Resistant Starch and Health

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Topic Highlights

- What is resistant starch?
- Resistant starch intake: measurement and consumption
- Effect of resistant starch intake on gut health
- Metabolic effects of resistant starch intake

Learning Objectives

- To get a basic understanding of what resistant starch is and where it is found
- To learn about how its consumption has been linked to a variety of potential beneficial health outcomes in the area of gut health and various metabolic effects such as blood glucose, insulin, and lipid levels

What Is Resistant Starch?

Starch is the major source of carbohydrates in the human diet. Starch is present in many different fruits, vegetables, roots, and grains. Starch and starch derivatives are a nutritive, abundant, and economical food source. Starch can be consumed unprocessed in the form of raw fruits and vegetables or in the form of more shelf-stable processed foods. Food starches contribute to the characteristic viscosity, texture, mouthfeel, and consistency of many food products.

In the human body, starch is digested by \(\alpha\)-amylases. First, salivary \(\alpha\)-amylase in the mouth catalyzes the hydrolysis of amylose to maltose, maltotriose, and maltotetraose and the hydrolysis of amyleptin to the same products plus two \(\alpha\)-limit dextrins. The partially digested starch then passes into the stomach. After some resident time in the low pH environment of the stomach, the partially hydrolyzed starch then passes into the small intestine where it is neutralized. The majority of hydrolysis of the starch is performed by pancreatic \(\alpha\)-amylase that is secreted from the pancreatic duct via a multiple attack mechanism. \(\alpha\)-Amylases hydrolyze the starch into small mono-, di-, and oligosaccharides that then need to be further broken down to be absorbed as glucose. Two other enzymes are necessary to convert the hydrolysis products of the \(\alpha\)-amylases into glucose, which can be actively transported across the small intestine membrane. These two enzymes are the brush-border glucogenic enzymes maltase-glucoamylase and sucrase-isomaltase. The resulting \(\alpha\)-glucose is then actively transported across the luminal membrane of the small intestine and passes into the blood via the sodium–glucose cotransporter, which is located at the luminal surface of enterocytes.

Several factors influence the rate and extent of starch digestion. The main hydrolysis of starch is performed by the \(\alpha\)-amylases. Starch digestion by \(\alpha\)-amylases requires a series of steps. First, the enzymes diffuse into the starch matrix of the food. In the second step, the enzymes bind to the substrate, and finally, the enzymes cleave the \(\alpha\)-1,4-glycosidic linkages of the substrate (starch). The structure of the food matrix and the structure of the starch itself influence the kinetics of the amylase hydrolysis.

Resistant starch (RS) has been defined as “the starch and products of starch digestion that are not absorbed in the small intestine of healthy individuals.” Based on the source of the enzyme resistance, RS has been classified into five different types (Table 1).

In type 2, type 3, and type 5 RS, the enzyme resistance is due to the physical structure of the starch molecules. Type 2 RS is found in raw starch granules and the enzyme resistance is due to the natural organization of the starch within the starch granules. Significant amounts of type 2 RS can be found in green banana, potato, and high-amylase maize.

In type 3 RS, the enzyme resistance is due to the physical structure of starch chains that have undergone some type of restructuring due to retrogradation or heat treatment. Different factors, such as amylose/amyleptin ratio, chain length, lipid content, and processing conditions, have been shown to influence the amount and quality of type 3 RS. Annealing and heat moisture treatment are two types of heat treatments that are often used to create RS. Both of these treatments, as well as gelatinization, either fully or partially melt crystalline structure present in the native starch granules. After heat treatment, linear amylose molecules and linear regions of amylopectin molecules can organize into a mix of amorphous and crystalline areas with varying degrees of enzyme resistance. Formation of the crystalline structures usually takes place above the glass transition temperature and below the melting temperature, and any components present that influence the glass transition temperature can therefore be expected to influence the formation (yield and quality) of the formed type 3 RS. The amylose content of starch has been positively correlated with RS yield and the formation of type 3 RS is strongly related to the crystallization of amylose. The amount of RS formed is also dependent on the water content and temperature used during the heat treatment. Water does act as a plasticizer in the system and a minimum water content is necessary to achieve the chain mobility needed to form crystalline structure resistant to enzyme digestion. At high-starch concentrations, the starch chains interact more easily, leading to increased crystal and RS formation. The presence of lipids has been shown to decrease the formation of type 3 RS due to formation of amylose–lipid complexes (type 5 RS).

