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Review Article

Low-carbohydrate diets: what are the potential short- and long-term health implications?

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Low-carbohydrate diets for weight loss are receiving a lot of attention of late. Reasons for this interest include a plethora of low-carbohydrate diet books, the over-sensationalism of these diets in the media and by celebrities, and the promotion of these diets in fitness centres and health clubs. The re-emergence of low-carbohydrate diets into the spotlight has lead many people in the general public to question whether carbohydrates are inherently 'bad' and should be limited in the diet. Although low-carbohydrate diets were popular in the 1970s they have resurged again yet little scientific fact into the true nature of how these diets work or, more importantly, any potential for serious long-term health risks in adopting this dieting practice appear to have reached the mainstream literature. Evidence abounds that low-carbohydrate diets present no significant advantage over more traditional energy-restricted, nutritionally balanced diets both in terms of weight loss and weight maintenance. Studies examining the efficacy of using low-carbohydrate diets for long-term weight loss are few in number, however few positive benefits exist to promote the adoption of carbohydrate restriction as a realistic, and more importantly, safe means of dieting. While short-term carbohydrate restriction over a period of a week can result in a significant loss of weight (albeit mostly from water and glycogen stores), of serious concern is what potential exists for the following of this type of eating plan for longer periods of months to years. Complications such as heart arrhythmias, cardiac contractile function impairment, sudden death, osteoporosis, kidney damage, increased cancer risk, impairment of physical activity and lipid abnormalities can all be linked to long-term restriction of carbohydrates in the diet. The need to further explore and communicate the untoward side-effects of low-carbohydrate diets should be an important public health message from nutrition professionals.

Key Words: low-carbohydrate diets, health risk, diets, weight loss, cancer, osteoporosis, heart disease

Introduction

While the concept of low-carbohydrate diets have been with us for many decades, they appear to have had a resurgence in recent times and are currently generating a wide-degree of public interest and media attention, fuelled by the rising tide of obesity and insulin resistance in the general population. There are many variations on just what a 'low-carbohydrate' diet is. Some popular diet books such as *Dr. Atkins' Diet Revolution*,[1] *The Carbohydrate Addict's Diet*,[2] *Protein Power*[3] and *Sugar Busters*,[4] have common recommendations in that they advise consuming protein as the primary macronutrient for the body, with the remainder of the energy to be made up from fat. Ad hoc restriction of carbohydrate may also be done by using such simple rules as 'no carbohydrates after midday', as a way of self-restricting dietary carbohydrate. While some may classify the aforementioned diets as 'high-protein' they are invariably hypoenergetic diets where energy from carbohydrate is restricted such that the percentage contribution of energy from protein and fat is raised.

Table 1 broadly characterises four generic diets used for weight loss in terms of macronutrient contribution. The common thread amongst the diets listed in Table 1 is a similar energy restriction, the primary reason for weight loss. While a 'high-fat, low-carbohydrate' diet does severely restrict carbohydrate; total protein and fat intake are only raised by a small degree at the cost of a decrease in the overall nutritional adequacy of the diet.[5] For the purpose of this review a 'low-carbohydrate' diet is considered to be a diet containing less than 100 g/d of carbohydrate with typical percentages by nutrient contribution to energy being 50% - 60% for fat, less then 30% for carbohydrate, and 20% - 30% for protein. Furthermore, in order to adequately compare low-carbohydrate diets to conventional diets higher in carbohydrate a reference diet is assumed where carbohydrates contribute approximately 50% to the energy of the diet derived from an extensive variety of unrefined wholegrain cereals, legumes, fresh fruit, and vegetables (~200 g/day), as part of an overall hypo-energetic diet. For the aforementioned reference 'high-carbohydrate diet', protein is considered to represent approximately 20% of the energy with fat contributing the balance.

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Table 1. Average nutrient composition of different diets

Type of diet	Total kJ (kcal)	Fat g (% E)[#]	CHO g (% E)[#]	Protein g (% E)[#]
Typical American	9250 (2200)	85 (35)	275 (50)	82.5 (15)
High-fat, low-carbohydrate	5950 (1414)	94 (60)	35 (10)	105 (30)
Moderate-fat, balanced nutrient reduction	6100 (1450)	40 (25)	218 (60)	54 (15)
Low- and very-low-fat	6100 (1450)	16-24 (10-15)	235-271 (65-75)	54-72 (15-20)

[#]percent of total energy intake; table modified from Freedman *et al.*[21]

