Reaping the Most Nutrients: Working With Starch and Nonfiber Carbohydrate Digestibility

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INTRODUCTION

Cows survive, grow, produce milk, reproduce, and store energy reserves based on the amount of digestible nutrients they get from their diets. There is consensus that cows do not have a starch requirement, but starch has been a staple source of digestible nutrients in dairy cattle diets. With concerns about grain supplies and prices, the question of how to approach meeting the nutrient needs of our herds becomes more pressing. Questions we need to answer to figure out how to meet the needs include:

- How do we capitalize on nutrients raised on farm?
- What off-farm options do we have for feed supplies?
- What factors will change how well the nutrients are utilized for production?

These are simple, straightforward questions that force us to look down many avenues.

FORAGES AND HIGH MOISTURE FEEDS

No matter what supplements are purchased, homegrown or purchased forages still lay the base for dairy cattle rations. Forage quality and digestibility greatly influence how well cows perform; deficiencies in the forages often cannot be fixed with supplements. Allowing for the differences among growing seasons, the goal is to produce forages that are harvested at times optimal for digestibility and yield, are processed to maximize digestibility of grain, are well-preserved (limited spoilage), provide the physically effective fiber (**peNDF**) to maintain good rumen function, and can be fed in a form so that cows cannot sort them. Understand that individual forages can have digestibility that is too high or too low to maintain cows well, so forages have to be examined in the context of the ration in which they will be fed.

So, the first step in getting the most nutrients from carbohydrates in forage is a focus on crop management. Select crop varieties that are suitable for your soils, growing conditions, and management. Choose the types and amounts of forages you grow to alter the amount of starch and other digestible carbohydrates you need to purchase, while maintaining peNDF. To optimize the digestible nutrients and yields of haycrops, harvest alfalfa at approximately 40 % NDF and cool season grasses at 50 to 55 % NDF (% of dry matter (**DM**). These concentrations have potential to provide a good balance of digestible nutrients, plus the peNDF that the cows require (more on that later). Selection of varieties that have improved digestibility (particularly for fiber) while not greatly sacrificing yield could be useful to the dairy herd, but may have unforeseen effects. More on the impact of increased fiber digestibility in the later discussion on factors affecting utilization.

Since the DM content of feeds affects their preservation, and potentially the digestibility of the grain, make all efforts to get them within acceptable ranges (Table 1; R. E. Muck, personal communication). Do all you can to avoid feeding moldy or spoiled forages. This includes removing any spoiled layers from bunk silos before feeding. Feeding spoilage from silage can have negative effects on rumen function (K. Bolson, Kansas State Univ., personal communication) as well as giving cows diarrhea, making them sick, and reducing their production. Feeding spoiled or moldy feeds can sabotage the other efforts made to provide nutrients to support production.

Corn variety, maturity of the plant, and processing can change starch digestibility in corn silage (Andrae et al., 2001; Figure 1). The decrease in digestibility with increasing maturity makes sense, as the corn kernel gets harder and more of the vitreous protein matrix accumulates.

This also explains the greater impact of processing on more mature corn kernels (0 % milk line) than on milkier kernels (50 % milk line) that do not have as hard a protein matrix.

Table 1. Recommended dry matter contents for ensiling.

	Moisture, %	
Crop	Upright Silo	Bunker silo
Alfalfa silage	50-60	55-65
Corn silage	55-65	60-70
Grass silage	55-65	60-70
High moisture corn	28-30	28-30

Corn variety and its interaction with processing could affect starch digestibility, as the varieties differ in the vitreousness of the grain and have greater or lesser need of processing. Corn plants contain the most starch at the greatest maturity. In the study by Andrae et al. (2001) at 50 % milk line, the silages contained 27 to 30 % starch, and 37 to 41 % at 0 % milk line (DM basis). To get the most starch with the greatest availability, allow the corn to mature and process it properly.

At last year's Mid-South conference, Dr. Bill Weiss gave a very good overview of the effects of a variety of factors on the digestibility of starch in silages (Weiss and Firkins, 2007). Two key points he made that bear repeating here are:

- Kernel processing has increasing benefit for starch digestibility as corn matures.
- It can allow greater length of chop to provide more peNDF without sacrificing starch digestion.