The enzyme resistance in type 5 RS is due to the molecular structure of amylose–lipid complexes that can be either present in the native starch or formed by controlled reactions using non-granular starch and lipids to form the resistant amylose–lipid complex.

The enzyme resistance in type 4 RS is due to chemical modification of the starch. Chemical modification of
starch creates chain irregularities or branches in the starch chains. Cross-linking of starch covalently links two starch chains together, in effect creating a branch point on both chains. Chemical substitution introduces a bulky side group to the starch chains. The introduction of these chemical groups may create a steric hindrance to one or more human digestive enzymes.

### RS Intake

#### Quantification of RS

To determine the effect of RS intake on health, it is important to determine the amount of RS consumed as accurately as possible. Ideally, RS consumption would be determined in vivo by quantification of undigested carbohydrate and potential identification of ileal effluent from healthy subjects using a long triple lumen tube.

The measurement of hydrogen breath to determine the amount of RS in a diet is based on the concept of fermentation of dietary fibers including RS. When RS enters the colon, it may be fermented by the colon microbiota that leads to the production of short-chain fatty acids (SCFAs) (acetate, butyrate, and propionate) and gases like hydrogen (methane and carbon dioxide). Most of the gases produced by colonic fermentation are absorbed into the circulation, but about 10% is present in the breath on exhalation. Since hydrogen breath is not specific for only RS fermentation, but does indeed measure fermentation from any dietary fiber source, care has to be taken when interpreting these results for RS content in a food/diet.

Direct collection of ileal effluents would be expected to give more accurate results than hydrogen breath measurement especially when different forms of dietary fibers and RS may be present in a diet. Analysis of the ileal effluent allows for quantification of undigested carbohydrate and potential identification of the different sources of dietary fiber within the effluent. Most ileostomy models are, however, based on the use of patients that had their colon removed due to health issues and their digestive patterns may therefore not be representative of a healthy population. Analysis of ileal effluent from healthy individuals should provide the most accurate data, but these measurements are difficult and intrusive and can therefore not be done on large scales.

It is generally accepted that any in vitro method used to measure RS should give values in line with those obtained with ileostomy patients. In 1986, Berry developed a new in vitro method by modification of a method previously developed by Englyst, Wiggins, and Cummings in 1982. This modified method was subsequently confirmed to give results in line with healthy ileostomy subjects. In 1992, Englyst developed a method that could measure rapidly digestible starch (RDS), slowly digestible starch (SDS), and RS. This method employed incubation of the samples at 37 °C with pancreatic amylase and amyloglucosidase and measures the amount of RS by subtracting the sum of RDS and SDS from the total starch present in the sample. Several new methods for the measurement of RS were developed during the European Research Program EURESTA. Even though many different methods were developed during the 1990s for the measurement of RS, none of these methods were successfully subjected to interlaboratory evaluation to be adopted as an official AOAC method of analysis. In 2002, McClure and Managhan developed a new RS method by modifying existing methods to obtain a method that would yield robust, reproducible results that correlated with results from ileostomy patients. This method underwent interlaboratory evaluation and was later adopted as AOAC Official Method 2002.02. An Integrated method for the measurement of total dietary fiber was later developed and was published in 2007. This method allows the accurate measurement of all dietary fibers including RS. The enzymatic incubation step uses pancreatic α-amylase and more closely simulates digestion in the human digestive tract and yields RS values in line with those obtained with AOAC Official Method 2002.02 and with results from ileostomy patients. This method was accepted as AOAC Method 2009.01.

#### Sources of RS and Intake Levels

Of all unprocessed foods, the green banana has the highest RS content of between 47% and 57%. While flour can be prepared from green bananas and incorporated into different foods as a source of RS, it is important to keep in mind that food processing methods such as cooking may gelatinize the starch granules and destroy the structures responsible for the enzyme resistance originally present and responsible for RS formation. Raw potato starch is also high in RS, but since raw potato starch is seldom consumed, it is not a good source of RS. However, cooling of cooked potatoes or potato products can lead to retrogradation of the starch and may lead to formation of new RS (type 3) if the right conditions (heat, moisture, time, and starch concentration) are met. The level of RS in different legumes can vary widely and RS content in the legumes as consumed depends on processing and legume variety.

