved nutrition, and increased physical activity.

Government initiatives that may help curb the obesity epidemic include healthier food programs, exercise plans, and dietary guidelines. Several options for weight management would include practices that promote the following: increased body metabolism, increased satiety, reduced caloric intake, reduced glycemic index, and consumption of low-carbohydrate foods. Low glycemic index foods promote low and slow blood glucose release that can make an individual feel full longer. This was shown in a British study of 38 children who had lower lunch intakes after consuming low-glycemic index breakfasts compared with higher lunch intakes after high-glycemic index breakfasts (23).

Short-term use of low-carbohydrate, high-fat diets was shown to be both safe and efficacious among obese patients with heart disease (24). These patients experienced a 5% loss of body weight without adverse health effects. In another study, 160 subjects weighing an average of 220 pounds (99.8 kg) were placed on one of four diets—Atkins, Zone, Ornish, or Weight Watchers (25). On average, the subjects lost 5% (approximately 10–12 pounds [4.5–5.4 kg]) of their body weight. In addition, those who lost weight also reduced their heart disease risk by 5–15% through reduction of risk factors such as cholesterol levels.

GOVERNMENT REGULATIONS ON CARBOHYDRATE LABELING

Current Regulations

While consumers witness an abundance of nutrient claims on a multitude of food product labels, claims such as "low-carb", "reduced-carb", or "only *x* grams carbs" are not authorized by the U.S. Food and Drug Administration (FDA). Statements such as these were never defined as part of the Nutritional Labeling and Education Act of 1990 (NLEA), and therefore their presence is considered misbranding of the product (2, 6, 26). Standards do not currently exist and there are no firm FDA definitions for terms such as "low-carbohydrate", "reduced-carbohydrate", "net-carbohydrate", "good source of carbohydrates", or "excellent source of carbohydrates". A simple factual statement of the amount of carbohydrates present in the product (typically based on the food's serving size) is the sole permissible type of carbohydrate label statement. For example, a food label that states "9 grams of carbohydrates per serving" would be permissible. However, labels such as "only 9 grams of carbohydrates per serving" or "contains 9 grams of carbohydrates per serving" would not be sanctioned by FDA. Either one would constitute a misbranding violation because the word "only" is considered a relative/comparative claim and the word "contains" equates to a "good source of" statement within the application of labeling regulations. In lieu of an official FDA standard, many food companies sidestep potential labeling issues by using terms including "Carb Smart", "Carb Aware", "Carb Sense", "Carb Well", "Carb Simple", or "Low-Carb Life Style".

Proposed Regulations

Making carbohydrate claims is confounding because this is the only nutrient in foods for which there would be both "low" and "high" claims. Clearing up the labeling confusion may be critical to extending the life of the low-carbohydrate movement. FDA, at the urging of the Grocery Manufacturers of America, American Bakers Association, and major food companies, is considering labeling legislation. The petition to establish new regulations for carbohydrate nutrient claims will help provide more accurate carbohydrate content information on food labels. The agency stated that it would commence rulemaking procedures and labeling guidelines, and that it would publish its proposed regulations regarding carbohydrate terminology in the Federal Register. The FDA further stated that it plans to fund a year-long dialog on the subject of carbohydrates and their dietary effects.

The Macronutrient Report of the National Academy of Sciences and recommendations of the Grocery Manufacturers of America, the American Bakers Association, and several major food companies may serve as the basis for establishing labeling standards (1–2, 27). Threshold levels were proposed covering five separate claims: "carbohydrate-free", "low-carbohydrate", "reduced-carbohydrate/less carbohydrates", "good source of carbohydrates", and "excellent source of carbohydrates" (Table I).

Carbohydrate-Free: It was proposed that foods qualifying for a "carbohydrate-free" claim should contain no more than 0.5 gram of carbohydrates per serving and per reference amount customarily consumed (RACC). This value is consistent with current regulations applying to such claims as "sugar free" and "fat free".

Low-Carbohydrate: For the "low-carbohydrate" claim, three proposals were presented. One suggested that individual foods should have less than 2% of the federal government's daily suggested reference value of 300 grams for carbohydrates, or 6 grams per labeled serving or RACC. For meal-type and main dish products, the recommended threshold level was set at not more than 6 grams of carbohydrates per 100 grams of food, and that no more than 50% of calories could come from carbohydrates. The second proposal would raise the upper limit for a "low-carbohydrate" claim to 9 grams for both individual foods and meal-type products. The third proposal relates to a statement by the Institute of Medicine of The National Academies that a healthy diet consists of receiving 45–65% of calories from carbohydrates, and that consumption of food with 9 grams or less of carbohydrates would allow receiving only 28% of calories from carbohydrates. Thus, thresholds of 6 or 9 grams could potentially lead to "unhealthy diets", so the third proposal would place the threshold at 15 grams. The Alcohol and Tobacco Tax and Trade Bureau issued an interim policy (TTB Ruling 2004-1) on "low carbohydrate" when marketing alcoholic beverages, defining the term as less than 7 grams of carbohydrates per 12 fl. oz. (355 ml) serving of malt beverage, 5 fl. oz. (148 ml) serving of wine, or 1.5 fl. oz. (44 ml) serving of distilled spirits (4).

Reduced-Carbohydrate or Less Carbohydrates: In order for food products to qualify for this claim, it has been proposed that the food should contain at least 25% less carbohydrates when compared to an appropriate reference food. This proposal would essentially follow FDA's current guidance for relative nutrient claims. It is speculated that reduced-carbohydrate foods would command a larger market than low-carb or carbohydrate-free products because product taste and price are not greatly compromised.