Very few things are worse than thinking you have properly processed corn silage, only to find that you do not. The price of properly processed corn silage is monitoring the crop through the harvest so you can make needed adjustments to the processor and chopper. Dr. Kevin Shinners of the University of Wisconsin developed a simple way to evaluate corn silage processing: Put a quart of freshly chopped corn silage in a basin, then fill the basin with water. Swirl and mix the corn silage in the water, remove the floating forage part of the silage, and carefully pour off the rest of the water to leave the heavier grain at the bottom. Examine the grain. All kernels should be damaged, sliced, or preferably crushed if they are properly processed. A word to the wise: **MAKE SURE CORN SILAGE IS PROCESSED PROPERLY AT HARVEST!!!** After the corn is in the silo, there are few desirable processing options.

Monitoring Corn Silage Processing

Proper processing and storage of high moisture corn is also needed to maximize its digestibility. Drier high moisture corn (less than 28 % DM) or dry, hard corn within corn silage will have some of the same issues as dry corn, and likely will need to be ground finer before feeding to increase starch digestibility.

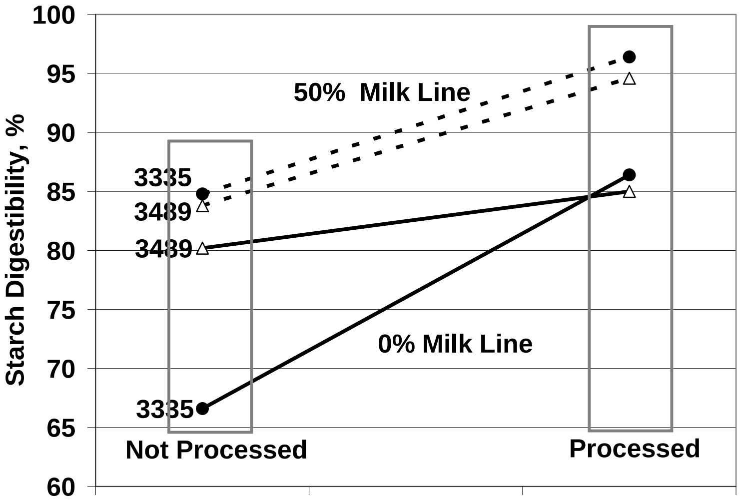

Figure 1. The effect of processing, maturity, and variety on 24 hr in situ starch digestibility (from Andrae et al., 2001, data from table 4). Numbers identify the two varieties (3335 and 3489).

CARBOHYDRATE SOURCES AND MEASUREMENTS

Sugars, starch, soluble fiber (pectins, etc.), and NDF are among the digestible carbohydrates that supplemental feeds can provide. Reports from the field suggest that there are lower concentrations of starch in some by-product feeds than we have seen historically, so reliance on table values may not serve well. With the starch fermented to ethanol, the by-products from the ethanol industry will largely provide sources of protein and fiber. Corn bran which contains approximately 69 % NDF has been reported to have an extent of NDF digestion of 87 % (6.2 %/hr), but this is reduced at lower ruminal pH (Klopfenstein et al., 2007).

Carbohydrate Measurements

In order to evaluate feeds for what they can contribute to the cow's digestible nutrient supply, we need to know their composition. Nonfiber carbohydrates (**NFC**) that is calculated by difference as 100 % of DM minus crude protein (**CP**), NDF, ash, and fat, has been a gross number used to estimate the readily digested carbohydrates in feeds. This number may be substantially incorrect for some feeds (e.g., molasses: approximately 10 to 15 % of molasses DM comes from reducing substances, etc. that are not carbohydrate, CP, NDF, ash, or fat; but are allocated to NFC mathematically; Binkley and Wolfram, 1953). Generally, the NFC number can give us a starting point for evaluating carbohydrate sources.