Murphy et al. examined the RS intake in the United States by comparing reported RS contents of different foods with dietary recall records from participants in the 1999–2002 National Health and Nutrition Examination Survey. They showed that the RS concentration varies greatly, even within the same food category. This could be due to natural differences (cultivar), differences in food preparation methods, and also differences in analytic methods used to determine the...
amount of RS present. The RS content of different breads varied between 0.1% in wheat rolls and 4.5% in pumpernickel bread. Ready-to-eat breakfast levels contained between 0% (rice cereal) and 6.2% (puffed wheat) of RS and cookies/crackers had between 0.2% (oatmeal) and 2.8% (crackers and crisp bread) of RS. The category of cooked cereal and pastas had the widest range of RS contents between 0.4% (noodles and chow mein) and 11.3% (oats and rolled uncooked). Within the vegetable category, the lowest RS content was shown for sweet corn (cooked/canned) and potatoes (slow-cooked) with 0.3% while the highest content was observed for fried potatoes with 2.8%. In the legume category, RS content ranged from 0.6% for chickpeas (cooked/canned) to 4.2% for white beans (cooked/canned).

Comparison of the RS content of different foods and the food intake records showed that Americans on average consumed an estimated 3–8 g of RS per day. In Europe, the intake of RS has been estimated to be between 3 and 6 g per day while the intake in developing countries has been estimated to be between 30 and 40 g per day.

**Health Benefits of RS**

**Gut Health**

By definition, RS escapes digestion in the human small intestine. RS therefore passes into the colon where like other dietary fibers, it may be fermented. Fermentation of carbohydrates in the colon leads to the production of SCFAs. SCFAs are the metabolic products of anaerobic bacterial fermentation and consist of butyrate, propionate, and acetate.

The SCFAs produced by bacterial fermentation in the human gut are the preferred fuel for the cells lining the colon (colonocytes) and have been shown to lower luminal pH, increase the excretion of bile acids, and help prevent the development of abnormal colonic cells. A lower pH has been associated with protection against colorectal cancer and has been shown to inhibit the conversion of primary to secondary bile acids. Secondary bile acids are thought to promote tumors as they are cytotoxic to colonic cells. It is therefore reasonable to assume that RS may confer health benefits to gut health by production of SCFAs, which in turn have a positive effect on pH and reduced production of secondary bile acids. A low pH has also been found to suppress the growth of potentially pathogenic organisms and reduce the absorption of toxic compounds (such as ammonia).

Individual SCFAs have also been shown to have more specific actions in the colon. Most RS is readily fermented into SCFA and many are a good source of butyrate. Butyrate is a preferred energy source for colonocytes and helps drive the uptake of electrolytes and water. Intake of butyrate producing RS as part of oral rehydration solutions has been shown to significantly reduce the recovery time for children with watery diarrhea. Butyrate has also been shown to help maintain barrier function in the gut by enhancing mucin production. The barrier function is important to reduce bacterial translocation, which may be a key element in the development of diseases such as inflammatory bowel disease (IBD). Intake of RS has been suggested to be beneficial for the reduction of IBD.

Butyrate has been shown to induce apoptosis, decreasing the risk of cancer development. Animal studies have shown that an increased supply of butyrate to the large bowel decreases the induction of large bowel tumors in rats. However, despite the fact that the data strongly suggest the link between butyrate and reduced risk of colonic cancer, studies examining the link between RS intake and colonic cancer have not been able to prove such a relationship. One reason for this may be the importance of RS intake levels. Studies examining the butyrate production from RS intake have shown significant increase in fecal butyrate when 22 g of RS was consumed per day, but no changes in butyrate or pH levels were observed when 12.5 g of RS was consumed per day. The level of butyrate produced may also depend on the type of RS consumed.

Another aspect of gut health often linked to dietary fibers is laxation and fecal bulk. An increase of fecal bulk is thought to be beneficial and is often reported as a potential health benefit of different dietary fibers. Increases in fecal mass are important for relief of constipation and prevention of diverticulosis and other disorders such as hemorrhoids. The effect of RS on fecal bulk has been studied and an increase of fecal output was reported from different studies. Phillips et al. reported an average increase in fecal output of 42% and also showed that the fecal output increased with increased RS intake. This increase fecal output could be due to increased water in the fecal material, undigested and unfermented starch and dietary fibers, or possible bacteria from the digestive tract. Increased fecal nitrogen was observed in diets high in RS indicating either an increase in bacterial mass or protein excretion.

