A Critical Literature Review on Energy Regulation of Solid Foods, Liquid Foods, and a Relationship between the Two

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Abstract

The aim of the present review is to examine the research concerning energy regulation of solid foods, energy regulation of liquid foods, and a comparison between the two food forms. Energy regulation of solid foods seems to be governed by a multitude of factors. The governing factors that will be considered in the present review include hormones, macronutrient content, and energy density. Energy regulation in liquid foods does not appear to be as effective as energy regulation of solid foods; however, viscosity of the beverage, macronutrient content (especially fiber content), and speed at which the beverage is consumed all appear to regulate energy consumption of liquid foods.

There is no clear consensus in the scientific community about the factors influencing the differences in energy regulation between liquid and solid foods; however, it is clear that when comparable solids and liquids are consumed, the solid food leads to greater feelings of satiety and lesser feelings of hunger. Food form seems to greatly affect hunger and satiety.

The implications of this research are vast. As people in the United States continue to consume more high-calorie and high sugar beverages, the inadequate energy regulation of liquid foods leads to positive energy balance and weight gain. However, in other clinical populations, such as those with anorexia nervosa and older adults with weight loss due to lack of appetite, the positive energy balance from consuming liquids may be beneficial as it can lead to weight gain without the patient being aware of his or her increased calorie consumption.
A Critical Literature Review on Energy Regulation of Solid Foods, Liquid Foods, and a Relationship between the Two

Humans obtain energy from a wide variety of food sources. These food sources fall into two basic categories: liquids and solids. However, the mechanisms that govern the energy regulation, or amount of energy a person consumes from a meal, and the signals that lead to an initiation and termination of eating solid foods or liquid foods are not the same (Mattes & Campbell, 2009).

Energy regulation of solid foods is governed by a multitude of factors. Hormone signals from the gut, especially ghrelin and leptin, are correlated with feelings of hunger and satiety. Specifically, high levels of ghrelin are correlated with feelings of hunger and high levels of leptin are correlated with feelings of satiety (Huda, 2009). Low levels of leptin are also associated with modulation of activity in the striatal region of the brain and increased rewarding value of food, causing a person to seek out food (Farooq et al., 2007).

Also involved in the regulation of energy in solid food forms is macronutrient content. Different foods contain different mixtures of fats, proteins, carbohydrates, sugars, and other macronutrients. However, these macronutrients differentially affect feelings of hunger and satiety. In order to determine the effects of different macronutrients on feelings of hunger and satiety, researchers have given subjects specific macronutrients and examined the effects of each. From this research, it becomes clear how different macronutrients affect hunger.

Energy regulation of liquids is less understood. Energy regulation in liquids is also incomplete, meaning that humans are not capable of accounting for energy
consumed from liquids and adjusting subsequent energy consumption to compensate. The result of this is liquid meals and beverages adding to the total amount of energy and total number of calories consumed rather than substituting for later calories. This positive energy balance can ultimately lead to weight gain (Tieken et al., 2007). However, the mechanisms behind why energy regulation of liquids is incomplete as opposed to energy regulation of solids are not fully understood. Some research has indicated that the hormones involved in initiating and terminating eating session, ghrelin and leptin, are not adequately stimulated by liquids (Leidy et al., 2010). Viscosity, energy density, macronutrient content, and fiber content have also been implicated as possible mechanisms by which energy regulation occurs, although this regulation is incomplete; however results remain inconclusive.

When comparable liquids and solids are consumed, differences are striking. When solids and liquids are matched across various dimensions, such as macronutrient content, energy density, and volume of food consumed, solid foods still remain more satiating than liquid foods. Research in this area is entirely inclusive. More research comparing the satiating effects of solids and liquids is needed to answer this question.

The following paper serves as a review of the research that has been conducted regarding energy regulation of solid foods and the regulation of liquid foods, and how energy regulation between the two groups is not equivalent, and why.
Energy Regulation in Solid Foods

When discussing how humans regulate energy consumption from solid foods, a wide variety of variables have to be considered. Macronutrient content, energy density, speed at which food is eaten are some of the factors that greatly influence how people regulate the consumption of solid foods. Consumption of solid foods is also regulated by various hormones, such as ghrelin, leptin, Glucagon-like peptide-1 (GLP-1) and cholecystokinin (CCK), glucose, and insulin; these hormones have an incomplete affect in the governing of energy consumption from liquids, which will be discussed in a later section.

Hormones regulating energy consumption dictate when a person initiates an eating session and terminates an eating session, as well as how rewarding foods are perceived to be at various times. It is not surprising that when a person is hunger, food is perceived as being more rewarding and a person is more motivated to seek out food. The mechanism behind why this occurs appears to be governed by hormone regulation, specifically leptin regulation (Farooq, 2007). Ghrelin has also been implicated in feelings of hunger and decreased ghrelin correlates with feelings of satiety (Cummings, 2001).