Good Source of Carbohydrates: One proposal for "good source of carbohydrates" claims would re-

TABLE I

PROPOSED DEFINITIONS BEING CONSIDERED BY FDA FOR CARBOHYDRATE LABELING OF FOODS

Nutrient Claim	Proposed Levels of Carbohydrate [a]
Carbohydrate-Free	Less than 0.5 gram
Low-Carbohydrate	Less than 6 grams [b] Less than 9 grams [c] Less than 15 grams
Reduced-Carbohydrate or Less Carbohydrates	25% reduction [d]
Good Source of Carbohydrates	More than 15 grams [e] More than 20 grams [f] More than 30 grams [g] More than 45 grams [g] At least 60% of calories from carbohydrates
Excellent Source of Carbohydrates	More than 30 grams [e] More than 40 grams [f] More than 45 grams [g] More than 60 grams [g] More than 75% of calories from carbohydrates
Net Carbohydrates	No definition to be issued Provide guidance on how to calculate

[a] Per serving or per Reference Amount Customarily Consumed (RACC) and for individual foods unless otherwise noted

[b] For individual foods, per serving or per RACC; for meal-type and main dish products, per 100 grams and with less than 50% of calories from carbohydrates

[c] For both individual foods and meal-type products

[d] Compared to an appropriate reference food

[e] Foods qualifying for this claim should have less than 6 grams sugar

[f] Foods containing more than 30% simple sugars should not qualify for the claim

[g] For meal-type or main dish products

quire individual foods to contain 15 grams or more of carbohydrates per serving or RACC with an added caution that no food qualifying for this claim should have more than 6 grams of sugar. Another proposal would set the minimum limit for this claim on individual foods at 20 grams per RACC, but adds that foods containing more than 30% simple sugars should not qualify for the claim. Meal-type and main dish products would have the carbohydrate threshold being either 30 or 45 grams. A third proposal would allow foods to qualify for the "good source of carbohydrates" claim if at least 60% of the calories come from carbohydrates.

Excellent Source of Carbohydrates: Proposals for "excellent source of carbohydrates" claims include requiring individual foods to contain at least 30 or 40 grams of carbohydrates per serving or RACC, with qualifiers that foods using this claim should not have more than 6 grams of sugar or contain more than 30% simple sugar. For meal-type and main dish products, the carbohydrate level is recommended to be 45 or 60 grams. Another proposal would allow foods to qualify for the claim if at least 75% of their calories come from carbohydrates.

Net Carbohydrates: FDA has indicated that it does not plan to issue a proposed rule defining "net carbohydrates". Instead, the agency will offer guidance on how companies should calculate and list "net carbohydrate" amounts on food packages. It is likely that FDA will recommend food companies use an equation that subtracts both fiber and sugar alcohol contents from total carbohydrates. Because of concerns that consumers will mistake foods containing low "net carbohydrates" for foods also containing few calories, the agency is also being asked to issue guidance that any label promoting net carbohydrates also feature a prominent declaration of calories per serving.

INGREDIENTS FOR LOW-CARBOHYDRATE FORMULATIONS

Some of the low-carbohydrate food and beverage products that have been marketed (1, 26, 28) include: a) pasta available as spaghetti, rotini, elbows, lasagna, and penne with net carbohydrates per serving of 19 grams as compared with the normal 39 grams; b) sandwich breads in white and wheat varieties with 9 grams of carbohydrates per serving, which represents a 40% reduction in carbohydrates compared with regular breads; c) breads available in white, wheat, and multigrain varieties containing 10 grams of total carbohydrates, 4 grams of dietary fiber, and 6 grams of net carbohydrates per serving; d) tortilla chips with 6 grams of net carbohydrates, 10 grams of protein, and 3 grams of fiber per serving; e) frozen, ready-to-eat controlled-carbohydrate and sugar-free bakery products that include muffins, half-ring crème cakes, and decorated round iced white cakes; f) organic bread with 4 grams of net carbohydrates per slice; g) energy bar that uses zero net carbohydrate ingredients; h) breakfast cereal containing 8 grams of net carbohydrates and 13 grams of protein; i) beer with 2.6 grams of carbohydrates per 12 oz. (355 ml) serving; j) fruit juice with 75% less carbohydrates; k) cheesecake with 6 grams of net carbohydrates per serving; l) low-carbohydrate ice cream and frozen novelty products; m) low-carbohydrate beverages, sauces, marinades, spreads, soup mixes, bars, and shakes; n) low-carbohydrate fryer coatings, breadings, pizza crust blends, and bases/mixes for breads, rolls, bagels, tortillas, and pizza products; and o) ketchup with a 75% reduction in carbohydrates.

Carbohydrates, proteins, and fats are the essential building blocks of low-carbohydrate foods as well as of traditional food products. Restricting the carbohydrate content of food products is fraught with difficulty because it can compromise the taste, texture, and consistency of the food. The so-called "bad carbohydrates", which are derived from simple sugars and starches that are rapidly digested to glucose, are being replaced by other types of carbohydrates, proteins, dietary fiber, alternative sweeteners, or water.

Proteins

Replacing digestible carbohydrates with proteins to achieve low-carbohydrate status is widely practiced but adds cost (29). Bakeries look for protein sources such as wheat protein concentrate and isolate, soy protein concentrate and isolate, and dairy proteins that offer clean flavor. Whey proteins are suitable for snack bars, beverages, and confectioneries because they have excellent solubility, water binding, emulsification, gelation, whipping, foaming, and viscosity characteristics (30). Wheat and soy protein isolates supplement durum semolina in low-carbohydrate pasta. The use of soy protein in nutritional bars, beverages, and bakery products is significant due to its functionality and heart health claim. Wheat proteins and their properties are covered later in this Bulletin. Apart from these protein ingredients, most low-carbohydrate products often include ingredients such as nuts, flax seed, amaranth, garbanzo beans, fava beans, oat flakes, and whole grain ingredients.