**Metabolic Effects**

Several studies have shown that replacement of digestible carbohydrate with RS leads to a reduced blood glucose response. This has formed the basis for approval of a European Food Safety Authority (EFSA) claim for RS (EFSA, ID 681, April 2011). While this claim was granted, there was insufficient evidence for the effects of RS when the glycemic load (amount of digestible carbohydrate) remains constant. In 2012, Robertson reviewed several studies on the effect of RS addition to the diet when the available carbohydrate load was held constant and noted a significant inconsistency between the studies reviewed. While some found no effect of RS on glycemia and significant reduction in insulin secretion, others found the opposite, that is, a reduction in glycemia and an elevation in postprandial insulinemia. The difference in these results could be due to differences in the RS tested or simply be due to the difficult relationship between glucose absorption, clearance, and hepatic release, which makes accurate measurements and conclusions difficult. Another important factor to consider is the sources of RS used in different studies. RS can come from foods such as beans, high-amylose corn starch, or potatoes, and these foods all have different physiochemical properties that can affect the response to RS ingestion. The fat content of the diets is also important as fat is known to have a significant impact on the glycemic response to a meal. A careful review of studies with appropriate fat and protein levels showed that RS consumption does indeed lead to a small decrease in postprandial glycemia and a larger attenuation of postprandial insulinemia. These acute changes in plasma
glucose and insulin concentrations caused by the addition of RS to the diet could have important metabolic implications. Both hyperglycemia and hyperinsulinemia are affected in the development of insulin resistance. Increases in plasma glucose concentrations have been linked to increased concentrations of free fatty acids. Glucose uptake in the muscles and increased glucose uptake in the adipose tissue have been linked to hyperinsulinemia.

The potential chronic effects of RS intake on metabolism and associated diseases are even more interesting than the acute effects discussed earlier. There are animal data showing a significant relationship of RS inclusion in the diet and improved insulin sensitivity. Decreased insulin sensitivity, or insulin resistance, has severe metabolic consequences as it is strongly associated with several diseases known as metabolic syndrome. Metabolic syndrome describes diseases such as type 2 diabetes, obesity, coronary heart disease, hypertension, and dyslipidemia.

Even if RS only leads to reduction in blood glucose response when digestible carbohydrates are replaced, such an effect may have significant benefits to human health. Diabetes affects about 8% of US population and is increasing globally. Diabetes is characterized by hyperglycemia that can subsequently lead to systemic tissue toxicity. Risk factors for diabetes include increased glucose response (both fasting and postprandial), decreased insulin sensitivity, and obesity. These risk factors may be reversible with lifestyle modifications that have been shown to be effective in delaying the onset of type 2 diabetes. One lifestyle change could be to reduce the glycemic load of the diet that could be achieved by replacing ordinary starch in foods with RS.

RS has been shown to have significant effects of serum triglyceride and cholesterol concentrations. Several animal studies have shown significantly lower plasma cholesterol and triglyceride concentrations when RS was included in the diet in replacement of digestible starch. A decrease in fasting cholesterol and triglycerides was observed when RS was consumed chronically (5–14 weeks). The mechanism responsible for these effects seems to be increased bile acid excretion caused by consumption of RS, but some study showing reduced plasma cholesterol and triglyceride concentrations even compared to the bile acid sequestant cholestyramine suggests that the effects of RS extend beyond just bile acid secretion. The effects of RS on cholesterol and blood triglyceride levels seem to be mediated through a combination of enhancement of bile acid secretion, a significant decrease in cholesterol absorption, and an increase in hepatic LDL receptor expression. Both high blood lipid and cholesterol levels are associated with coronary heart disease and the effects of RS consumption may therefore have important health ramifications.