Macronutrients differentially affect these hormones, as well as differentially affecting feelings of hunger and satiety. Carbohydrates appear to suppress ghrelin more than other hormones; however, fat has been shown to suppress ghrelin, as well. Interestingly, fat causes a sharp drop in ghrelin levels, but that is followed by a larger spike in ghrelin levels quickly, causing a person to eat more in his or her next eating session (Erdmann, 2003).
The factors influencing energy consumption in solid foods are discussed more fully in the following section.

**Hormones regulating appetite**

**Leptin**

Leptin is often referred to as the satiety hormone. This hormone is released by adipocytes in response to the presence of food in the gastrointestinal tract. Leptin is released in the bloodstream, and is transported to the brain, where receptors in various areas have been implicated in the termination of eating sessions. However, locations activated by leptin are widely debated. Research has demonstrated that mere exposure to food leads to increased serum leptin in the hypothalamus and increased activation of hypothalamic neurons, suggesting a role of the hypothalamus in energy regulation (Karhunen et al., 1999). Extending these findings, research has shown that leptin acts on the striatal region, which modulates the reward properties of food. A decrease in leptin enhances the reward properties of food. But when higher concentrations of leptin is present, when food reaches the gastrointestinal tract and leptin is released, causes leptin increases in striatal region, decreasing the rewarding values of food and terminating an eating session (Farooq et al, 2007).

This serves as an explanation for the more appetitive nature of food when a person is hungry. When a person is hungry, meaning there is no food in the gastrointestinal tract, there would be no leptin being secreted. This decrease in leptin acts on the striatal region to enhance the rewarding properties of food, which would cause a person to seek out food, as food is now deemed rewarding.
During fasting sessions, serum leptin levels drop dramatically. However, once a person initiates an eating session, serum leptin levels increase dramatically. What is interesting, though, is that higher levels of fasting, meaning longer length of fast and higher subjective hunger ratings, do not correlate with greater increases of leptin once an eating session has been initiated (Mars et al., 2005, Chan et al., 2003, Chan et al., 2008). This would imply a threshold for leptin release. Perhaps, once a certain amount of food has entered the gastrointestinal tract, a certain amount of leptin will be released. When more food enters the gastrointestinal tract, no more leptin can be released as leptin has already reached threshold.

This would also imply that more than one hormone affects satiation. If a person is eating more food after an extended fast (up to 72 hours) rather than a normal fast, such as time spent asleep, but the same amount of leptin is being secreted, which should terminate an eating session, then other hormones certain have to affect the amount of food being consumed or else a person would eat the same amount after an eight hour fast and a 72 hour fast.

However, research by Carlson and colleagues (2009) supported the findings of Karhunen et al., showing that leptin secretion is correlated with the termination of an eating episode. Researchers monitored subjects’ gut hormones levels before an eating session, throughout an eating session, and at the termination of an eating session and found that serum leptin levels were low prior to the initiation of an eating session but increased dramatically during an eating session and peaked following eating periods. In the fasting period that followed an eating session, leptin
dropped dramatically, leading researchers to support the assumption that leptin is an important hormone in initiating satiety and ending eating periods.

In the aforementioned studies, measures of calorie consumption always used solid foods. Solid foods cause distention of the gastrointestinal tract, which has been implicated in causing adipocytes to secrete leptin into the bloodstream (Karhunnen et al., 1999). Because liquids cause less gastrointestinal distention than solid foods, liquid foods do not cause a sufficient release of leptin, which allows the drinking session to involve consuming more calories than an eating session. More concerning leptin regulation of liquid foods will be discussed in the regulation of liquid calories section.

_Ghrelin_

Ghrelin is an important hormone involved in regulating hunger and has opposite affects of leptin. Research has demonstrated that humans receive peripheral injections of ghrelin, _ad libitum_ food intake at a subsequent meal increases in both lean and overweight adults (Druce et al., 2005; Huda et al., 2005; Wren et al., 2001). Researchers have also monitored gut hormones throughout a twenty-four hour period and found that ghrelin is highest just before a meal and lowest just after a meal, suggesting that ghrelin plays a vital role in initiating meals and regulating hunger in humans (Cummings et al., 2001). Many studies have suggested that overweight children and adults may have a hypersensitive response to ghrelin, which would lead to overeating (Mittelman et al., 2010).

However, in the previously mentioned research, subjects were anticipating a mealtime, which may have also led to increased hunger and responsiveness to food.
In order to account for this limitation, Cummings et al. (2004), conducted a study in which subjects were required to request food prior to receiving food. Researchers fed subjects a meal at lunch, and subsequently monitored gut hormone levels until the subject requested dinner. Research found a similar characteristic rise in ghrelin levels just prior to the initiation of eating the second meal, suggesting a vital role of ghrelin in initiating meals even without anticipation of food. Researchers also found that increasing ghrelin levels were related to increased hunger ratings for all subjects.

As discussed in the macronutrient section that follows, macronutrient content greatly affects the secretion of leptin.