Dietary Fibers

Dietary fibers serve primarily as a bulking agent for low-carbohydrate applications, replacing the more easily digestible carbohydrates and fats. Boosting the fiber level can reduce the net carbohydrate level. However, high-fiber ingredients can impart heavy taste and texture that are challenging to overcome. For example, high-fiber breads are typically heavy and may have an unacceptable flavor.

Sources of dietary fiber include resistant starch, inulin, digestion-resistant maltodextrin, polydextrose, gums, and flax seed, as well as soy, oat, barley, and wheat fibers. As an insoluble fiber and non-digestible carbohydrate, resistant starch can replace rapidly digestible carbohydrates such as flour and can convert high-glycemic foods into moderate or low-glycemic alternatives (26). Resistant starch is discussed in greater detail later in this Bulletin. Inulin is a non-digestible soluble fiber with prebiotic properties. It can replace digestible carbohydrates in foods, reducing calories and limiting blood sugar level increases. A digestion-resistant maltodextrin is described as odorless, tasteless, and having 90% soluble fiber. It is stable in most processing conditions and can enhance the texture of low-carbohydrate products. Polydextrose with 90% fiber content and low glycemic response can replace both sugar and fat, resulting in calorie reduction. Gums or hydrocolloids can be used in low-carbohydrate formulas to provide body and help retain moisture. Fiber derived from citrus pulp possesses high water-binding capacity and can reduce net carbohydrates in baked products by 7–8%, increase softness and yield, and improve grain, texture, and flavor. Flax seed contributes 27% fiber, and its significant contents of protein, omega-3 fatty acids, and lignans provide additional health benefits to low-carbohydrate products.

Alternative Sweeteners

Sugars in traditional food products supply calories but are limited in other nutrients. When taken as an all-inclusive term, sugars refer not just to sucrose but also to glucose (dextrose), fructose, maltose, lactose, corn syrups, maltodextrin, honey, molasses, malt, fruit-juice concentrates, maple syrup, and trehalose (31). When removing these sugars from food products, sweetness is addressed by adding high-intensity sweeteners and/or sugar alcohols (30). Because of their elevated sweetness level, high-intensity sweeteners are often used in small quantities and, therefore, do not contribute bulk nor provide a significant amount of calories to the food. These sweeteners include sucralose, acesulfame K, aspartame, saccharin, and neotame with respective sweetness intensities of 600, 200, 180–200, 300–400, and 7,000–13,000 relative to sugar (32).

Sugar alcohols are particularly effective in low-carbohydrate applications because they can be used weight-for-weight in the same amount as sugars. These sugar alcohols or polyols include erythritol, isomalt, lactitol, mannitol, maltitol, sorbitol, xylitol, and hydrogenated starch hydrolyzates or polyglycitol syrups. All polyols, with the exception of erythritol, contribute a non-trivial amount of dietary calories (32). Caloric contributions of the individual polyols in calories per gram are as follows: erythritol, 0.2; isomalt, 2.0; lactitol, 2.0; maltitol, 3.0; mannitol, 1.6; sorbitol, 2.6; xylitol, 2.4; and hydrogenated starch hydrolyzates, 3.0. Many of these calories are absorbed through the large intestine in the form of short-chain fatty acids and other glycolytic intermediates. Some negative effects of polyols on bowel function include flatulence and diarrhea in susceptible individuals.

FOOD PROCESSING ADJUSTMENTS

During the low-fat craze of the 1990s, the primary challenge to food formulators was how to take out or reduce fat in food products, yet still retain the desired taste and texture (33). Similarly, developing low-carbohydrate bakery and pasta products poses enormous difficulties to food designers. The product development process requires removing easily digestible carbohydrates (flour, starch, oligosaccharides, and sugars) and replacing them with proteins, non-digestible carbohydrates like fibers (including resistant starch and fructo-oligosaccharides like inulin), alternative sweeteners, or water (30). Troublesome technical challenges, including flavor, texture, and processing functionality, may arise due to substitution of ingredients. Taste issues may result from protein off-flavors, flavor masking by complex carbohydrates, or trying to match sweetness level. Removing lower molecular weight ingredients and replacing them with water and higher molecular weight ingredients can lead to moisture retention and control issues, which often result in texture and mouthfeel deterioration. In addition, formulators must contend with equipment adjustment, expanded clean-up time, learning how to use ingredients yet to be incorporated into low-carbohydrate formulations, and upcoming government regulations.

Low-carbohydrate bakery products often contain increased levels of protein and fiber and minimal sugar. High intensity sweeteners and/or sugar alcohols are frequently used. Protein and fiber ingredients tend to absorb more water and affect mixing time. High levels of water can elevate the relative vapor pressure and can potentially lead to rapid development of mold in the product after baking. Hence, calcium propionate in many low-carbohydrate baked foods is increased to 0.2–0.3% (flour basis, fb) compared to conventional formulations. Mold inhibitors at 0.5–1.5% (fb) are used in low-carbohydrate tortillas. Due to low levels of sugar, adequate gas production in low-carbohydrate breads can be provided by increased yeast levels. High protein addition in the form of wheat gluten and/or wheat protein isolate can lead to dough buckiness, which can be remedied by proper protein balance. This high protein level may allow the removal of oxidizing agents but would require an increased shortening level for lubricity. Doughs from low-carbohydrate, high-protein formulas normally require extended baking time, which amounts to roughly 20% longer than traditional bread formulation. Underbaking can cause the bread to collapse.

