ABSTRACT
It seems that many people, including dietetics profession-
als and other nutrition experts, are unclear about some of
the fundamental yet complex concepts behind the influ-
ence of dietary macronutrients (ie, protein, carbohydrate,
and fat) on appetite regulation. Recent research has be-
gun to unravel some of the more complicated physiologi-
ical processes of appetite control and regulation generated
by hormones such as leptin, ghrelin, and the gut hormone
peptide YY3-35. Although the processes by which the
macronutrients in our foods influence appetite regulation
have been a topic of study for decades, they remain con-
fusing and are often misunderstood. The objective of this
article is to define the terminology commonly used to
discuss the macronutrients’ roles in appetite regulation
and to discuss the interrelated concepts and roles of taste,
palatability, and energy density.

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HABIT PRACTICE
Effects on Satiation and Satiety
Clarifying Concepts about Macronutrients’

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petite is influenced by a multitude of biological,
behavioral, and environmental stimuli. To better
understand the biological and physiological pro-
cesses that stimulate and inhibit food consumption, a
number of general terms and concepts need to be defined
(Figure). The biological drive that impels individuals to
search for food is hunger. The feeling of hunger is an
important component in determining what, how much,
and when to eat (1). When food consumption reduces
hunger, physiological processes are stimulated that in-
hibit further eating; this process of feeling full and con-
sequently terminating food consumption during the
course of eating is termed satiation. Satiation develops
during a meal and tends to bring the period of eating to
an end. Satiation (intrameal satiety), therefore, reduces
hunger and limits the amount of energy consumed during
that meal (1). Satiety (intermeal satiety), on the other
hand, develops after foods have been ingested. It is the
state of satiety that delays the onset of the next meal and
may reduce food consumption at the next eating occasion
(1).

The impact of individual macronutrients on satiety is
typically measured in experimental studies using a pre-
load design. Participants consume preloads differing in
energy density (the caloric content of a given weight of
food) or in the amount of carbohydrate, protein, or fat,
and their energy intakes at the same meal are observed
(2). A food that is reported to have high satiety tends to
produce a longer intermeal period (a period of time be-
tween eating episodes during which an individual does
not experience hunger). Alternatively, foods that are re-
port to have lower satiety tend to produce a shorter
intermeal period. Satiety and satiation are distinct but
interrelated factors that influence both the type and
amount of food consumed (1).

Foods, and more specifically macronutrients, with the
same caloric content exert different effects on satiation
and satiety independent of their caloric value (1,3). In
other words, not all calories are treated equally by the
body. In Stubbs and colleagues’ review of the energy
density of foods (calories/g) (4), they noted that under
normal circumstances in which fat contributes dispropor-
tionately to energy density, protein, carbohydrate, and
fat exert hierarchical effects on satiety in the order of
protein > carbohydrate > fat; some additional research
has confirmed this phenomenon (5,6). However, one study
suggests that this effect is mediated almost exclusively by
energy density (7). Although most research has suggested
that the macronutrient protein has the most potent ac-
tion on satiety (5,6,8,9), there is less clear consensus
regarding the relative satiety values of carbohydrates
and fats. The relative satiety values of these macronutri-
teins (carbohydrates and fats) tend to vary depending on
whether the macronutrients are studied in isolation or in
foods (10).

Blundell and colleagues (2) found that fats and carbo-
hydrates do not have identical effects on the appetite
profile. Their studies, in agreement with those of others
(11), showed that high-fat foods have a weak effect on
satiation and satiety compared with sucrose. Holt and
colleagues (3) calculated satiety index scores by dividing
the area under the curve (AUC) for the satiety response to
commonly consumed test foods by the study group mean satiety AUC for the satiety response to white bread, in this case, and multiplying by 100. They found that more energy-dense (calorie/g), fat-rich foods had lower satiety index scores, whereas bulky, hydrated foods that were high in protein, fiber, or water content had higher satiety index scores. The sugar, starch, and total carbohydrate content of the foods were not statistically related to the satiety index scores; however, the direction of the relationship with starch was positive. Not all carbohydrates necessarily exert the same effect on intermeal and intrameal satiety. For example, fiber has consistently been shown to have a higher satiety value when compared with digestible complex carbohydrates and simple sugar (12,13).