The most commonly measured NFC are sugars and starch. Sugars are currently measured by extracting them from feeds with water or a water+alcohol solution, and measuring the hydrolyzable or total carbohydrate extracted. Such approaches measure the simple sugars (glucose, fructose) and disaccharides (e.g., sucrose) as well as oligosaccharides, and some portion of the fructans (found mostly in cool season grasses). These different carbohydrates may differ in their digestion characteristics. Starch is analyzed by gelatinizing the starch, hydrolyzing it with starch-specific enzymes, and measuring the released glucose. Current starch methods are fairly good. Low or excessively high values for starch in different feeds can relate to inadequate hydrolysis, or detection of interfering carbohydrates, such as sucrose as starch. Analysis of soluble fiber is a challenge. Estimates of content in feeds can be measured by difference (Hall et al., 1999) or directly (Prosky et al., 1992), but the assays are not perfectly reliable (may be related to estimation of CP mass among other things). An estimate of soluble fiber content can be approximated by NFC minus starch and sugar in feeds that do not have a high organic acid content or appreciable amounts of material that do not analyze as carbohydrate, NDF, CP, fat, or ash.

Current methods for measuring digestibility of NDF or starch give relative, not absolute, values for digestibility. Besides the issues of how we process feeds to analyze them, the *in vitro* or even *in situ* or *in vivo* methods cannot tell how a fraction of a feed will behave under a wide variety of rations and feeding conditions. For starch digestibility estimates, both particle size (Blasel et al., 2006) and the quality of the starch (Hibberd et al., 1982) affect the values. Both characteristics are important, but the effect of one or the other typically predominate in different starch digestibility analyses. That said, relative values can still be useful to assess changes in or comparative values of NDF or starch digestibility among feeds, and can be useful in considering our options for ration formulation.

FACTORS THAT MAY AFFECT CARBOHYDRATE UTILIZATION

The key to getting best conversion of feed carbohydrates to lactation performance is to process the feeds to enhance carbohydrate digestion, then formulate and manage the ration so that the nutrients can be well used by the cow for production.

Starch

Feed processing clearly affects starch utilization. The finer the particle size, the more rapid the fermentation (Galyean et al., 1981; Figure 2). This is likely due to breaking up the protein matrix that surrounds the starch granules so that they are open to digestion. Gelatinization, or the opening up of the crystalline structure of starch using heat and moisture, can also increase the rate of digestion (Figure 2). Small grains like wheat, barley, and oats tend to ferment more rapidly than corn or sorghum (Herrera-Saldana et al., 1990). High moisture corn ferments more rapidly than dry corn, and the same amount can decrease ruminal pH to a greater extent than will dry corn (Krause et al., 2002). Low ruminal pH can depress fiber digestion. An advantage to using blends of rapidly (high moisture, gelatinized) and slowly (dry ground) fermented starch sources is the ability to manipulate the digestible starch supply to maintain a digestible carbohydrate supply while

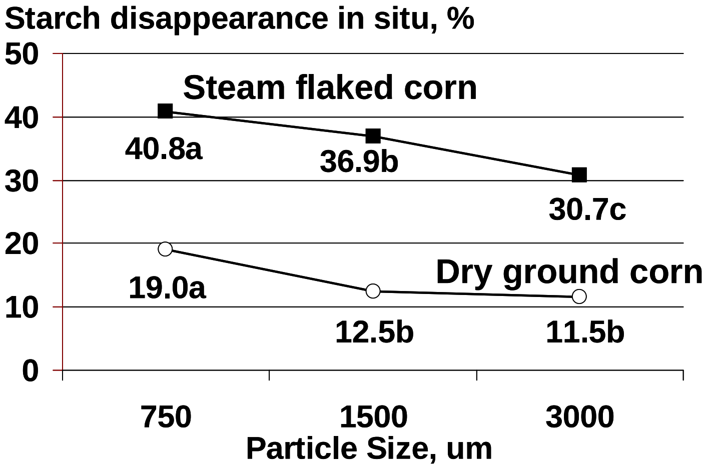

Figure 2. Effect of processing and particle size on rate of ruminal starch fermentation. Smaller particles ferment more rapidly than large particles, steam flaked (gelatinized) faster than dry ground (Galyean et al., 1981; average of 2, 4, 6, and 8 hr values).

reducing the chance of depressing rumen pH and fiber digestion.