EVALUATION OF HIGH-PROTEIN, HIGH-FIBER (LOW-CARBOHYDRATE) BREADS

The baking industry is beginning to be a major player in the low-carbohydrate arena as can be gleaned from the preponderance of "low-carb" or "reduced-carb" bakery products in the market. Initially, attempts were made to decrease the carbohydrate level in bakery products by substituting a protein source for flour in the formulation. While this approach addressed the problem of providing a high-protein, low-carbohydrate product, the resulting product generally did not possess the handling characteristics, loaf volume, crumb grain, texture, or flavor of a traditional bakery product. For example, if vital wheat gluten is used in large amounts, the dough will be too strong or bucky and difficult to handle during the mixing, dividing, sheeting, and molding operations. Also, high levels of protein additives, such as those from soy, may adversely affect the flavor, loaf volume, and crumb structure. Consumer responses to the sensory attributes of breads with decreased carbohydrates are mixed, ranging from "acceptable" to "fair" to "awful".

Most commercially available "low-carb" or "reduced-carb" bakery products are formulated with wheat protein isolate, soy protein isolate, or milk proteins as evidenced by the ingredient statements. In addition, cereal brans, hydocolloids, resistant starches, or other fiber sources as well as polyols or other sweeteners are utilized to decrease the level of digestible carbohydrates. Because resistant starches and wheat proteins appear to be preponderant ingredients used for this purpose, they are discussed in greater detail below.

Resistant Starches

The Expert Committee on Dietary Fiber Definition of the American Association of Cereal Chemists defines dietary fiber as "the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation" (34). Resistant starch (RS) is defined as "the sum of starch and products of starch degradation not absorbed in the small intestines of healthy individuals" (35). It is included in the definition of dietary fiber under analogous carbohydrates. Analogous carbohydrates (34, 36) are materials not necessarily intrinsic to a part of a plant as consumed, but that exhibit the digestion and fermentation properties of fiber. These analogous carbohydrates are produced by purposeful synthesis, by food processing and storing, or by chemical and/or physical processes affecting the digestibility of starches. Carbohydrates with structures analogous to those of naturally occurring dietary fibers have been shown to provide desirable physiological benefits (37–39).

Numerous countries have adopted the AOAC International *Official Methods of Analysis* as the basis for enforcing dietary fiber labeling regulations. Internationally, the generally accepted methods for measurement of dietary fiber are *AOAC Methods 985.29* and *991.43* (40–41). These methods involve enzyme treatment for starch and protein removal, precipitation of soluble dietary fiber by alcohol, isolation and weighing of dietary fiber, and correction for ash and protein in the residue. When analyzed by *Method 991.43*, commercially available RS samples have total dietary fiber contents of 30–80%. Thus, resistant starches, which consistently resist digestion in well-designed and validated fiber assays, are classified as dietary fiber (34, 36).

RS is categorized into four types depending upon its mechanism of enzyme resistance (37, 42–43): RS 1 (entrapped), RS 2 (ungelatinized), RS 3 (retrograded), and RS 4 (modified). Currently, there are ten commercially available sources of RS: three RS 2 (all based on high-amylose maize), three RS 3 (two based on high-amylose maize and one on tapioca), and four RS 4 (based on wheat, potato, high-amylose maize, and tapioca). Scanning electron micrographs show a granular appearance for RS 2 and RS 4, whereas RS 3 (high-amylose maize) has a collapsed or shrunken appearance and RS 3 (tapioca) exhibits a congealed or agglomerated structure. Reported total dietary fiber (*Method 991.43*) contents based on manufacturer's product brochures for commercial RS 2 and RS 3 high-amylose maize range from 30 to 60%. Commercial RS 4 wheat, potato, high-amylose maize, and tapioca products contain 70–80% total dietary fiber. Scanning electron microscopic examination of RS residues from *Method 991.43* indicate that, in the case of RS 4 starches, the enzyme digestion proceeds by surface erosion of the starch granule rather than by boring holes or by pitting.

Water-holding capacities of commercial RS 4 starches are lower than RS 2 and RS 3 products. RS 4 products exhibit low swelling power and low solubility in water at 95°C (203°F) and in dimethyl sulfoxide (44–46). Animal and human feeding studies reveal the physiological benefits of RS in general. These benefits include: reducing available calories, decreasing glucose and insulin responses, lowering blood cholesterol, providing fermentable substrate to bowel microflora, increasing short chain fatty acid production in the large bowel, decreasing secondary bile acids in the large bowel, increasing fecal output, and reducing fecal transit time (37–39).

Wheat Proteins

Wheat gluten is the viscoelastic protein-starch-lipid complex separated after wet processing of wheat flour (47–49). Following drying, the product contains at least 75% protein content (N x 5.7, dry basis). The protein portion is a binary mixture of two polymers: gliadin and glutenin. These components can be separated by alcohol extraction or by using a non-alcoholic process employing organic acids (50). Commercial-grade gliadin produced by this non-alcoholic process has at least 90% protein, and the glutenin has at least 80% protein (N x 6.25, dry basis). Upon hydration, gliadin exhibits extensibility characteristics whereas glutenin shows elastic properties (47, 49, 51).