Satiety may develop for foods that taste, look, or even feel like previously ingested foods. This is termed sensory-specific satiety. Rolls reviewed several studies that showed this phenomenon, showing that after eating a test meal the pleasantness of the taste, smell, texture, and appearance of the eaten foods decreased significantly more than for the uneaten foods (14). A similar phenomenon was observed by Raben and colleagues; their subjects reported lower desires for something sweet after carbohydrate-rich meals and higher desires for something sweet after protein-rich meals (7). De Castro (8) reported a comparable macronutrient-specific effect whereby consumption of a given macronutrient tended to suppress the intake of that macronutrient for up to 2 days.

TASTE, PALATABILITY, AND ENERGY DENSITY
It is important to keep in mind that individuals do not eat solely based on hunger. Taste is usually the number-one reason given for eating a specific food, and a decrease in good taste is often given as a reason for terminating or reducing food intake (15). Taste and more specifically palatability (a subjective measure of the pleasantness of food) have consistently been shown to influence food choice (15). Palatability and energy density, which is determined by comparing the food’s caloric energy with the food’s weight, are inextricably linked (15,16); foods are preferred because they are energy dense. On the other hand, low-energy-dense foods, foods that typically contain more water and less fat, tend to be more satiating but less palatable (15,16). Holt and colleagues (3) found a significant inverse correlation between palatability ratings and satiety index scores, so that the more palatable foods were generally less satiating.

The fact that high-fat foods are more energy dense, have a higher palatability, and have lower intrameal and intermeal satiety value helps explain why individuals tend to overconsume high-fat foods, a process termed passive over-consumption (1,11). Raben and colleagues (7) compared the effects of protein-rich, carbohydrate-rich, fat-rich, and alcohol-rich meals on satiety while controlling for energy density and fiber and found no independent effect of macronutrient content. Therefore, energy density and fiber content may account for most of the differences in the macronutrients’ differential effects on satiety. However, under normal free-living conditions, fat contributes disproportionately to the energy density of the diet (17), and research has shown that when food is unrestricted, gains in body weight are greater when high-fat foods are consumed as compared with low-fat foods (1). Therefore, the hierarchical effect of macronutrients on satiety still has practical significance.

CONCLUSIONS
To create and consume a satisfying diet with high intrameal and intermeal satiety, we ideally want our diet to consist of low-energy-dense foods with high palatability; however, such foods do not commonly exist. A diet that is rich in low-energy-dense foods would enable individuals to experience a sense of fullness during meals (high meal satiation), would inhibit overconsumption, and would give a sense of extended between-meal satisfaction (high intermeal satiety), so that subsequent hunger and eating are delayed. Such a diet would be low in fat, provide adequate protein and fiber, and include plenty of fruits, vegetables, whole grains, and foods with high water content (naturally or incorporated during preparation) (18).

The dietary recommendations of the American Heart Association, American Dietetic Association, and other agencies have been consistent with these principles for decades. However, the emphasis on specific components of these recommendations has varied as the research has evolved and the needs of the population change, as is the case with the renewed interest in energy density as a key factor in obesity prevention. This process of fine-tuning recommendations and more accurately framing the issues does not represent an about-face. Rather, new research has helped us to understand and substantiate, for example, the mechanisms by which high-fat diets tend to lead to excess gains and how other energy-dense foods can have a similar effect.

Unfortunately, foods that are low in fat and energy density, especially the more palatable of these, are typically more costly and/or inconvenient to purchase or prepare. In fact, our current food supply is abundant in low-cost, convenient foods that have high energy density,
high palatability, and low satiety. Thus, one of our greatest challenges as dietetics professionals and nutrition experts is to not only promote the consumption of low-fat, high-fiber, and low-energy-dense foods to the public, but also to work with the food suppliers and producers to make these types of foods as inexpensive and palatable as possible while advertising and packaging them aggressively to increase their appeal and convenience.

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