Types of low-carbohydrate diets

The most widely used low-carbohydrate diet is the one advocated by Robert C. Atkins, M.D. His 1972 book *Dr Atkins' Diet Revolution*[1] sold millions of copies within the first two years. His 1992 update, *Dr Atkins' New Diet Revolution* has sold over six million copies world wide.[6] Typically the diet involves four steps: a two-week 'induction' period, during which the goal is to reduce carbohydrate intake to under 20 g/d to take the individual into ketosis. During the induction phase, protein intake from such foods as beef, turkey, fish, chicken, and eggs are encouraged, although high protein intakes well above the individual's habitual diet are not recommended - however, an unlimited consumption of fat is allowed. This phase of the diet allows no fruit, bread, grains, starchy vegetables or dairy products other than cheese, cream or butter. Carbohydrate restriction is lessened during the following stages until individuals determine the level of carbohydrate they can consume while maintaining weight loss. For some, this level of carbohydrate restriction could be as low as 25 g/d and for others it could be as high as 90 g/d. The diet also encourages the person to check their urine for ketone bodies to ensure that ketosis is maintained.

The Carbohydrate Addict's Diet[2] aims to break cravings for 'fat-causing carbohydrates' by limiting the intake of carbohydrate-containing foods to only one meal per day. The Protein Power diet[3] provides for 0.75 g/d of protein per kilogram of body weight with less than 30 g of carbohydrates per day allowed in the induction phase and up to 55 g/d thereafter. The Protein Power diet is, by its nature, a carbohydrate- and protein-restrictive diet when compared against habitual intakes of carbohydrate and protein of most individuals. The Sugar Busters! diet[4] advises the avoidance of sucrose and high-glycaemic index foods such as potatoes, pasta, corn, white rice, and carrots. According to the Sugar Busters! diet, it is high-glycaemic index foods that cause a spike in insulin response that are responsible for the deposition of fat and the cause of insulin resistance (the fact that sucrose has a medium glycaemic index seems to be ignored in the rationale behind the diet). The main premise of most popular low-carbohydrate diet books is that a reduction in carbohydrates will result in a lowered basal insulin level and hence promote more triglyceride lipolysis into free fatty acids - leading to fat loss in overweight people. In reality, these diets work in the short term as they result in a reduction in total kilojoule intake which inherently leads to weight loss due to an energy deficit.

Weight loss achieved on low-carbohydrate diets

In one of the few published papers on the Atkins' diet, 18 subjects who followed the dietary regimen lost 7.7 kg in 8 weeks.[7] The dietary protocol represented an average kilojoule restriction of approximately 4500 kJ/d relative to the subjects' average previous isoenergetic diet. The dieters lost on average 3.6 kg in the first two-week induction period. In the following three two-week periods, weight loss was in the order of 1.4 kg per fortnight. The results showed that weight loss was entirely due to energy restriction achieved through a decrease in carbohydrate consumption by 90% while the actual amounts of fat and protein eaten changed little compared to the habitual intake of the participants prior to the commencement of the diet.

Comparing ketogenic and non-ketogenic hypo-energetic diets for weight loss in a one-month study showed no statistical advantage of either diet over the other in terms of weight loss.[8] These aforementioned studies confirmed many previous studies, which concluded that lower energy intakes rather than low carbohydrate intakes may be the key to successful weight loss.[9] The US National Weight Control Registry, which compiles details of individuals who have lost more than 13 kg for a year or more, analysed the diets of 2681 members.[10] They found that fewer than 1% of these successful people had followed a diet classified as 'low carbohydrate' (defined as 24% or less total daily kilojoules coming from carbohydrate) suggesting that this type of diet is not realistic for the achievement of long-term weight loss. Further to this, a study analysing the diets of over 10,000 free-living adults in the United States[11] found that those individuals consuming a diet with 55% of energy from carbohydrates, compared to those whose diets comprised zero to 30% energy contribution from carbohydrates, actually ate the same amount of food in terms of weight (2,271 ± 21g versus 2,225 ± 103g), however consumed less energy (7,728 ± 71kJ versus 8,530 ± 307 kJ), more fibre (18 ± 3 g versus 9 ± 0.4 g), and less fat (52 ± 1 g versus 101 ±3g). Individuals

consuming a greater percentage of carbohydrates ate more low-fat foods, unrefined grain products and fruits and these adults were more likely to have a BMI less than 25 kg/m^2. Such data suggests that a high-carbohydrate diet, which contains unrefined grains, cereals, and plenty of fibrous matter is more nutritionally adequate than low-carbohydrate diets and of a lower energy density which may be important in weight control.