A relatively recent study showed that the rate of starch fermentation can increase with the amount of starch fed. In cows offered rations with 10 or 30 % dry ground or high moisture corn, the rate of rumen fermentation of the starch went from approximately 17 to 28 %/hr for the high moisture corn and from approximately 12 to 15 % for the dry ground corn (Oba and Allen, 2003). If this holds true in herds, it could help to explain why wet, finely ground high moisture corn can be so touchy to feed sometimes; increasing the amount increases the amount of starch AND its fermentation rate. Lastly, there is some evidence that rate of starch fermentation may increase the longer the feed is in the silo (Benton et al., 2004). This may be due to changes in the protein surrounding the starch granules. In any case, changes related to time spent ensiled require that rations be re-evaluated through the course of the feeding year for fiber or fermentable carbohydrate content in order to maintain production and minimize chances for ruminal acidosis.

As a carbohydrate source, starch does have the advantage of having the potential to be digested in the rumen or small intestine, but site of digestion will alter the nutrients available to the cow. Starch will yield microbial protein and organic acids from ruminal fermentation or glucose from small intestinal digestion. A change in site of digestion and change in nutrients has potential to change animal performance, as well.

Physically Effective Fiber and Fiber Digestibility

The physical form of the ration, often expressed as peNDF, is crucial in its role for maintaining rumination and rumen function. If rumen function is abnormal, diets will not be properly digested, feed efficiency will be reduced, and animals may become sick. Since adequacy of peNDF is a function of the interaction of the animal and her diet, one of the best determinants of having reached the desired level of peNDF is that 40 to 50 % of the cows not eating, drinking, or sleeping (or heat stressed) are chewing their cuds. The Dairy NRC (2001) provides recommendations on amounts of total dietary NDF, NDF from forage (a proxy for peNDF), and NFC that can be safely fed to maintain animal health and performance (Table 2).

The need to evaluate the animal's response rather than diet particle size per se becomes understandable if we consider potential effects of selection of forages for fiber digestibility. If a forage is more digestible, does particle size alone best describe its peNDF value? For example, it was found that a brown midrib (**BMR**) corn silage and a non-BMR control corn silage had *in vitro* 30 hr NDF digestibilities of 59.9 and 46.5 %, respectively; but the diets containing them did not differ in NDF digestibility when fed to cows. Instead, cows consuming diets containing the BMR corn silage had lower ruminal pH, had a higher rate of NDF passage, greater intakes, and overall greater efficiency of microbial nitrogen production (Oba and Allen, 2000b). What appeared to be happening was that the BMR corn silage was breaking down into finer particles that could pass from the rumen more

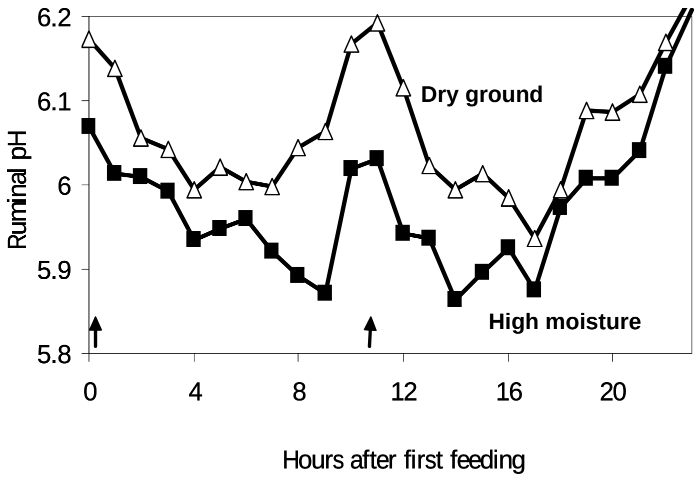

Figure 3. Rumen pH as affected by corn source. Dry ground corn gave a higher average pH than high moisture corn (slow vs rapid rate). Note that the pH goes down after feeding (arrows) as more fermentable feed enters the rumen. (Krause et al., 2002; figure courtesy of K. A. Beauchemin, Agriculture and Agri-Food Canada, Research Centre, Lethbridge, Alberta, Canada.)

rapidly than the control corn silage, leading to a more rapid rate of passage. Did the BMR provide the same level of peNDF as did the control silage? It does not seem so. The authors reported: “The beneficial effects of (BMR) corn silage on productivity of lactating cows were greater for the cows fed a high NDF diet.” (29 % NDF was the low NDF diet and 38 % NDF for the high NDF diet; Oba and Allen, 2000a). When more readily digestible fiber sources are fed, feeding more of them or including a small amount of a concentrated peNDF source (straw or clean corn stover) may be useful for maintaining rumen function. Changes in rate of passage will alter site and perhaps extent of digestion of dietary carbohydrates.