**Cholecystokinin (CCK) and Glucagon-like peptide-1**

It has also been suggested that cholecystokinin (CCK) may have implications in terminating meals and initiating satiation. Studies show that when CCK is injected in humans, amount of food consumed greatly decreases. However, previous research has used levels of CCK higher than that would be normally found in physiologically. In order to account for the limitations in previous studies, researchers conducted a study in which subjects were received intraduodenal injections of a saline or fat in levels comparable to what would occur in an eating session, as well as injections of either saline or a CCK antagonist. When subjects received injections of intraduodenal fat and a CCK antagonist, CCK did not reduce food intake as when subjects received injections of only intraduodenal fat. This suggests that CCK plays a vital role in terminating eating sessions and initiating satiation (Goke et al., 1999)
GLP-1 has been implicated in initiating satiety in humans also. GLP-1 is released from the gut when food is present in the gut. GLP-1 has also been demonstrated to reduce eating in rats if injected into the cerebrospinal fluid of the central nervous system, but not if injected into the bloodstream of the animal (Gutzwiller et al., 1999). When a GLP-1 antagonist has been injected into the cerebrospinal fluid, rats that were not hungry because they had just previously terminated an eating session began to eat. In order to study the effects of GLP-1 in humans, researchers gave subjects various doses of GLP-1 intravenously while monitoring hunger levels and food intake. Results indicate that as circulating levels of GLP-1 increase, hunger levels and eating rates drop. Interestingly, researchers also noted that fluid ingestion decreased in response to GLP-1 increase. Researchers concluded that GLP-1 plays an important role in initiating satiety in humans (Guitzwiller et al., 1999).

The factors that influence the regulation of energy consumption from solid foods in humans are vast, and far too much large for the scope of this article. However, important factors such as insulin and glucose levels, top-down processing, orosensory properties, mechanical process of food, and a multitude of other factors play a role in the regulation of hunger and satiety of solid foods.

In regards to the factors discussed in this section, more research is yet to be done. A novel area of research that requires much more research is the effects of top-down processing on energy regulation. It has been demonstrated anecdotally and in laboratory settings that people may eat when they do not actually feel compelled to eat. Certain studies have shown differences in circulating hormone
levels, specifically leptin, in response to the mere presence of food (Mars et al., 2005).

**Macronutrient content and energy density**

The human diet is composed of a variety of macronutrients. Under normal conditions, humans consume a mixture of these macronutrients in their meals. However, these different macronutrients affect hunger and satiation to varying degrees. In order to tease apart the differential effects of different macronutrients on hunger and satiety, researchers will often provide subjects with a meal either entirely composed of one macronutrient or a meal that is exceptionally high in one macronutrient, such as a high protein breakfast. From this work, researchers have discovered that carbohydrate-rich meals suppress ghrelin more so than meals high other macronutrients. Similarly, high fat meals reduce ghrelin levels in the short term, but also lead to higher subsequent ghrelin levels and greater energy-intake in subsequent meals (Erdmann, 2003). Surprisingly, in some research, protein has not been demonstrated to reduce ghrelin levels to same extent as fat or carbohydrates (Erdmann et al., 2003, Misra et al., 2009, Lomenick, et al., 2009). In testing allowing subjects to eat various macronutrients until satiation, a carbohydrate-rich meal was the only meal to reduce circulating ghrelin levels after ingestion. Ingestion of fat, proteins, and fruits and vegetables actually led to an increase in circulating ghrelin. However, fat, proteins, and carbohydrates led to less calories consumed in a subsequent meal than ingestion of fruit and vegetables (Erdmann et al., 2004).

Behavioral studies have supported findings that carbohydrates suppress hunger more than other macronutrients. When researchers gave subjects a pre-
load of bread, a carbohydrate-rich food, overall energy consumption, including the pre-load, was less than energy consumption with any other or no pre-load (Lorian Kohen, 2011).

However, the research in this area is not entirely conclusive. Some research has demonstrated greater suppression of ghrelin and greater reduction in hunger associated with high protein meals. However, carbohydrates still suppressed ghrelin more than fat and also led to greater satiety (Foster-Shubert et al., 2008).

In a study by Goetze et al. (2006), researchers used a magnetic resonance imaging (MRI) to study the effects of macronutrients on gastric volume responses and gastric emptying. Gastric volume is associated with a feeling of fullness, and gastric emptying is associated with increased hunger were fat, glucose, and protein, which make up the majority of the human diet. Equal samples of these mixtures were administered through a nasogastric tube in order to remove the effects of orosensory perception of the nutrients.

Results indicated that gastric emptying was higher fat and protein then for glucose. Immediate gastric volume responses were significantly higher for glucose than for protein or fat. However, the perception of satiety was not related to which macronutrient was present, but rather than the amount of macronutrient present, which is contrary to what was initially predicted (Goetze et al., 2006).