One advantage that has been attributed to low-carbohydrate diets over conventional diets is the potential higher satiety value of protein and fat and the anorectic effect of ketosis in helping to enhance a decrease in appetite. Many factors however are able to influence appetite, hunger and subsequent food intake, with macronutrient intake being just one of these factors, hence the issue of satiety in dietary restriction is an area of great controversy. In terms of the greatest degree of satiety for controlling nutrient intake, fat-restricted diets are generally regarded as optimum with the efficacy of weight loss on such diets attributed to low energy density.[12,13] Further studies also suggest that diets where the macronutrient contribution is modified where carbohydrate contributes approximately 40% to energy and fat to 36% of energy (fat source mostly mono-unsaturated) can also achieve realistic weight loss and allow a greater chance of long-term compliance.[14,15] The chance of long-term compliance to any diet will most likely result from short-term weight-loss strategies that have the best chance to become habitual rather than restriction of macronutrient consumption per se.

Potential short-term health implications

Ketosis

One of the common metabolic changes seen when a person follows a low-carbohydrate diet is ketosis. When dietary carbohydrates are in limited supply, the body will utilise its reserves of glycogen in order to meet glucose demands. Glycogen stores in the body are quite small with approximately 70-100 g in the liver and 400 g in muscle. Most of these glycogen stores are exhausted within 24 to 48 h of carbohydrate restriction. As each gram of glycogen is bound with 3g of water, then a simple calculation shows that a 'weight loss' of around 1-2kg can be achieved within the first week of the diet, albeit due to diuresis and not to the burning of fat stores. Loss of glycogen and water is not a true measure of weight loss as glycogen and water stores will be replenished once the diet ends. The diuretic effect of a low-carbohydrate intake is limited to the first week of the diet, with ongoing weight loss after this time entirely due to the laws of energy balance.[16]

Once glycogen stores are depleted, the body begins to increase fat oxidation as a means of meeting the majority of its energy demands that can not otherwise be met by gluconeogenesis (the production of glucose from certain amino acids) and glycerol liberation from triglyceride breakdown. Fatty acids liberated into the blood are able to be oxidised by the liver for energy production. Fatty acids can also be partially oxidised by the liver to form acetoacetate, which can then be further converted to β-hydroxybutyric acid, both of which are collectively termed ketone bodies. Ketone bodies are able to be used by all tissues containing mitochondria, which includes muscle and brain. Ketone bodies themselves are filtered by the kidneys and cause an increased renal loss of sodium, thereby increasing water loss.[16] Currently, there is no consensus as to what is the absolute cut-off limit for the maximal amount of carbohydrate intake necessary to induce ketosis. Induction of ketosis is likely to vary on an individual basis, however, intakes in the range of 50-100g of carbohydrate a day are generally reported - typically representing less than 20% of energy from carbohydrate.[17]

Studies examining the long-term safety of ketogenic diets are few in number with most of the available data coming from the application of ketogenic diets in the treatment of paediatric epilepsy.[18] The diet used in this patient group is a high-fat, adequate protein, low-carbohydrate diet designed to mimic the biochemical changes that occur during starvation. Studies of children who have followed a ketogenic diet for management of epilepsy found that about 50% of children will continue on the diet for at least a year.[18] Reasons for discontinuing the ketogenic diet were due to either a lack of efficacy or due to the restrictive nature of food choices. Common adverse events attributed to the diet included dehydration, gastrointestinal symptoms, hypoglycaemia, as well as carnitine and vitamin deficiencies. Cognitive effects, hyperlipidaemia, impaired neutrophil function, urolithiasis, optic neuropathy, and osteoporosis have also been reported to occur in some patients following ketogenic diets.[19] In addition, elevation of blood uric acid levels is a well-recognised side effect of prolonged ketosis.[7] Long-term effects of exposure of the body to elevated uric acid levels while on ketogenic diets have not been studied, but potential does exist for arthritic and renal complications due to long-term hyperuricaemia. Studies on a normal adult population using a ketogenic diet for weight loss for periods of a year or more (as described in the aforementioned paediatric group) have not been performed, though the documented side-effects may potentially pose a serious health risk to individuals.