Sugars and Soluble Fiber

Excessive heating can destroy sugars, or other organic materials, but I could not find information on processing to improve digestion of sugars or soluble fiber. Molasses, almond hulls, waste candy, and similar feeds are excellent sources of sugar (so long as they are not from *sugar-free* foods). Citrus and beet pulps contain substantial concentrations of soluble fiber as pectic substances. Sugars and soluble fiber are very digestible (though soluble fiber from soyhulls will be more slowly degraded than from the pulps). Fermentations of sugars, soluble fiber, and starch can each give different products, so they may differ from each other in the production they support.

There have been many questions from the field about supplementing sugars. The ruminal fermentation products of sucrose and lactose can include lactic acid (Strobel and Russell, 1986; Thivend and Ehouinsou, 1977) and these sugars have been reported to yield more butyrate than other nonfiber carbohydrates (Strobel and Russell, 1986; DeFrain et al., 2006). So, on the one hand, sugars can produce lactate, a stronger acid than other organic acids in the rumen that might be suspected to cause problems with ruminal pH; but they also produce butyrate, a lipogenic organic acid that can be used for the production of fat by the cow. Substituting sucrose for starch does sometimes

Table 2. 2001 Dairy NRC recommendations for NDF and NFC formulation.

Minimum NDF from Forage, %	Minimum NDF in Ration, %	Maximum NFC in Ration, %	Minimum ADF in Ration, %
19	25	44	17
18	27	42	18
17	29	40	19
16	331	38	20
15	33	36	21

NDF = neutral detergent fiber, NFC = nonfiber carbohydrates

Table 3. Changes in milk yield and composition with changes in sucrose and starch supplementation (Broderick et al., 2000).

Sucrose, % of diet DM	0	2.5	5.0	7.5
Starch, % of diet DM	7.5	5.0	2.5	0
DMI, lb*	54.0	56.4	57.3	57.3
Milk, lb†	85.8	89.1	88.2	86.9
Fat, lb*	3.24	3.37	3.64	3.57
Protein, lb	2.73	2.82	2.84	2.82
Rumen pH	6.19	6.16	6.19	6.21
Milk/DMI*	1.60	1.58	1.54	1.52
FPCM/DMI	1.64x	1.63x	1.66x	1.64x
MN/IN*	0.312	0.291	0.291	0.295

*$P < 0.05$, † $P < 0.10$, linear response to increasing sucrose.
DM = dry matter, DMI = dry matter intake, FPCM = 3.5 % fat- and protein-corrected milk, MN = milk nitrogen, IN = intake nitrogen, x = calculated from data tables.

appear to have the potential to increase butterfat yield; however, results have been mixed. The results no doubt depend upon what amount of sugars and other fermentable carbohydrates were in the base ration. Some reports suggest that the impact of sugar additions can change by growing season (L. E. Chase, personal communication), which may speak to the influence of changing forage composition.

In one study, when sucrose was substituted for corn starch (0 to 7.5 % of diet DM, dietary NFC = 43 %, NDF = 29.6 %, CP = 16.8 %; alfalfa silage, corn silage and high moisture shell corn as 40.0, 20.0, and 20.5 % all on DM basis; Broderick et al., 2000), there were increases in dry matter intake (**DMI**), milk fat content and fat yield with increasing sucrose, and fat-corrected milk production tended to increase (Table 3). For feed efficiency, milk/DMI and milk nitrogen /intake nitrogen (protein use efficiency) decreased linearly with increasing sucrose. The fat- and protein-corrected milk feed efficiency did not appear to change (no statistics applied). Ruminal pH did not differ among the treatments.

The results of studies in which lactating cows were fed diets that contained a greater proportion of soluble fiber and sugars (from citrus pulp or beet pulp), or more starch (from corn products) are in Table 4. Cows fed citrus or beet pulp diets had lower intakes (on 2 studies), decreased milk protein percentage and yield (on 3 studies), and increased butterfat percentage (on 2 studies). The feeding of pulps did not increase the yield of butterfat on any of the studies, and milk yield was numerically lower on these diets. It seems that addition of the pulps that provide soluble fiber and sugars may decrease intake and milk protein. Although not evaluated statistically, the feed efficiencies based on fat and protein corrected milk do not appear to differ much.