Energy density is directly related to macronutrient content. Energy density is defined as the calories in a given unit of food, and macronutrient content directly affects this. Energy density has been implicated in the regulation of energy consumption independently of macronutrient content. High-energy dense foods
tend to be more palatable than low-energy dense foods, and may lead to overeating (Bell et al., 1998). Meal viscosity in solid foods has also been shown to have an effect on feeling of satiety because more viscous meals induce a greater gastric response to the presence of food, which means that the more viscous food is perceived as being more satiating (Marciani et al., 2000). Viscosity has also been shown to reduce ad libitum food intake, presumably because more viscous meals are eaten more slowly (Zijlstra et al., 2008).

When taken together, the research presented clearly indicates a wide variety of influences that affect energy consumption from solid foods. Hormones, macronutrient content, and energy density of foods all influence the satiating properties of foods. As will be seen in the following section, these factors are not the same for the regulation of energy consumption from liquids.

**Regulation of Energy from Liquids**

The mechanisms controlling hunger and satiation with liquid foods are much less understood than the mechanisms controlling satiation and hunger with solid foods. Some researchers have postulated that viscosity of the liquid determines the satiation qualities of liquid food, and more viscous liquids slow the gastric emptying rates more than less viscous liquids do (Marciani et al, 2000). However, other researchers speculate that the macronutrient makeup of liquid beverages influence the satiation abilities of liquids food (Almiron et al., 2005, Bolton, 1981, Lyly et al, 2010) with proteins and carbohydrates being the most satiating macronutrients and sugars being the least satiating. However, there is other research that suggests that the fiber content of beverages influences the satiation quality of liquid foods.
Researchers concluded that liquid foods high in fiber reduce hunger and lead to longer satiation than liquid foods with little to no fiber (Juvonen et al., 2009, Perringue et al., 2010, Zijlstra et al., 2009).

However, what is apparent in the research concerning liquid foods is the additive nature of liquid energy consumption. Rather than liquid foods being a substitute for solid foods, it appears that humans do not have the ability to compensate for the calories consumed in beverages, thus beverages act to add calories to the diet rather than substitute for calories. (Tieken et al., 2009)

**Viscosity**

Researchers have speculated that more viscous liquids have greater satiating effects than less viscous liquids. When matched for macronutrient content but varying in viscosity, the effects of consuming less viscous or more viscous beverages appear very similar in their abilities to appease hunger in short term testing. However, as time passed, it became apparent that more viscous liquids were superior at reducing subjective hunger ratings and suppressing ghrelin secretion over time than less viscous liquids (Juvonen et al., 2009, Perringue et al., 2010).

More viscous drinks, e.g. milkshake, have been shown to suppress ghrelin more so than less viscous drinks when both drinks are matched for macronutrient content (Juvonen et al., 2009, Zijlstra et al., 2009). As discussed in previous sections, decreased ghrelin levels are associated with decreased hunger ratings. Because more viscous drinks are associated with decrease in ghrelin levels, they are also associated with decreased subjective feelings of hunger.
Viscosity of a beverage has also been shown to affect serum leptin concentrations. Research has shown that consuming soft drinks, which are high in calories but not viscous, results in decreased secretion of leptin as opposed to more viscous liquids with similar macronutrient and caloric profiles (Bray et al., 2004, Stanhope & Havel, 2008, Kimber et al., 2008). Leptin is involved in the cessation of eating sessions and the feeling of satiety. If a soft drink with an equal number of calories and macronutrient content as a solid food is consumed but does not result in the secretion of leptin, a person will still feel hungry and compelled to eat. This could result in a positive energy balance and weight gain.

Orosensory properties, such as more viscous or less viscous, can greatly influence digestion, as well. This appears to be the effects of top-down processing on energy regulation. As a general heuristic, the greater the viscosity of a beverage, the more energy that beverage will contain. More viscous liquids generally contain more calories and are more energy dense, resulting in more energy being derived from that liquid. This heuristic may act to influence hunger and satiety independently of actual energy content (Mattes & Rothacker, 2001).

However, the speed with which beverages are consumed may impact how foods affect satiety, as well. Because liquids are swallowed and do not require the mechanical processing involved with consuming solid foods, consuming more energy requires less time. More calories are consumed before the food is processed by the gastro-intestinal tract and before ghrelin is suppressed and leptin is secreted. It has been demonstrated that consuming a beverage at a slower rate leads to increases in ghrelin suppression and leptin secretion (Kokkinos et al., 2010). A more
viscous liquid cannot be consumed as rapidly as a less viscous liquid; therefore
more time consuming the product may lead to increased ghrelin suppression and
leptin secretion.

Also important in the ingestion of food and the regulation of energy intake
from food is GLP-1 and CCK, both of which are responsible for the uptake of
nutrients in the intestines after food ingestion and slowing of gastric motility.
Interestingly, researchers found no significant effects of viscosity of fluids on
different hormones levels, including CCK, and GLP-1. However, subjects still rated
more viscous liquids as being more satiating than less viscous liquids. It appears
that viscosity of beverages is involved with subjective ratings of hunger more than
the physiological mechanisms controlling hunger and satiating (Zijlsta et al., 2009).