Wheat protein concentrates are proteinaceous compositions having protein contents of at least 75% (N x 5.7, dry basis). These concentrates are manufactured by dispersing wheat gluten in aqueous solutions of organic acids at ~pH 4 or aqueous solutions of ammonia (~pH 10–11) in the presence or absence of reducing agents, sucrose esters, or other food-grade additives that impact gluten rheology (47, 49). These concentrates exhibit lesser viscoelastic properties than wheat gluten and tend to be more extensible.

Wheat protein isolates with greater than 90% protein content (N x 6.25, dry basis) are generally derived from wheat gluten by taking advantage of gluten's solubility in dilute aqueous solutions of acids or alkalis. They exhibit the classical "U-shaped" solubility curve (47) with minimum solubility at the isoelectric point of 6.5–7.0. After dissolving gluten, the proteins can be separated through processes such as filtration, centrifugation, or membrane processing followed by spray drying. Hydrated wheat protein isolates are less elastic but more extensible than wheat gluten (47, 49). Alternatively, the protein content of wet gluten obtained during the wet processing of flour can be enhanced by repeated kneading, water washing, and dewatering followed by flash drying. This flash dried isolate demonstrates higher elasticity than wheat gluten.

Wheat gluten can be rendered non-vital or devitalized by exposure to moisture, heat, pressure, shear, enzymes, and/or chemicals (47). Devitalized gluten is characterized by denaturation of proteins where structural changes occur either by formation or breaking of certain bonds resulting in a product that is non-cohesive and lacks viscoelasticity. Typical processing equipment utilized for this purpose are jet-cookers, ovens, heated mixers, drum-driers, extruders, and boiling water tanks. Extruders, in particular, can also accomplish the texturization of wheat gluten, turning the protein into a product that when hydrated resembles the appearance and texture of meat (52). The textured product can be in the form of powders, granules, shreds, flakes, chips, cubes, and chunks.

Hydrolyzed wheat protein products are manufactured by reacting dispersed gluten with proteases having endo- and/or exo-activities to produce low-molecular weight peptides. After protease deactivation, the hydrolyzed mixture is spray dried, and the resulting powder has at least 75% protein (N x 5.7, dry basis) and at least 50% solubility in water (47, 49).

Deamidated wheat protein products can be manufactured by treating wheat gluten with low concentrations of hydrochloric acid at elevated temperatures to transform glutamine and asparagine residues in the polypeptide chain into glutamic acid and aspartic acid, respectively (47, 49, 53). This modification causes a shift in the isoelectric point of protein from neutral pH to ~pH 4. Hence, the deamidated wheat protein exhibits water solubility at neutral pH.

RESEARCH PROJECT

A research project was conducted at AIB International (AIBI) to evaluate protein-enhanced, high-fiber (low-carbohydrate) bread formulas. The test products were compared with standardized control breads.

Materials and Methods

Wheat protein isolate (Arise™ 5000), RS 4-type resistant wheat starch (Fibersym 70™), and vital wheat gluten were supplied by MGP Ingredients, Inc. (Atchison, KS). Typical nutritional profiles of these wheat-based ingredients are provided in Table II. AIBI provided the wheat flour and all other common bakery ingredients.

High-protein, high-fiber (HPHF) formulas for white and wheat bread varieties are presented in Table III. A 100% analog or synthetic flour was developed consisting of 32% flour, 20% vital wheat gluten, 23% Fibersym 70, 12% Arise 5000, and 13% soy fiber (FI-1, The Fibred Group). The HPHF straight dough formulas (white and wheat) were tested against equivalent control straight dough formulas (Table IV) in the following manner:

- white vs. white, using hard red spring (HRS) wheat flour
- wheat vs. wheat, using whole hard red winter (HRW) wheat flour
- wheat vs. wheat using whole hard white winter (HWW) wheat flour

All doughs were produced under controlled conditions in duplicate. Doughs were subjectively evaluated for handling characteristics during mixing and at make-up. Loaves were proofed to height in pans prior to baking. Weight and volume of the baked breads were measured one hour after baking. Loaves were then double wrapped in polyethylene bread bags for storage. Baked breads were subjectively evaluated for external, internal, and eating quality characteristics one day after baking.

Firmness of the breadcrumb and crumb firming rate were measured at 1, 3, 7, and 10 days after production using the Texture Technologies TA.XT2 Texture Analyzer (Stable Micro Systems, Surrey, England). At 3, 7, and 10 days after production, an informal panel conducted sensory evaluation of the breads. Internal

TABLE II

MACRONUTRIENT COMPOSITION (g/100 g) OF TEST MATERIALS USED IN THE HIGH PROTEIN, HIGH-FIBER BREAD RESEARCH PROJECT

Macronutrient	Vital Wheat Gluten	Arise 5000	Fibersym 70
Moisture	6.5	3.5	10.6
Protein	72.0	81.9	0.0
Ash	1.0	0.8	1.0
Fat	5.5	5.8	0.5
Total carbohydrates	15.0	8.0	87.9
Total dietary fiber	1.4	1.7	70.0
Net carbohydrates *	13.6	6.3	17.9

* Net carbohydrates = total carbohydrates – total dietary fiber

TABLE III

HIGH-PROTEIN, HIGH-FIBER (HPHF) BREAD FORMULAS USING WHITE OR WHOLE WHEAT FLOURS

Ingredient	Amount (Baker's %)		
	White Flour	Whole Wheat Red Flour	Whole Wheat White Flour
Flour, bread	32	–	–
Flour, fine whole wheat–Red	–	32	–
Flour, whole wheat–White	–	–	32
Vital wheat gluten	20	20	20
Fibersym 70	23	23	23
Arise 5000	12	12	12
Soy fiber, FI-1	13	13	13
Salt	1.9	1.9	1.9
Soybean oil	5	5	5
Sodium stearoyl lactylate (SSL)	0.35	0.35	0.35
Ethoxylated monoglycerides (Elasdo)	0.35	0.35	0.35
Calcium propionate	0.375	0.375	0.375
Granulated sugar	1.5	1	1
Data esters (DATEM)	0.35	0.35	0.35
Ascorbic acid	0.015	0.015	0.015
Yeast, compressed	8	8	8
Sucralose	0.008	0.008	0.008
Water	77	78	80