So, is it a mistake to feed sugar + soluble fiber sources if you are interested in milk components and production? That seems to depend upon what the

Table 4. Lactation studies comparing starch and sugar + soluble fiber sources**.**

	Mansfield et al., 1994		Solomon et al., 2000		Leiva et al., 2000	
	Corn	Beet Pulp	Corn	Citrus	Hominy	Citrus
DMI, lb	47.4*	44.8*	46.1*	44.8*	47.2	46.1
Milk, lb	71.0	70.3	78.3	76.3	72.3	69.0
Fat %	3.64*	3.82*	3.33	3.38	3.43	3.54
Fat lb	2.60	2.67	2.60	2.56	2.47	2.45
Protein %	3.01*	2.90*	3.00*	2.93*	2.83*	2.71*
Protein, lb	2.14*	2.03*	2.31†	2.23†	2.05†	1.87†
Milk N/Intake N	0.24x	0.25x	0.31x	0.29x	0.24†	0.22†
FPCM/DMI	1.51x	1.59x	1.63x	1.64x	1.48x	1.45x

* $P < 0.05$, † $P < 0.15$. Values within same study differ.
DMI = dry matter intake, DM = dry matter, N = nitrogen, x = calculated from data in paper.
Milk N/Intake N = milk nitrogen divided by intake nitrogen, a measure of feed efficiency.
FPCM/DMI = 3.5 % fat- and protein-corrected milk divided by DMI; a measure of feed efficiency.

soluble fiber source is replacing in the diet and the proportion of the diet for which it accounts. If a concern is overfeeding of starch and its negative impact on rumen function, substitution of the other feeds is well warranted. I have the sense that our knowledge is incomplete regarding how protein feeding should be modified to complement the non-starch carbohydrate sources.

Protein x Carbohydrate Interactions

A possible relationship between ruminally degradable protein and low ruminal pH has been reported when rapidly fermenting carbohydrates are provided (Aldrich et al., 1993; Hatfield et al., 1998). Lactating dairy cows consuming diets providing higher concentrations of ruminally degradable protein (**RDP**) had lower ruminal pH (6.28) and a tendency towards greater ruminal concentrations of volatile fatty acids than animals fed more ruminally undegradable protein (6.39; $P < 0.01$); irrespective of whether the nonstructural carbohydrates (starch from high moisture shell corn or ground ear corn) was more or less ruminally degradable (Aldrich et al., 1993). The same type of response was noted for molasses-fed sheep, where an 18 % CP diet gave a lower ruminal pH than a 10 % CP diet achieved by supplementing soybean meal ($P = 0.02$; Hatfield et al., 1998). Based on current thought, this should not happen – more ruminally degradable protein should yield more microbes, not more acid. However, the cows and sheep are not wrong. In the cow study, there was no difference among protein treatments in organic matter digested ruminally, which could have provided more organic acids. *In vitro*, it appears that greater ratios of degradable protein to carbohydrate can increase the amount of volatile fatty acids and microbial protein produced from a given amount of carbohydrate (Hall and Weimer, 2007). Greater production of acid can give the advantage of providing more energy, or disadvantage of depressing ruminal pH. The challenge is that we do not know under what conditions the protein feeding will alter the organic acid production.

Management, Environment, and Demands

Being concerned about providing sources of digestible nutrients without minimizing non-production nutrient demands on the animal is like working a hand water pump as fast as you can while ignoring the hole in the bucket you are filling. Heat stress (survival), excessive walking (how far is it to parlor?), not providing cows with comfortable stalls or having them standing in holding pens for more than an hour (how much time will she spend standing?), take nutrients away from milk production. To reap the most nutrients for production from rations, remove obstacles to production. Focus on maintaining cow comfort, minimize the other work animals are expected to do (walk and stand), and provide them a well-mixed, balanced ration to support their requirements.

SUMMARY

- Maximize the use of homegrown forages to meet digestible carbohydrate needs.
- Harvest and process the feeds to enhance digestibility, maintain needed amounts of peNDF, and minimize spoilage.
- Maintain ration balance to maintain good rumen function and animal health.
- Reduce the demands that the environment and management place on cows so they can use nutrients for production rather than maintenance and survival.

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