However, it is exceptionally difficult to differentially affect viscosity of a
liquid without affecting other factors, such as macronutrient content. Often, liquids
that are viscous are higher in macronutrients such as carbohydrates or fats as
opposed to less viscous liquids. However, some researchers have managed to tease
apart these variables and analyze the effects of just viscosity on food intake. In
Viscosity and ad libitum food intake (Ziljastra et al., 2008), subjects consumed
significantly more of the liquid food than the semi-liquid and significantly more of
the semi-liquid food than the semi-solid food before reporting feeling satiated, even
though beverages were matched for macronutrient content. Researchers concluded
that the differences in eating were due to eating rates, time the food was in the oral
cavity, and the amount of the food consumed per minute. Liquid food remained in
the oral cavity for far less time than either of the other foods, which resulted in less
time exposed to sensory receptors in the oral cavity.

**Macronutrient content**

Research has suggested that different macronutrients have
differential effects on hunger and satiety. It has been proposed that specifically the
addition of protein, fat, and fiber (fiber is discussed in further detail in the next
section) all reduce hunger and increase satiety when added to a liquid; it is
presumed that these macronutrients act to increase satiety and decrease hunger by
slowing the rate of gastric emptying (Della Valle et al., 2005). Milk has especially
been implicated in these studies. Because of its fat and protein content, milk has
been shown to greatly reduce energy intake at subsequent meals. However, in a
study by Della Valle and colleagues (2005), researchers saw no differences in
subsequent energy consumption when subjects consumed 1% milk, fruit juice,
water, diet soda, or soda. The only difference seen was in hunger ratings for
consuming no beverage at all, which led to greater hunger before the meal.
Researchers did see significant differences in the amount of calories consumed after
different beverage pre-loads, but this was only due to the differences in caloric
intake from the different beverages, not different intakes at subsequent meals.
Researchers found that consuming caloric beverages may lead to a positive energy
balance because of the inability to regulate caloric intake from beverages. The
macronutrient properties of beverages had no effect on subsequent meal intake,
meaning the amount of protein, fat, and fiber in each drink did not affect subsequent
energy intake (Della Valle et al., 2005). Research by Almiron-Roid and Drewnoski
(2003) reported very similar findings in the 1% milk, orange juice, and a high calorie soda did not have differential effects of subsequent food intakes, but all these beverages reduced subsequent food intake more than water. While conflicting with the findings of the study by Della Valle and colleagues, this implies that while macronutrient content does affect the satiating properties of liquids, regulation of liquid energy consumption is not complete and leads to a positive energy balance. However, in this study, the amount of food consumed in the meal was not different between any of the groups, including water. This demonstrated that the sensory quality of drinks did not have a significant effect on hunger and satiety (Almiron-Roid & Drewnowski, 2003).

**Fiber Content**

The presence of fiber has been shown to increase satiety and decrease hunger, presumably because the soluble fiber decreases the speed of gastric emptying. Pectin is a type of soluble fiber found in fruits and vegetables, and has been implicated in the reduction of hunger when consumed. Many studies have focused on the effects of adding fiber to liquids on satiation and hunger.

Perringe and colleagues (2010) compared the effects of fruit juice without pectin to fruit juice with pectin on intake at a subsequent meal. Researchers saw no effect of fiber on subjective ratings of hunger or desire to eat; however, subjects who drank a fruit juice with pectin consumed less at a later meal than subjects who drank fruit juice without pectin. In an experiment by Lyly and colleagues (2010), researchers found that adding fiber to beverages increased feelings of satiety and decreased feelings of hunger more than a beverage of equal calories but no fiber.
Interestingly, when researchers doubled the amount of fiber added to a beverage, satiety ratings did not increase and hunger ratings did not decrease from the ratings associated with less fiber (Lyly et al., 2010). Perhaps these findings suggest a threshold for the satiating ability of fiber in liquids. More research in this area will need to be done in order to determine if a threshold for the satiating abilities of fiber truly exists, but if doubling the amount of fiber in a beverage does not increase the satiating abilities, there certainly appears to be evidence of this fact.

Similar findings have been seen when soluble fiber is added to both low-energy-dense yogurt and high-energy-dense yogurt. In fact, when the soluble fiber was added to the low-density yogurt, it increased the yogurt’s satiating abilities to that of the higher energy-dense yogurt without fiber. The addition of fiber did increase the satiating abilities of the low-energy-dense yogurt but not the satiating abilities of the high-energy-dense yogurt, it is necessary for more research to be focused on what combination of fat, protein, and fiber leads to the greatest satiety (Perringe et al., 2009).

The manner in which fiber acts to reduce hunger has been widely debated; however, research points to the effects of fiber on the production of CCK after ingestion of a viscous liquid. In a study by Geleva and colleagues (2003), researchers added cellulose, a soluble fiber commonly found in vegetables, to beverages and measured the effects of added fiber on CCK levels in the small intestines.