Dietary adequacy

All hypoenergetic diets result in loss of body weight and body fat. Losses of protein and fat are the same during a ketogenic diet as during a hypoenergetic, non-ketogenic diet hence no diet is superior to another in terms of preservation of lean body mass.[20] However, low-carbohydrate diets are at greater risk of being nutritionally inadequate as they enforce restriction of food choices. Typically, low-carbohydrate diets are low in fibre, thiamin, folate, vitamins A, E, and B_6, calcium, magnesium, iron, and potassium.[21] In the absence of supplemental multivitamins, there is a real risk of nutritional deficiencies occurring. Low-carbohydrate diets are also usually higher in saturated fat and cholesterol with protein mainly being derived from animal sources.[21] Comparison of a range of popular diets revealed that low-carbohydrate diets (defined as less then 30% of energy from carbohydrate) fared worse in terms of dietary adequacy (as defined by the amount of inclusion of the five major foods groups and alignment with the U.S. Dietary Guidelines) while high-carbohydrate diets (defined as greater than 55% of energy from

carbohydrates) gave the highest dietary adequacy score.[5] The aforementioned study gave a rating, known as the Healthy Eating Index (HEI) to the discussed dietary types: high-carbohydrate diets received a HEI score of 82.9 (highest possible score is 100) which was the highest score recorded for the range of diets analysed while low-carbohydrate diets received a score of 44.6 (the lowest recorded score in the study).

Physical activity

Short-term effects of low-carbohydrate diets often reported by individuals include nausea, thirst, polyuria, headache, dizziness, halitosis and fatigue.[21] Dehydration is very common during periods of restricted carbohydrate consumption due to increased water loss associated with ketotic-induced diuresis and water loss from depletion of glycogen stores. Substantial losses of water through sweat during exercise can lead to further losses of water and electrolytes.[22] Commencing any form of physical activity whilst in a dehydrated state, whether it be an elite athlete or the average person on a weight loss diet, is known to impair performance and metabolic function and have negative effects such as; an early onset of fatigue, impairment of mental function, increase in body temperature, changes in blood pressure, and heat stroke.[22,23] Hydration prior to commencement of, and during physical activity, should be an area of high priority for all individuals, but especially those that may be following a carbohydrate-restricted diet.

As an increase in physical activity is often undertaken in conjunction with dieting, the influence of carbohydrate restriction on physical performance is an important issue to examine. High-intensity anaerobic exercise requires creatine phosphate breakdown as well as muscle glycogen utilisation.[24] It has been shown that low-carbohydrate diets reduce mean power output due to a reduction in muscle glycogen stores and hence a decreased rate of glycolysis.[25] Several studies have shown that the time until the onset of fatigue during high-intensity exercise (defined as at, or close to, 100% VO_2max) is accentuated in untrained subjects who had been following a low-carbohydrate diet prior to exercise when compared to individuals following moderate- or high-carbohydrate diets.[26-30] However, similar studies to those just described found that in subjects defined as highly trained or physically active, onset of fatigue when following a low-carbohydrate diet was not significantly different compared to conventional diets.[27-29,31] A low carbohydrate intake over a period of three to four days results in metabolic acidosis due to increased circulation of free fatty acids and 3-hydroxybutyrate concentrations. It has been suggested that the presence of metabolic acidosis may be a factor in leading to fatigue after the adoption of the afore-mentioned dietary regime,[32] however few studies support this proposal.

In aerobic exercise, muscle glycogen is an important substrate for ATP production within contracting skeletal muscle. The importance of ATP availability is demonstrated by the fact that fatigue is often associated with muscle glycogen depletion.[33] The significance of carbohydrate availability during moderate-intensity exercise (60-70% VO_2max) is demonstrated by the earlier onset of fatigue once glycogen stores are depleted as the body is unable to oxidise fat at sufficient rates to meet energy requirements. Work rates are hence reduced to lower levels of intensity (30-50% VO_2max) to compensate for the reduced rate of energy production.[34] While little published data exists examining the effects of carbohydrate restriction on the physical performance of average untrained individuals, there is evidence to suggest that such individuals do have a diminished fat oxidative capacity hence have a greater reliance on glucose as fuel source during exercise.[35] Taking these findings into consideration, it is worth to pose the question as to what effect carbohydrate restriction may have on the physical performance of inactive, overweight and untrained individuals and if such dietary regimens may compromise weight loss due to impairment of the ability to exercise at the individuals maximal potential. Such studies at present have not been performed.