TABLE IV

CONTROL STRAIGHT DOUGH FORMULAS USING WHITE OR WHOLE WHEAT FLOURS

Ingredient	Amount (Baker's %)		
	White Flour	Whole Wheat Red Flour	Whole Wheat White Flour
Flour, bread	100	–	–
Flour, coarse whole wheat–Red	–	70	–
Flour, fine whole wheat–Red	–	30	–
Flour, whole wheat–White	–	–	100
Vital wheat gluten	–	8	8
Salt	2	2	2
Sodium stearoyl lactylate (SSL)	–	0.5	0.5
Ethoxylated monoglycerides (Elasdo)	–	0.5	0.5
Mineral yeast food (no oxidant)	–	0.5	0.5
Calcium propionate	0.12	0.12	0.12
Granulated sugar	7	–	–
High fructose corn syrup	–	9	9
Shortening, plastic, unemulsified	3	3	3
Yeast, compressed	2	2.5	2.5
Ascorbic acid	–	60 ppm	60 ppm
Water	63	69.7 total	75.7 total

crumb structure of the breads was objectively measured using CrumbScan™. All formulas were submitted to the AIBI Nutrition Labeling Group for generation of 100-gram Nutrition Reports of the baked breads.

Results and Discussion

As shown in Table V, the HPHF doughs had higher absorptions and required considerably less high-speed mixing time (3 to 5 minutes shorter) than the control doughs. The higher absorptions were primarily due to higher protein content, and the shorter mixing times were attributed to the wheat protein isolate, Arise 5000. Dough consistency out of the mixer was generally good for all, trending to slightly sticky and elastic for the HPHF doughs. The same doughs improved over the course of the thirty-minute floor time, to the point that most were judged good at the makeup stage. Proof times were very quick for the HPHF doughs, about 17 to 20 minutes shorter than control doughs. Bake times were increased from 20 minutes normally used for control breads to 24 minutes for the HPHF breads in an effort to bake out the greater amount of moisture and reduce the tendency to shrink on cooling. HPHF breads exhibited significantly greater volume (260 to 325 cc higher) than the corresponding control breads.

Total quality bread score results as provided in Table V showed no remarkable differences in total quality between variables. However, the HPHF breads exhibited weak crumb body, non-typical flavor, and spongy mouthfeel. It must be noted that most "low-carbohydrate" pan breads currently on the market suffer from similar sensory shortcomings, which are apparently due to the ingredient substitutions employed to arrive at the "low-carbohydrate" status. No significant functional differences were detected between the HPHF whole wheat breads made with red wheat flour and those made with white wheat flour, indicating that a bakery would not have to switch to one or the other to make acceptable product. However, crust and crumb color were lighter for the breads made with the white wheat flour, in keeping with its nature.

Texture analysis results are graphically represented in Figures 1–3. Breads made from the control formulas were the quickest to firm. Breads made from the HPHF formulas resisted firming to a much greater extent over the 10-day storage period. The firmness values of HPHF breads were in the 50 to 100-gram range for the duration of shelf life testing; these are among the softest values recorded in experimental bread samples for some time.

During Days 3, 7, and 10 shelf life testing, the panelists detected no significant flavor or aroma issues in HPHF breads. However, the soft and spongy mouthfeel and the weak crumb body were the subject of many comments.

Internal bread crumb structures measured by CrumbScan™ are presented in Table VI. Higher values for Composite Fineness and Composite Elongation indicate better quality. As crumb grain and cell fineness are easily improved by the baker through ingredient manipulation and process adjustments, the CrumbScan™ results must be thought of as snapshots of quality. Further development work almost always leads to improvement.

Finally, 100-gram Nutrition Reports of the baked breads are provided in Table VII. Reductions in calories and in total carbohydrate contents, along with significant

TABLE V

DOUGH AND BREAD CHARACTERISTICS OF CONTROL AND HIGH-PROTEIN, HIGH-FIBER (HPHF) FORMULAS

Property	White Flour		Whole Wheat Red Flour		Whole Wheat White Flour	
	Control	HPHF	Control	HPHF	Control	HPHF
Absorption, %	63	77	69.7	78	75.7	80
Mixing time, min.	10	5	8.5	5	8	5
Proof time, min.	68	45	53	36	52	34
Bread volume, cc	2441	2766	2200	2460	2144	2416
Specific volume, cc/g	5.18	6.06	4.63	5.32	4.52	5.21
Quality						
Dough score	24.2	24.0	22.0	24.5	19.2	22.8
External score	12.8	12.2	15.0	13.0	14.2	13.2
Internal score	46.8	43.2	49.5	43.2	46.8	42.5
Total score	83.8	79.4	86.5	80.7	80.2	78.5