As discussed earlier, CCK is a hormone released by the small intestine in response to food being digested. CCK is released rapidly and has effects on gut
motility and controls gastric emptying. Because fiber increases viscosity of beverage, it has been proposed that the method by which fiber increases satiety and decreases hunger is by creating a more viscous fluid that does not pass through the small intestine as rapidly. Because a more viscous fiber requires more time to pass through the small intestine, more nutrients can be absorbed by the microvilli, and more response from CCK can be elicited (Lyly, 2003).

Adding fiber to beverages has also been demonstrated to suppress ghrelin. By adding fiber to beverages, researchers have measured decreased levels of circulating ghrelin in subjects. Decreases in ghrelin were greater in beverages with fiber added than compared to beverages with no added fiber (Gruendel et al., 2006).

Results from studies involving leptin are less conclusive. Research has demonstrated that increases in fiber in liquid foods do not lead to increases in leptin levels (Tieken et al., 2007). This would suggest that even when fiber is added to a beverage, which initially suppresses ghrelin secretion, suppressing hunger, increased leptin secretion does not follow. Therefore, a person may not feel hungry, but they may not feel satiated either. The lack of response of leptin to beverages, even with response of ghrelin to beverages, may account for the incomplete energy regulation seen in beverage consumption. However, because leptin levels remain low, food may still have high rewarding properties, which cause a person to continue to seek out food though the person has consumed energy and does not feel hungry.

When taken together, research clearly indicates that energy regulation of beverage consumption is incomplete; however the reasons behind the ineffective
regulation of energy consumption are not wholly understood. Research has indicated that mechanisms such as orosensory properties of liquids may effect energy regulation, as well as viscosity, fiber, and macronutrient content. However, what is clear is that liquid and solid calories are not equal.

It may be assumed that beverages, particularly calorically dense beverages, may have a negative impact on human healthy as these beverages lead to a positive energy balance. But the inability of humans to regulate energy consumption from beverages, thus the fact that beverages add calories to the diet rather than substitute calories may in fact be beneficial. The positive energy balance could positively affect many clinical populations.

For example, older adults benefit greatly from the addition of calorie-heavy beverages to their diets. Older adults tend to not feel hungry and thus may not consume as much food as may be necessary for them to sustain healthy weights and skeletal muscle masses. However, when given liquid nutrition supplements, subjects were not able to compensate for intake of liquid calories, as expected from previous research. This inability to compensate for liquid calories consumed led to a positive energy balance and weight gain, which can positively affect for the elderly population (Wouters-Wesseling et al., 2003).

**Comparison between liquid and solid calories**

When researchers compare the effects of consuming calories from a liquid with consuming calories from a solid, the differences are striking. As discussed earlier, the mechanisms for regulating energy intake for a liquid as compared to a solid differ greatly, however, when liquids and solids are matched across various
dimensions, such as macronutrient content, fiber content, and various other macronutrients, it is clear that liquid calories are not equivalent to solid calories and may ultimately lead to a positive energy balance.

Fruit is often used to study the effects of liquid versus solid food on satiety and hunger because the inherent properties fruit allow for a variety of manipulations. Fruit is normally very low energy density, which, as explained earlier is the amount of energy in the form of calories per volume. This is because of large amount water present in fruits. Fruits also tend to contain a large amount of fiber in the solid form, but not in the liquid form. Pureed fruits, such as apple juice, tend to have negligible amounts of fiber in it, because the peels, which have the most fiber are removed, and because the mechanical processing of the fruit destroys the fiber in the fruit. However, using apples allows the researchers to manipulate many the variables implicated in satiety. For example, apples can be presented in the whole, as a semisolid in applesauce, and as a liquid in apple juice. Macronutrient content, other than fiber, is equivalent, and fiber can be added to any state (Flood-Obbagy & Rolls, 2009).

In a study by Flood-Obbagy and Rolls (2009), researchers controlled for a wide variety of variables in food form, including weight, energy, fiber content, and energy density. Subjects consume apples peeled and cut, applesauce with some fiber, apple juice with added fiber, and apple juice with no fiber, or no pre-load as a control. Subjects then consumed an *ab libitum* test meal. Subjects who ate the apple pre-load consumed less at lunch than those who ate apple sauce; those who ate apple sauce consumed less than those who drank either juice; those who drank
apple juice with added pectin consumed the same as those who drank apple juice without added pectin; those who drank apple juice with or without added pectin consumed less than the subjects who had no preload. Researchers saw a similar pattern as described with consumption differences, whereby subjects who had consumed apples in whole were less hungry than those who consumed the other pre-loads, and all pre-loads resulted in significant lower hunger ratings than no pre-load (Flood-Obbagy & Rolls, 2009).

Hunger ratings were significantly lower for any of the preloads as opposed to no pre-load. However, in contrast to the results from the amount of food consumed, apple juice with added pectin showed significantly lower hunger ratings than those who consumed apple juice without added pectin. Results from satiety ratings mirrored those of the hunger ratings: satiety ratings were highest for apples in whole and lowest for apple juice with no added pectin, but all pre-loads had higher satiety ratings than the satiety ratings for subjects who had consumed no pre-load at all (Flood-Obbagy & Rolls, 2009).