Potential long-term health implications

Insulin response

One of the main rationales promoted by advocates of low-carbohydrate diets is that insulin secretion, in response to carbohydrate ingestion, is the cause of the metabolic imbalance that promotes obesity. Carbohydrate ingestion results in increased insulin secretion with subsequent glucose uptake by cells and inhibition of lipolysis. If the post-prandial secretion of insulin could somehow be attenuated by restriction of carbohydrate-containing foods then this would promote a more favourable environment for fat breakdown and hence, as advocated by supporters of low-carbohydrate diets, weight loss. While such a situation is true in theory it is in fact overly simplistic and the actual reality is much more complex. What is known is that energy restriction, irrespective of dietary composition, promotes weight loss and improvement of glycaemic control.[21] A study by Golay *et al.*,[20] in human subjects demonstrated that an intake of either 15% or 45% carbohydrate as part of a total daily energy intake of 4.2 MJ over 6 weeks produced no significant difference in weight loss, (8.9 ± 0.6 and 7.5 ± 0.5 kg respectively) despite significantly different insulin levels of 57.6 ± 0.6 and 88.2 ± 9.6 pmol/L respectively. To focus on one particular metabolic response, that being post-prandial carbohydrate-stimulated insulin secretion, presents a very unbalanced view of the complex metabolic changes leading to obesity.

What is overlooked in the simple metabolic situation promoted by proponents of low-carbohydrate diets is that dietary amino acids are also able to stimulate insulin secretion without augmenting glucose concentrations.[36-39] Investigations examining the insulin response to whole foods showed that protein foods such as meat and fish elicited a greater peak insulin concentration than white pasta.[36] The effect that protein can have on insulin secretion is an interesting finding as it raises several areas of concern, primarily what the rise in insulin secretion may have in terms of glycaemic control, particularly in individuals with diabetes or impaired glucose tolerance. In one long-term study of the metabolic effects of high-protein diets, subjects were fed either 1.87 g/kg/d (high protein) or 0.74 g/kg/d (normal protein) for 6 months.[37]

It was found that the glucose-stimulated insulin response in the high-protein group was significantly increased when compared to the normal protein group. Interestingly, insulin levels in the high protein group remained elevated for up to eight hours in the postprandial state. In a recent review of the glycaemic response of foods as a predictor of insulin response it was concluded that the glycaemic response accounted for only 23% of the variability in insulinaemia.[40]

Chronic ingestion of a low-carbohydrate diet, coupled with elevated amounts of protein as a major macronutrient results in increased hepatic glucose production and decreased peripheral glucose utilisation, both indicative of an insulin resistant state.[41,42] Although more study in this area is needed, early findings suggest that increased basal insulin release, higher fasting-glucose production and enhanced gluconeogenesis all increase the demand on insulin release from the pancreas and may hasten the onset of diabetes in susceptible individuals due to pancreatic beta cell failure.[37,38] In contrast, the use of high-protein, hypo-energetic weight-loss diets (as opposed to high-protein, isoenergetic diets) in the management of type 2 diabetes has shown comparable results to reduced-fat diets in terms of improvements in metabolic para-meters such as blood glucose, lipids, insulin response as well as overall weight loss.[39]

Cardiovascular complications

Any diet that results in weight loss will elicit a favourable response on blood lipid parameters.[44,45] Typical reported changes include a reduction in total cholesterol, triglycerides, LDL- and HDL-cholesterol while free fatty acids are elevated. However, nutrient composition of energy-restricted diets can have differing effects on absolute changes in blood lipids. Greater decreases in LDL-cholesterol are seen during active weight loss when diets are low in saturated fat, however a low-carbohydrate diet is typically higher in saturated fat than conventional weight-loss diets. A review of the effect of the use of isoenergetic ketogenic diets on blood lipids found that, overall, LDL-cholesterol and total cholesterol tended to be elevated while HDL-cholesterol levels were lowered.[21] As LDL-cholesterol is considered a major contributor to the process of atherogenesis, then long-term use of low-carbohydrate diets, be it for weight reduction or weight maintenance, may have the potential to put an individual at greater risk of heart disease. Proponents of low-carbohydrate diets often point to the fact that high-carbohydrate diets increase plasma triglycerides.[46] The clinical significance of carbohydrate-induced hypertriglyceridaemia in individuals who are otherwise healthy is an area of great debate and currently no firm conclusions can be made. In many persons however, the effect of carbohydrate feeding on triglyceride synthesis can be significantly diminished by weight loss, exercise, and dietary restriction irrespective of the macronutrient make-up of the diet.[47]

While important tissues such as the brain, muscle, and heart can utilise ketone bodies as a primary fuel source during carbohydrate restriction, there may be a metabolic cost associated with the use of fatty acids as a fuel due to the inability of the body to replenish key intermediates of the citric acid cycle necessary for energy production. One study performed in isolated rat hearts found that when the heart was perfused in a solution containing primarily acetoacetate (a ketone body) as a fuel source, contractile ability of the heart was reduced by 50% within 60 minutes.[48] This contractile failure was reversed by the addition of pyruvate, which can be synthesised from glucose. Such results demonstrate that ketone bodies are not a self-sufficient fuel for the working heart, but require augmentation from a carbohydrate-derived substrate such a pyruvate.

