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THE ROLE OF DIET IN KIDNEY STONE FORMATION: A COMPREHENSIVE NARRATIVE REVIEW

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Abstract: INTRODUCTION The review discusses the critical role of diet in the pathogenesis and prevention of kidney stones, highlighting that different dietary components, such as calcium, proteins, sodium, oxalates, fluids, and certain micronutrients like citrate and magnesium, can either increase or decrease the risk of stone formation. The introduction establishes the complexity of dietary influences on stone risk, emphasizing the need for individualized dietary recommendations based on the patient's metabolic profile and risk factors. **OBJETIVE** To explore the influence of various dietary components on the formation and prevention of kidney stones, emphasizing the role of calcium, proteins, sodium, oxalates, fluids, citrate, magnesium, purines, carbohydrates, and specific foods and beverages. **METHODS** This is a narrative review which included studies in the MEDLINE – PubMed (National Library of Medicine, National Institutes of Health), COCHRANE, EMBASE and Google Scholar databases, using as descriptors: "Dietary Calcium" AND "Kidney Stones" OR Animal Protein" AND "Sodium Intake OR Stone Formation" OR "Oxalate-rich Foods" OR "Fluid Intake" in the last years. **RESULTS AND DISCUSSION** The results highlight the paradoxical role of dietary calcium, where higher intake is associated with a reduced risk of calcium oxalate stones, in contrast to the increased risk posed by calcium supplements. The discussion covers the adverse effects of high animal protein and sodium intake, which contribute to increased urinary excretion of stone-forming solutes. It also addresses the protective roles of adequate hydration, dietary citrate, and magnesium, alongside the potential benefits of plant-based proteins and fiber-rich diets. The section explores complex interactions between specific foods and beverages and their varying effects on stone risk. **CONCLUSION** The conclusion emphasizes that kidney stone formation is a multifactorial process where diet is a key modifiable risk factor. It supports individualized dietary counseling tailored to the patient's unique metabolic and risk profiles, while advocating for further research to clarify the complex interactions between diet, metabolism, and stone formation. The review underlines the importance of integrating dietary management into the overall clinical strategy for preventing kidney stones.

Keywords: Nephrolithiasis; Dietary Interventions; Calcium Oxalate Stones; Hypercalciuri; Citrate and Stone Prevention

INTRODUCTION

Kidney stones, also known as nephrolithiasis or urolithiasis, are a prevalent and recurrent condition worldwide, significantly impacting both individuals and healthcare systems[1]. The formation of kidney stones involves a complex interplay between genetic, environmental, and metabolic factors[1]. Among these, diet plays a crucial role in both the pathogenesis and prevention of this condition[1]. The composition of kidney stones, which may include calcium oxalate, uric acid, struvite, or cystine, is heavily influenced by dietary intake[2]. Understanding how different foods contribute to the formation of these various types of stones is essential for developing targeted dietary recommendations that can help reduce the incidence and recurrence of nephrolithiasis[2].

Dietary calcium intake, traditionally considered a primary factor in kidney stone formation, has been the subject of extensive debate[2]. The paradoxical relationship between dietary and urinary calcium and their roles in stone formation remains a key area of research[2]. While high urinary calcium is a known risk factor for stone formation, recent studies have demonstrated that a diet low

in calcium may actually increase the risk of kidney stones, particularly calcium oxalate stones[3]. This is attributed to the increased intestinal absorption of oxalate when dietary calcium is insufficient, underscoring the need for a nuanced understanding of calcium metabolism in nephrolithiasis[3].

The consumption of animal proteins has also been implicated in stone formation due to its effects on urine chemistry[3]. High intake of animal protein can lead to increased urinary excretion of calcium, oxalate, and uric acid, and reduced urinary pH, all of which are known risk factors for kidney stone formation[4]. In contrast, plant-based diets appear to offer some protective benefits, although the underlying mechanisms are not yet fully understood[4]. The relationship between protein intake and stone risk is further complicated by variations in individual metabolic responses and underlying health conditions, suggesting that dietary recommendations may need to be personalized[4].

Sodium intake is another dietary factor that significantly influences kidney stone formation[5]. A high-sodium diet is associated with increased urinary calcium excretion, which can promote the formation of calcium-containing stones[5]. The mechanisms behind this involve sodium-induced hypercalciuria, where sodium and calcium compete for reabsorption in the renal tubules[5]. This relationship suggests that dietary sodium restriction could be a valuable strategy in preventing kidney stones, particularly in individuals with a predisposition to hypercalciuria[6]. However, the impact of sodium intake on stone risk may vary depending on individual genetic factors and comorbidities, necessitating further research to clarify these interactions[6].