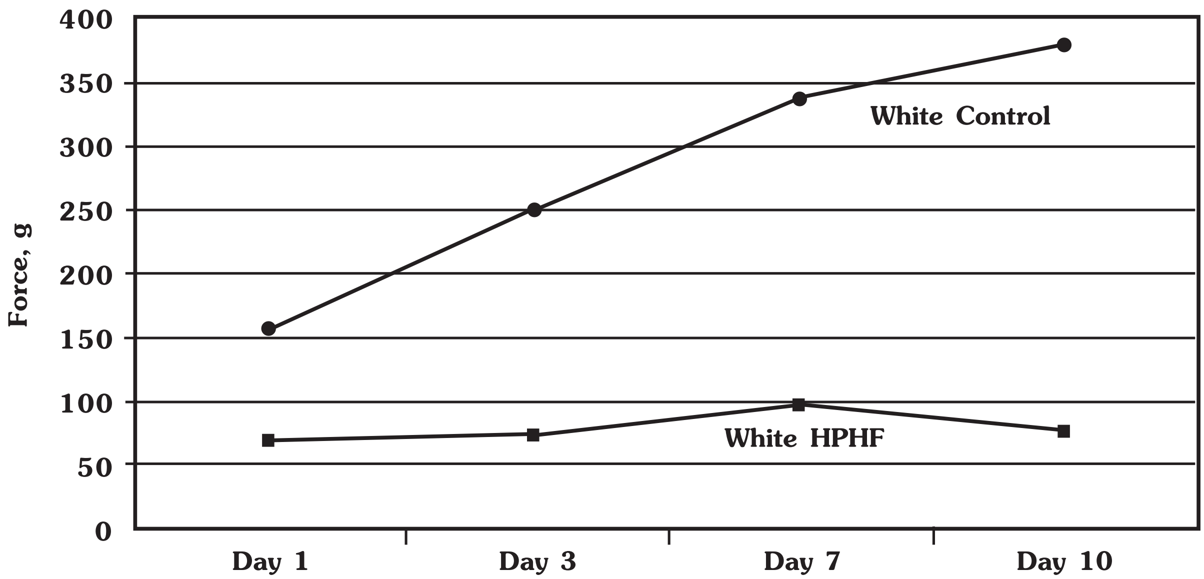

Figure 1. Crumb firmness of straight dough white pan breads.

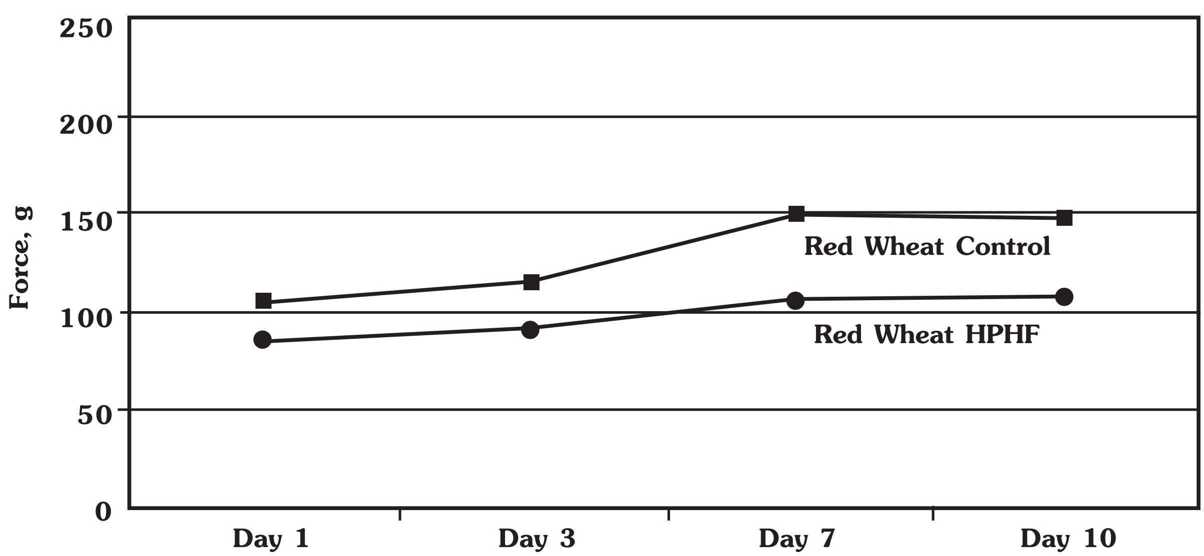

Figure 2. Crumb firmness of wheat breads from red wheat.