Consuming different forms of the same fruit with similar energy densities and energy content and weight can have very different effects on hunger and satiety and food consumption. Researchers speculated that differences in hunger and satiety may be due to the structural properties of food that lead to food to be mechanically processed different. Foods requiring chewing are eaten more slowly and require more mechanical processing than food that is swallowed without mechanical processing (Flood-Obbagy & Rolls, 2009).
Results from other studies involving consumption of apples, applesauce and apple juice indicated that in the initial thirty minutes, there was no significant difference in hunger and satiety ratings between the three groups. However, thirty minutes after consumption, differences begin to emerge. Hunger was significantly less for subjects who had consumed apple as opposed to applesauce or apple juice. And after the two-hour waiting period, subjects who consumed applesauce or apple juice had significantly lower satiety ratings than those who had consumed whole apples. There was also a shorter inter-meal interval after the apple juice and applesauce as opposed to the whole apples. However, there was no effect of food form on the amount of food eaten at a subsequent meal. So while subjects who consumed apple juice and applesauce ate their next meal sooner than those who had consumed whole apples, the meal size between all the groups was not statistically different (Mattes & Campbell, 2007).

However, one important limitation in this study would need to be addressed in future studies. The latency times between consuming the pre-load of apple juice, applesauce, or a whole apple and eating may have been too long to really capture the differences in satiating power of the various food forms. In future studies, it would be important to reduce the amount of time between a pre-load and a follow-up meal (Mattes & Campbell, 2007)

However, these results have been supported in studies utilizing oranges as compared to orange juice, as well as grapes versus grape juice. Researchers measured plasma levels of glucose and insulin after consumption of the liquid or solid form of the fruit. With whole foods there was a smaller insulin response than
with juices, and a smaller post-absorptive drop in glucose after ingesting whole foods as opposed to the fruit juices. Since the amount of sugar in the fruit and fruit juices was comparable, researchers concluded that fiber content in the food consumed had a significant effect on the levels of plasma glucose and plasma insulin, more of an impact than glucose content (Bolton et al., 1981). Research with grapefruit, grapefruit juice and water further supports these findings. Subsequent meal intake after eating grapefruit was lower than for grapefruit juice, which led to weight loss (Silver et al., 2011)

From the aforementioned studies, it can be concluded that when beverages are consumed alone, they have weaker appetitive effects than when solids are consumed alone. Energy-dense beverages may therefore lead to and maintain a positive energy balance in humans, and may ultimately lead to weight gain. People are not compensating for the amount of calories in a beverage that is being consumed, therefore they eat more calories than they would have initially eaten if they had not had the beverage.

In a study more applicable to the clinical setting, researchers examined the effects of liquid-meal replacement products and solid-meal replacement products on hunger and satiety rating, and appetite-regulating hormones in older adults (Tieken et al., 2007). Liquid meal replacement products are products that provide an appropriate balance of macronutrient content and calories to replace an entire meal, but in liquid form. Popular liquid-meal replacement products include SlimFast© meal replacement shakes, protein shakes, Ensure© meal replacement shakes. Solid-meal replacement products are products that provide an appropriate
balance of macronutrient content and calories and replace an entire meal, but are a single product. Popular solid-replacement meal products include Clif® energy bars and Special K® energy bars.

This issue of hunger and satiety in older adults is of great importance in the clinical community. As people age, they tend to consume less energy, which may result in older adults being underweight. Being underweight can lead to malnutrition, frailty, and ultimately death. However, as has been explained earlier, energy regulation is incomplete in liquid foods as compared to energy regulation in solid foods. Liquid foods elicit weaker satiation cues than solid foods, which may mean that older adults can consume liquid foods in order to add to their total energy consumption (Tieken et al., 2009).

In this study, researchers measured the ghrelin, leptin, glucose, and insulin levels, as well as subjective hunger ratings, at various points in time after older adults consumed either a liquid or solid meal replacement product. Results from this study indicate that satiety ratings were higher and remained higher the length of the study for solid-meal replacements than liquid-meal replacements; as expected, hunger rates were higher and remained higher for liquid-meal replacement products than solid-meal replacement products. Results also indicated lower desires to eat for subjects who consumed to solid-meal replacements as opposed to liquid-meal replacements. Plasma glucose levels were higher initially for subjects who consumed liquid-meal replacement products than for subjects who consumed solid-meal replacement products, but within 60 minutes, glucose levels for solid-meal replacement products reached comparable levels to those of liquid-
meal replacement products, and the glucose levels of subjects who consumed solid-
meal replacement products were no different than those of subjects who consumed
liquid-meal replacement products. Ghrelin levels tended to be lower for subjects
who consumed solid-meal replacement products as opposed to those who
consumed liquid-meal replacement products, but those levels never reached
significance. There were also no significant differences in leptin between subjects
who consumed liquid-meal replacement products and those who consumed solid-
meal replacement products (Tieken et al., 2009).