The effects of RS consumption on satiety and weight management are not as clear. One major reason for the current global obesity epidemic is the overconsumption of energy, and therefore, strategies that can manage the energy intake may be successful in reducing obesity. Dietary fiber is one way to decrease the energy value of foods if it is used to replace digestible carbohydrates that have a higher caloric value. Some dietary fibers have also been linked to increased satiety and lower BMI, but not all fibers have the same effects. RS is a type of dietary fiber and it would therefore be reasonable to expect some effect on satiety and/or total energy intake when RS is used to replace digestible starch in the diet. Animal studies have shown the production of satiety hormones GLP-1 and PYY when RS was added to the diet, which suggests an effect of RS on satiety. However, only a few human studies have been conducted to examine the effect of RS on satiety and the results were mixed. Some studies have shown an increase in satiety after RS consumption, but others have shown little or no effect. Satiety seems to be linked to changes in plasma glucose concentrations and studies that showed a decrease in plasma glucose/insulin response to a high RS meal also showed an increase in satiety while those studies that showed no change in plasma glucose also showed no difference in satiety. Overall, there is indication that there is at least a weak association between RS consumption and satiety. Some animal studies have shown reduced energy intake when RS was added to the diet. Aziz et al. showed that body weight was reduced by 40% in obese rats that were fed with a diet high in RS compared with rats fed with a low-RS diet. While this study seems to indicate a real positive effect of RS on energy intake and potentially obesity management, the levels of RS used for this study (23.4%) may not be realistic in a human diet. Long-term studies in humans with realistic RS inclusion levels are required to get a better understanding of the potential for RS to help in the management and reduction of the current obesity epidemic.

**Summary/Conclusions**

RS is a dietary fiber and can be used to replace digestible starch in foods. Many animal studies have been conducted to examine the effect of RS consumption. RS may be fermented in the colon and the resulting SCFA production has been linked to a number of health benefits such as reduced pH, which has been associated with the suppression of growth of potentially pathogenic organisms and reduction of the absorption of toxic compounds. Fermentation of RS has been shown to produce relatively high levels of the SCFA butyrate that has been linked to reduced risk of colon cancer. RS fermentation has also been linked to benefits in the risk reduction of IBD by strengthening of the gut barrier via increased production of mucus. RS has been shown to increase fecal bulk, which is important for relief of constipation and prevention of diverticulosis and other disorders such as hemorrhoids.

An EFSA claim was granted in 2011 for reduced blood glucose response when RS is used to replace digestible carbohydrate in the diet (EFSA, ID 681, April 2011). The effect of RS on glycemia and insulinemia is less clear, and studies have shown that different effects are possible due to study designs (e.g., amount of fat and protein in diets) and amount of RS tested. Overall, it does seem that RS consumption does indeed lead to a small decrease in postprandial glycemia and a more significant attenuation of postprandial insulinemia that could have important metabolic implications. Both hyperglycemia and hyperinsulinemia are affected in the development of insulin resistance, which in turn has been linked to several diseases known as metabolic syndrome, for example, type 2 diabetes, obesity, coronary heart disease, hypertension, and dyslipidemia.
RS has been shown to have significant effects on serum triglyceride and cholesterol concentrations. The effects of RS on cholesterol and blood triglyceride levels seem to be mediated through a combination of enhancement of bile acid secretion, a significant decrease in cholesterol absorption, and an increase in hepatic LDL receptor expression. Both high blood lipid and cholesterol levels are associated with coronary heart disease and the effects of RS consumption may therefore have important health ramifications.

The effects of RS consumption on satiety and weight management are not as clear. RS is a type of dietary fiber and it would therefore be reasonable to expect some effect on satiety and/or total energy intake when RS is used to replace digestible starch in the diet. Only a few human studies have been conducted to examine the effect of RS on satiety and the results were mixed. Overall, there is indication that there is at least a weak association between RS consumption and satiety, but long-term studies in humans with realistic RS inclusion levels are required to get a better understanding of the potential for RS to help in the management and reduction of the current obesity epidemic.

**Exercise for Revision**

- What are the different types of resistant starch?
- What is the link between resistant starch consumption and colon cancer?
- How does resistant starch affect insulin sensitivity and why is this important?

**Exercises for Readers to Explore the Topic Further**

While many animal studies have been conducted examining the relationship of resistant starch intake and various health benefits, a more limited number of human clinical studies have been conducted. The results of these clinical studies are sometimes contradictory, and strong conclusions on the health benefits of resistant starch are therefore difficult in some areas. More human studies with careful study designs are needed in the future.

**See also:** The Basics: The Grains that Feed the World; Grains around the World: Grain Production and Consumption, Overview; Food Grains and the Consumer: Grains and Health; Food Grains and Well-being: Functional Foods, Overview; Food Grains and the Consumer: Consumer Trends in Consumption; Grains and Health – Misinformation and Misconceptions; , Carbohydrates: Carbohydrate Metabolism; Beta glucans and health.

**Further Reading**