Oxalates, naturally occurring compounds found in many foods, play a critical role in the formation of calcium oxalate stones, the most common type of kidney stones[6]. High dietary intake of oxalate-rich foods, such as spinach, nuts, and certain fruits, has been linked to increased urinary oxalate excretion and a higher risk of stone formation[7]. However, the extent of this risk may be moderated by other dietary components, such as calcium and magnesium, which can bind oxalate in the gut and reduce its absorption[7]. Understanding the interplay between these dietary factors is essential for developing effective dietary interventions to prevent stone formation[7].

Fluid intake is widely recognized as a key modifiable factor in the prevention of kidney stones[8]. Adequate hydration reduces the concentration of stone-forming solutes in the urine, thereby decreasing the likelihood of crystal formation and growth[8]. The role of specific beverages, including water, tea, coffee, and citrus juices, has been the focus of numerous studies, with varying results[8]. While increased fluid intake is generally associated with a reduced risk of stone formation, the type of fluid consumed may also influence this risk[9]. For example, beverages containing citrate, such as lemonade, may provide additional protective effects by inhibiting calcium stone formation[9].

Citrate, a natural inhibitor of stone formation, is of particular interest in the dietary management of nephrolithiasis[9]. Low urinary citrate, or hypocitraturia, is a well-established risk factor for stone formation[10]. Dietary sources of citrate, such as citrus fruits, may help to increase urinary citrate levels and reduce the risk of stone formation[10]. However, the effectiveness of citrate supplementation or increased dietary intake in preventing stones may vary depending on individual metabolic factors and the presence of other urinary risk factors[10].

Magnesium intake has also been shown to play a role in the prevention of kidney stones[11]. Magnesium can form soluble

complexes with oxalate, thereby reducing the concentration of free oxalate available to form calcium oxalate crystals[11]. Some studies suggest that increasing dietary magnesium may be beneficial in reducing the risk of stone formation, although the evidence remains inconclusive[11]. Further research is needed to clarify the role of magnesium in stone prevention and to determine whether dietary or supplemental magnesium is more effective[12].

The relationship between purine-rich foods and uric acid stones is another important area of investigation[12]. High intake of purines, found in foods such as red meat, shellfish, and certain types of alcohol, can lead to hyperuricosuria, which promotes the formation of uric acid stones[12]. Understanding the metabolic pathways involved in purine metabolism and their interactions with other dietary factors is critical for developing effective dietary strategies to prevent uric acid stones[13].

Carbohydrates, particularly refined carbohydrates, have been suggested to influence kidney stone formation, although their role is less well defined[13]. Some studies have indicated that high intake of refined sugars may increase urinary calcium excretion, thereby raising the risk of calcium-containing stones[13]. Conversely, complex carbohydrates, particularly those rich in dietary fiber, may offer protective benefits[14]. The impact of different types of carbohydrates on stone risk may depend on various factors, including their effect on body weight, insulin resistance, and overall dietary patterns[14].

Dietary fiber, particularly from fruits, vegetables, and whole grains, is thought to play a protective role in the prevention of kidney stones[14]. Fiber can modulate the gut microbiota and reduce the intestinal absorption of oxalate, thereby decreasing urinary oxalate excretion[15]. Moreover, high-fiber diets are often associated with other beneficial dietary patterns, such as increased intake of fruits and vegetables and reduced consumption of animal proteins and sodium, which may collectively reduce the risk of stone formation[15].

The influence of specific foods and beverages on kidney stone risk is a complex area of study that requires a detailed understanding of individual food components and their metabolic effects[15]. Recent research has focused on the impact of various beverages, including coffee, tea, and alcohol, as well as specific foods such as chocolate, nuts, and green leafy vegetables[16]. The results of these studies have been mixed, highlighting the need for further research to elucidate the role of specific dietary components in stone formation[16].

OBJETIVES

To explore the influence of various dietary components on the formation and prevention of kidney stones, emphasizing the role of calcium, proteins, sodium, oxalates, fluids, citrate, magnesium, purines, carbohydrates, and specific foods and beverages.

SECUNDARY OBJETIVES

1. To evaluate the relationship between dietary calcium intake and the risk of calcium oxalate stones.
2. To investigate the impact of animal and plant-based protein consumption on urinary stone formation.
3. To assess the effects of sodium intake on urinary calcium excretion and the development of nephrolithiasis.
4. To analyze the role of fluid types and volumes in the prevention of stone recurrence.
5. To examine the protective effects of dietary citrate, magnesium, and fiber in reducing the risk of kidney stones.