A study by Best *et al.*,[49] investigating potential cardiac complications in 20 paediatric patients on a ketogenic diet for management of epilepsy found cardiac abnormalities (as defined by changes in the QT interval of an ECG) in three of the patients on the diet. Interestingly, there was a significant correlation between prolonged QT interval and low serum bicarbonate (suggesting increased blood acidity) and high beta-hydroxybutyrate (levels of which are elevated in ketosis). Prolongation of the QT interval is of clinical importance due to an increased risk for ventricular dysrhythmia and sudden death.[49,50] Such changes in the QT interval have also been observed in anorexia nervosa and very-low-kilojoule diets for obesity;[51] both metabolic states where ketosis is very likely to occur. Ketogenic diets result in an increase in plasma free fatty acids due to increased lipolysis while prolonged elevation of free fatty acids has been linked with cardiac arrhythmias.[52] Over 60 deaths in individuals on medically supervised very-low-kilojoule liquid protein diets have been reported[53] with the suggestion that cardiac arrhythmias were the cause of death.[54] Further studies however have suggested that low-energy diets with adequate supervision are safe and produce no ECG abnormalities,[55] while other studies suggest patients who ingest a nutritionally balanced low-kilojoule diet over seven days were also void of cardiac abnormalities.[56] Considering that both starvation diets[57,58] and starvation-like states such as anorexia nervosa can induce fatal cardiac dysrhythmias and both states can induce ketosis then the safety of low- and very-low-carbohydrate ketogenic diets needs to be explored further, especially in light of the lack of information on electrolyte and physiologic changes during such dieting regimes.

Bone health

A potential effect of low-carbohydrate diets on bone health is an important consideration. The loss of the body's calcium stores is a major concern, especially in women and the elderly, as it is strongly linked to osteoporosis.[59,60] Observational studies and controlled trials with children, young adults, and the elderly all support the important role for calcium intake in building and maintaining bone mass and reducing bone loss.[59,60] Low-carbohydrate diets promote the restriction of dairy products, particularly milk and yoghurt, which are the main sources of calcium in the diet. As peak bone mass is an important factor in determining long-term fracture and osteoporosis risk, adoption of dieting practices that restrict calcium intake (particularly in those under the age of 30) have the potential to compromise the attainment of peak bone mass. Individuals with the highest peak bone

mass after adolescence have the greatest protective advantage when the inexorable declines in bone density associated with increasing age, illness, and diminished sex-steroid production take their toll.[61] As low-carbohydrate diets are known to be deficient in calcium[21] then the adoption of this type of dieting practice, especially if followed as a long-term eating strategy in those under 30 years of age, pose a real possibility of increasing osteoporosis risk later in life.

Low-carbohydrate diets have the potential to generate a sub-clinical chronic metabolic acidosis (via the presence of ketone bodies in blood) which can then promote calcium mobilisation from bone.[62-65] Blood acidification can increase glomerular filtration rate and decrease renal tubular reabsorption of calcium with a concomitant increase in activity of osteoclasts and inhibition of osteoblasts, further increasing bone resorption. Studies have shown that by increasing the total proportion of protein consumed as meat, which contains sulphur amino acids (namely methionine and cysteine), in the diet increases calcium, potassium, sodium and ammonia loss in the urine due to a change in blood acidity.[66] Low-carbohydrate diets promote the consumption of animal protein as a good way of limiting carbohydrate intake hence compounding the potential effects on blood acidity and calcium loss. Barzel and Massey[62] proposed that diets with the potential to increase renal acid load lead to calciuria which can have adverse affects on bone unless buffered against the consumption of alkali-rich foods such as fruits and vegetables. Recent studies though appear to contradict this theory with a large-scale epidemiological study of over 900 adults showing no negative effect of consumption of animal protein on bone mineral density.[67] Conflicting reports on the effect of animal protein and bone health could be due in part to differences in participant ages, calculation of protein intakes, dietary data collection problems, and anatomic sites evaluated. Diets based mainly on plant proteins do not appear to augment calcium loss, an effect most likely attributed to a higher phosphate intake (dietary phosphate has the ability to increase renal tubular reabsorption of calcium) and a lower intake of sulfur-containing amino acids.[68] Studies have not been performed on the adverse aspects of low-carbohydrate diets on bone health in adults, but the potential metabolic mechanism to induce, or at least hasten, osteoporosis do exist.