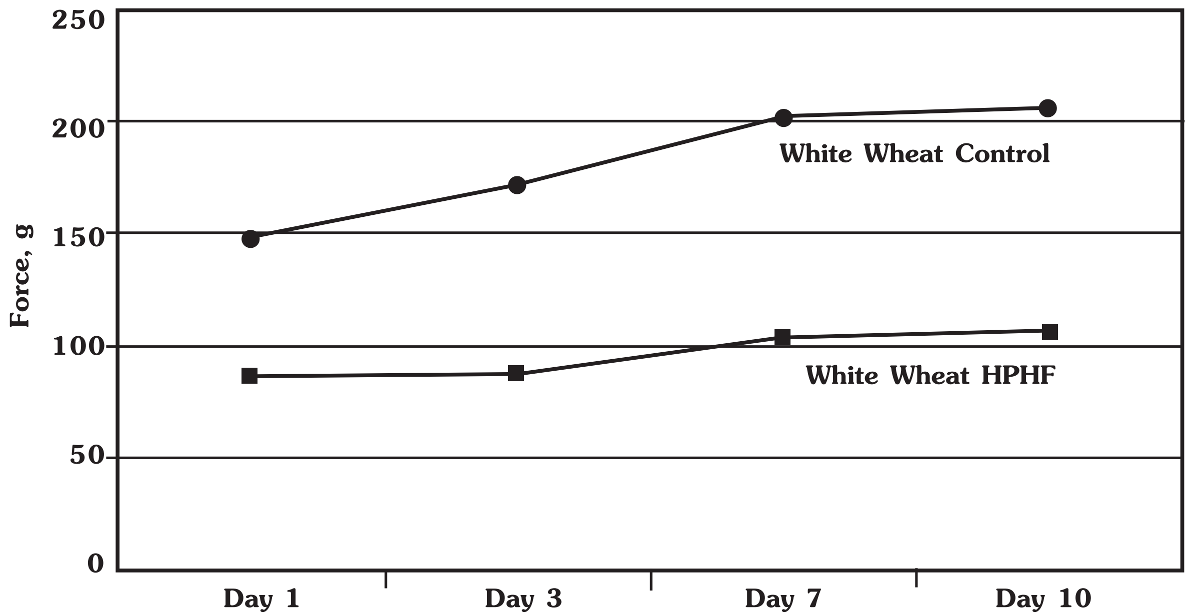

Figure 3. Crumb firmness of wheat breads from white wheat.

increases in fat, fiber, protein, and moisture, were achieved using the HPHF formulas. Calculated "net carbohydrate" (total carbohydrate – dietary fiber) contributions of the HPHF breads ranged from 16.7–18.5 grams per 100 grams of bread or 4.7–5.2 per 28-gram serving size. This is a very significant "net carbohydrate" reduction as the control breads contributed 40.2–49.2 grams per 100 grams of bread or 11.2–13.8 grams per 28-gram serving size. Additionally, caloric reductions in these HPHF breads as compared to their control products were adequate to meet the requirements for labeling as "reduced calorie" products (54).

It is worthwhile to mention that the two HPHF whole wheat breads in this study (Tables III and VII) can provide around 9–10 grams of whole grains in two slices (56 grams) and can potentially qualify for a "good source of whole grains" claim. A petition is currently in the hands of FDA to allow the use of the following designations:

TABLE VI

CRUMBSCAN™ DATA ON CONTROL AND HIGH-PROTEIN, HIGH-FIBER (HPHF) BREADS

Sample	Composite Fineness	Composite Elongation
White Flour		
Control	811	1.36
HPHF	865	1.40
Whole Wheat Red Flour		
Control	853	1.39
HPHF	777	1.41
Whole Wheat White Flour		
Control	891	1.41
HPHF	737	1.35

TABLE VII

100-GRAM NUTRITION REPORTS ON CONTROL AND HIGH-PROTEIN, HIGH-FIBER (HPHF) BREAD FORMULAS

Nutrient	White Flour		Whole Wheat Red Flour		Whole Wheat White Flour	
	Control	HPHF	Control	HPHF	Control	HPHF
Calories (kcal)	258.09	184.88	244.94	179.14	240.99	180.26
Calories From Fat (kcal)	23.67	36.45	29.84	37.29	29.45	37.46
Total Fat (g)	2.63	4.05	3.32	4.14	3.27	4.16
Saturated Fat (g)	0.64	1.09	1.14	1.10	1.15	1.12
Trans Fat (g)	0.37	0.01	0.34	0.01	0.33	0.01
Polyunsaturated Fat (g)	0.42	1.94	0.78	2.04	0.86	2.08
Monounsaturated Fat (g)	0.84	0.86	0.94	0.90	0.82	0.87
Cholesterol (mg)	0.00	0.00	0.00	0.00	0.00	0.00
Sodium (mg)	502.38	481.22	518.09	480.17	503.43	480.48
Potassium (mg)	135.72	89.99	256.66	129.50	241.49	127.08
Total Carbohydrate (g)	51.19	36.23	47.36	35.75	47.02	36.10
Dietary Fiber(g)	1.97	17.69	6.40	19.05	6.84	19.25
Sugars (g)	5.53	1.27	5.26	1.18	5.62	1.35
Protein (g)	8.56	17.64	11.62	17.75	10.82	17.60
Vitamin A (IU)	1.21	4.40	1.39	4.39	1.34	4.39
Vitamin C (mg)	0.00	0.00	0.00	0.00	0.00	0.00
Calcium (mg)	35.67	113.40	65.46	112.74	80.54	118.30
Iron (mg)	2.84	4.07	2.20	3.85	3.42	4.27
Thiamin (mg)	0.44	0.27	0.34	0.24	0.36	0.25
Riboflavin (mg)	0.27	0.14	0.12	0.10	0.09	0.09
Niacin (mg)	3.56	2.40	3.67	2.45	3.33	2.38
Folate (mcg)	105.99	55.71	33.18	34.85	32.18	34.85
Moisture (g)	35.90	39.79	35.28	39.89	36.40	39.62
Ash (g)	1.72	2.29	2.42	2.47	2.49	2.52

"excellent source" for foods with 16 grams or more of whole grain ingredients per labeled serving, and "good source" for foods with more than 8 grams but less than 16 grams of whole grain ingredients per labeled serving (55). Two slices of HPHF whole wheat breads represent about 11% of the daily amount of whole grain food recommended by the 2005 U.S. Dietary Guidelines Advisory Committee.

CONCLUSIONS

High-protein, high-fiber (low-carbohydrate) bread formulas produced white and whole wheat breads having comparable sensory attributes with other low-carbohydrate breads currently on the market. Flavor, texture, and mouthfeel require improvements when compared to regular white and whole wheat breads. The HPHF breads possessed greater volume and much better crumb softness attributes than the control breads as measured with a TA.XT2 Texture Analyzer. The HPHF formulas produced breads with reduced total carbohydrates and reduced "net carbohydrates". The magnitude of the reduction may need to be re-evaluated if and when FDA issues definitions and guidelines for carbohydrate labeling.

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