There were certain limitations in this study that would need to be addressed
in order for this study to be as influential as possible. Researchers reported that the
macronutrient content of liquid-meal replacement products and solid-meal
replacement products were not matched. The liquid-meal products contained more
carbohydrates, protein, and fiber. However, this is very interesting because, as
described earlier, these macronutrients should cause a product to be more satiating,
which may mean that the results of this study could be understated compared to
what may actually be transpiring. From this study, researchers concluded that the
physical properties of food may be a greater determinant in hunger and satiety than
macronutrients (Tieken et al., 2007).

In a similar study, subjects who consumed a liquid meal as opposed to a solid
meal had greater hunger ratings and reported having a greater desire to eat.
Ghrelin levels greatly decreased for subjects who had consumed solids as opposed
to liquids (Leidy et al., 2010).
In another study by Flood and Rolls (2007), researchers replicated a scenario seen in many restaurants and meals. Researchers had subjects consume soup at the beginning of a meal. The soup was a bowl of broth alongside a bowl of vegetables and butter; a chunky soup consisting of the broth with the same amount of vegetables and butter added in; a pureed soup consisting of the same amount of vegetables and butter blended together for 15 seconds, so the soup was not entirely smooth; and a completely pureed soup with the same amount of vegetables and butter, but in a completely liquid form. In a control condition, researchers had subjects sit quietly and read for 15 minutes prior to a meal being served; subjects in this condition received no soup pre-load. Researchers then provided subjects with a test meal of cheese tortellini 15 minutes later.

Results indicated that subjects consumed significantly less in the subsequent test meal when a soup pre-load was presented as opposed to no pre-load condition, and total energy intake was significantly less when subjects consumed a soup pre-load than no pre-load. Increased viscosity of the soup was correlated with a decrease in amount of food consumed in a subsequent meal. The more viscous a soup, like a chunky soup, the less food consumed at a subsequent meal.

From this research, a clear pattern emerges: liquid and solid calories are not equal. People are not able to compensate for energy consumed from liquids as opposed to solids. People cannot compensate for the amount of energy consumed from liquids, which may ultimately lead to positive energy balance. However, this may not always be a negative consequence of consuming liquid calories. Consider the case of older adults, who have lost their appetites. Adding liquid-meal
replacement products to their meals may ultimately lead to weight gain because of their inability to compensate for the calories consumed.

Discussion

This research is becoming increasingly more important for us as rates of obesity continue to increase in the United States. Consumption of high caloric and high sugar beverages has increased, and portion sizes have increased, as well. This has led to increased rates of obesity beginning in childhood (Piernas & Popkin, 2011). As clearly illustrated from the research concerning energy regulation from beverages, these beverages lead to positive energy balance by adding to energy intake rather than substituting for other sources of energy, leading to weight gain.

The implications from the research concerning intake of solid foods will be important in combating increases in obesity and positive energy balances. Gut hormones leptin and ghrelin have been recognized as of late as being important hormones in the regulation of eating and satiation. Obese individuals tend to show increased sensitivity to ghrelin and decreased amounts of circulating leptin, as well as decreased responsiveness to leptin in the hypothalamus.

Future research needs to focus on the clinical applications of leptin and ghrelin for combating obesity. Leptin replacement therapy may potentially be useful in combating obesity, and has been shown to be effective in normalizing body weight and helping individuals reach average body weight (Paz et al., 2010).

However, the positive energy balance and incomplete regulation of energy consumption that results from consuming liquid calories may have positive implications for many clinical populations. In patients with anorexia nervosa and
bulimia nervosa, having patients consume diets consisting of mostly liquid meals may result in positive energy balance and weight gain. Because this patients are not able to regulate the amount of calories being consumed from a liquid meal replacement, these individuals may be able to consume more calories because they are not able to perceive and account for the amount of calories consumed. Therefore, these patients may up-regulate the amount of calories consumed because of incomplete energy regulation of liquids.

Another clinical population that may benefit from consuming more liquid meal replacements is older adults. As discussed earlier, older adults risk becoming frail and malnourished because of they may not feel hungry or feel a desire to eat. However, having these older adults consume liquid meal replacements may be a very effective method of up-regulating the amount of energy consumed in a day. Older adults who consume liquid meal replacement products may not experience satiety from these products, so while their solid food intake decreases, liquid meal replacement may increase, allowing these patients to have a positive energy balance and increased weight gain.

Research in the area of liquid and solid calories is far from conclusive, nor do researchers fully understand the mechanisms that govern energy regulation in liquid and solid foods. It is clear that many different hormones, such as ghrelin and leptin; properties of food and beverage, such as viscosity, energy density, and macronutrient content; and top-down processing, such as expectations about consuming food, such as more viscous foods have more calories; and mechanical mechanism, such as mechanical processing of food all play an important role in
regulating energy intake in both liquid and solid foods. However, for a variety of reasons, this regulation is incomplete in liquid foods as compared to solid foods. More research is required in order to elucidate these finds further, and there is no clear agreement in the scientific community about what the exact mechanisms are that differ between liquid and solid regulation.
**Works Cited**


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