Cancer risk

There is overwhelming evidence for a protective effect of fruits and vegetables in almost all major cancers afflicting western society today including colorectal, breast, pancreatic, lung, stomach, oesophageal, and bladder cancer.[69,70] Fruits and vegetables contain a vast array of compounds that are implicated in providing protection against cancer. For examples, such substances such as antioxidants, fibre, isothiocyanates (in cruciferous vegetables), allyl sulphides (in onions and garlic), flavonoids, and phenols have all been linked to augmenting the body's protective mechanism against cancer promotion. The nature of a low-carbohydrate diet, however, is one that is low in fruits, vegetables (if starchy vegetables aren't adequately replaced with other types of low-carbohydrate-containing vegetables) and grains thus potentially placing an individual at an increased cancer risk if the diet is followed long term. Furthermore, the evidence strongly suggests that it is not the consumption of one or two varieties of vegetables and fruit that confer benefit, but rather the intake of a wide-variety of plant foods (the latter being a common factor in those who have a lower risk of cancer).

The potential link between increased intakes of meat (typically seen on low-carbohydrate diets) and bowel cancer risk can not be ignored as it has been suggested that the link between meat and the consumption of animal protein with cancer is as strong as the association of fat with cancer.[71] In a recent review of prospective cohort studies on meat consumption and colorectal cancer risk, it was found that daily increases of 100 g of all meat or red meat is associated with a significant 12-17% increased risk of colorectal cancer.[72] Epidemiologic evidence on colorectal cancer risk and meat consumption from 32 case-control and 13 cohort studies supported the hypothesis that meat consumption (in particular red meat), is associated with a modest risk of increased colorectal cancer risk.[73] Not all the evidence however is equivocal[74] and it has been suggested that the epidemiological data are much more consistent with there being a protective role of fruit, vegetables and whole-grain cereals and no role for meat in colorectal cancer.[75] A low-carbohydrate diet promotes increased meat consumption at the expense of fruit and vegetable intake.

Many mechanisms have been proposed for the association between red meat and colon cancer such as low intakes of protective dietary factors such as fibre and a displacement of protective compounds found in fruit and vegetables in the diet.[72,73] At present, however, no long-term consumption data exists to assess cancer risk in individuals following low-carbohydrate diets. A significant reduction in dietary fibre is typically seen when an individual follows a low-carbohydrate diet and this may explain reports of constipation in people following these type of diets[21] as dietary fibre is only found in foods of plant origin such as cereals, fruits and legumes. Dietary fibre can have a myriad of benefits in the colon such as diluting carcinogenic compounds, increasing stool transit time, production of beneficial fermentation products such as butyric acid and a lowering of pH, all of which have been proposed as being protective against colon cancer.[76]

Practical advice to health professionals

In terms of weight loss, the simple fact of energy balance can not be ignored; any diet that is hypoenergetic will result in weight loss. When using loss of body fat as a true measure of weight loss, then low-carbohydrate diets present no significant advantages to the dieter over nutritionally balanced, hypoenergetic diets. Based on the available evidence, the reverse may in fact be true, in that long-term compliance to a low-carbohydrate may put an individual at greater risk of an array of metabolic diseases without the achievement of sustainable weight loss. A comprehensive recent review of popular diets concluded that a diet that is high in fruit and vegetables, whole-grains, legumes, and low-fat dairy products as well as being moderate in fat and kilojoules will result in the

greatest chance of weight loss and maintenance.[21] Such diets are also associated with fullness and satiety and can reduce risk of chronic disease. Low-carbohydrate diets achieve very few of these aims. Certainly within the scope of the ideal type of diet to follow for long-term weight loss there is considerable scope for variation in the actual advice given. Diets can be recommended to suit the individual's own food preferences within the guidelines given previously. For some individuals this advice may be to have a higher protein intake, combined with a moderate reduction in fat and carbohydrate, while for others low-fat, high-carbohydrate food choices may be appropriate.

Advice should be given to an individual following a low-carbohydrate diet to help avoid some of the potential metabolic consequences known to be associated with this diet. For example, advice would include: to increase the intake of water to help prevent dehydration; ensure an adequate intake of fibre from non-starch containing foods; and to consume an adequate amount of calcium either from the consumption of low-fat dairy products, canned fish with bones or from the use of supplements. The use of a general multivitamin formulation would also seem prudent in light of the array of vitamin and mineral deficiencies that may potentially exist. Certainly those with a history of heart problems should be strongly dissuaded from restricting carbohydrates whilst undertaking vigorous exercise due to potential cardiac abnormalities associated with ketogenic diets.

Although this review has focused on the contribution of free fatty acids and ketone bodies to service the body's energy demands, the contribution of gluconeogenesis from the bodies amino acid stores has been estimated at 55% of endogenous glucose production in normal subjects 5 to 12 hours after a large evening meal thus potentially increasing muscle breakdown.[77] Further studies in this area would be useful to determine what minimal amount of dietary carbohydrate is enough to reduce gluconeogenesis, and thus reduce the demand on skeletal and cardiac muscle protein stores. Currently it is estimated that ~120 to 180 grams of carbohydrate is necessary for inactive individuals to consume to avoid catabolism of the body's protein stores to fuel glucose production.[78] Weight gain at the cessation of a low-carbohydrate diet needs also to be addressed. Although data on this issue are scarce, mechanisms for weight gain could be related to the up regulation of glycogen synthase activity causing a super-compensation of muscle and liver glycogen as in an athlete's carbohydrate-loading phase,[79] also resulting in greater hydration than pre-diet hydration status. This resultant weight gain is also important to understand from a health professional's point of view because the average person (who has been on a low-carbohydrate diet) may misinterpret weight gain after carbohydrates are increased in the diet as 'carbohydrates turning to fat' thus propagating the perception of the negative role of carbohydrates in the diet.

The potential message that low-carbohydrate diets send out into the public arena is 'don't eat carbohydrates because they'll make you fat'. This concept is clearly illustrated from a quote from Dr. Atkins "A carbohydrate-restricted diet is so effective at dissolving adipose tissue that it can create fat loss greater than occurs during fasting" and "For many of us, the bypassing of carbohydrates is our ultimate solution".[1] Many health clubs, TV programs, gymnasiums and personal trainers advocate a 'No carbohydrates after midday' policy as their interpretation of a low-carbohydrate diet. The authors' own studies, based on personal involvement in the health and fitness industry in Australia, suggest that well over 200 gymnasiums Australia-wide are advocating or promoting some variation of a low- or no-carbohydrate dietary regime (unpublished observations). It has been clearly demonstrated, however, that the conversion of carbohydrate to fat via de novo lipogenesis is not a major pathway in humans.[80] It has also been repeatedly shown in studies that it is the overall kilojoule content of the diet that dictates the magnitude of fat loss, not the nutrient composition.

With the promotion of the purported 'positive weight-loss effects' of low-carbohydrate diets in the media for the past decade, it is important that the general public are aware of the potential negative effects of this type of dieting practice. The marketing of celebrities such as Geri Halliwell and other Hollywood stars who have lost weight on these diets does little in the way to promote safe and realistic dieting practices. At the beginning of 2001 the British Dietetic Association called for a stop to celebrity-endorsed health and weight-loss claims that do not stand up to scientific scrutiny.[81] Many people in the community feel that carbohydrates are inherently unhealthy due to their perceived major role in promoting obesity. Nutrition health professionals need to correct this misconception with balanced, factual and realistic advice.

Conclusions

In the face of the rising tide of obesity in developed countries, the lure of easily attainable weight loss by following a low-carbohydrate diet is certainly appealing, yet little discussion is given to the potential negative health aspects potentially associated with this type of dieting regime. When health professionals speak of low-carbohydrate diets they often repeat the message of lack of concentration, kidney problems and bad breath and often say 'low-carbohydrate diets can be dangerous'. This does little to deter people in the quest for weight loss and there is the commonly held belief that 'As long as I lose weight I don't care what I have to do.' By delivering a stronger message in the future and addressing such serious potential health aspects to low-carbohydrate diets such as potential cardiac complications, osteoporosis, muscle loss and possibly insulin resistance, people are better able to make informed choices based on the latest scientific thinking about the risks associated with popular dietary practices such as low-carbohydrate diets. Future studies are certainly warranted, especially in the examining of the long-term efficacy of the use of low-carbohydrate diets and how much this type of dieting pattern may alter an individuals perception of foods and food choices well into the future.

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