METHODS

This is a narrative review, in which the main aspects of the influence of various dietary components on the formation and prevention of kidney stones, emphasizing the role of calcium, proteins, sodium, oxalates, fluids, citrate, magnesium, purines, carbohydrates, and specific foods and beverages in recent years were analyzed. The beginning of the study was carried out with theoretical training using the following databases: PubMed, sciELO and Medline, using as descriptors: "Dietary Calcium" AND "Kidney Stones" OR Animal Protein" AND "Sodium Intake OR Stone Formation" OR "Oxalate-rich Foods" OR "Fluid Intake" in the last years. As it is a narrative review, this study does not have any risks.

Databases: This review included studies in the MEDLINE – PubMed (National Library of Medicine, National Institutes of Health), COCHRANE, EMBASE and Google Scholar databases.

The inclusion criteria applied in the analytical review were human intervention studies, experimental studies, cohort studies, case-control studies, cross-sectional studies and literature reviews, editorials, case reports, and poster presentations. Also, only studies writing in English and Portuguese were included.

RESULTS AND DISCUSSION

The relationship between dietary calcium and kidney stone formation remains one of the most debated topics in nephrolithiasis research[16]. While high urinary calcium excretion is a recognized risk factor for stone formation, epidemiological studies have consistently shown that higher dietary calcium intake is associated with a reduced risk of calcium oxalate stones[17]. This paradox can be explained by the role of dietary calcium in binding intestinal oxalate, thereby reducing its absorption and subsequent urinary excretion[17]. Studies have demonstrated that patients with low dietary calcium intake have higher urinary oxalate levels, which increases the risk of calcium oxalate stone formation[17]. Therefore, dietary recommendations for individuals at risk of kidney stones should emphasize adequate calcium intake from dietary sources rather than supplements, as calcium supplements have been associated with an increased risk of stone formation[18].

The consumption of animal proteins has been shown to influence kidney stone risk through multiple pathways[18]. High intake of animal protein increases the urinary excretion of calcium, oxalate, and uric acid, while simultaneously lowering urinary citrate, an important inhibitor of stone formation[18]. Studies have demonstrated that individuals with high dietary protein intake have a significantly higher risk of developing both calcium and uric acid stones[19]. Conversely, plant-based proteins appear to have a neutral or protective effect on stone risk[19]. The difference in risk profiles between animal and plant proteins may be due to the presence of additional compounds in plant foods, such as potassium and magnesium, which may counteract the stone-promoting effects of protein[19]. These findings suggest that dietary recommendations should encourage a reduction in animal protein intake and a greater emphasis on plant-based sources of protein[20].

Sodium intake has a well-established role in the pathogenesis of kidney stones, particularly calcium stones[20]. Sodium and calcium are competitively reabsorbed in the renal tubules, and high sodium intake leads to increased urinary calcium excretion (hypercalciuria), which is a major risk factor for calcium stone formation[20]. Clinical studies have shown that patients who adhere to a low-sodium diet have significantly lower urinary calcium

excretion and, consequently, a reduced risk of stone formation[21]. Given the high prevalence of high-sodium diets in many populations, sodium reduction strategies, including public health interventions and dietary counseling, could play a critical role in reducing the incidence of kidney stones[21].

Oxalate, a naturally occurring compound found in many foods, is a key contributor to calcium oxalate stone formation[21]. High dietary oxalate intake has been associated with increased urinary oxalate excretion and a higher risk of stone formation, particularly in individuals with a predisposition to hyperoxaluria[22]. However, the risk posed by dietary oxalate is modulated by other dietary factors, such as calcium and magnesium, which can bind oxalate in the gut and reduce its absorption[22]. Studies have demonstrated that a diet low in oxalates and high in calcium can reduce urinary oxalate excretion and decrease the risk of stone formation[22]. These findings support the recommendation that individuals at risk of kidney stones should limit their intake of high-oxalate foods and ensure adequate calcium intake to minimize oxalate absorption[23].

Fluid intake is a cornerstone of kidney stone prevention, as it dilutes the concentration of stone-forming solutes in the urine[23]. Several studies have demonstrated that high fluid intake is associated with a lower risk of stone recurrence, particularly for calcium and uric acid stones[23]. While water is generally the recommended fluid of choice, other beverages, such as coffee and citrus juices, may also offer protective benefits[24]. Citrus juices, in particular, are rich in citrate, which can bind calcium in the urine and inhibit the formation of calcium-containing stones[24]. However, not all fluids have the same protective effect; sugary sodas and beverages containing high levels of fructose have been associated with an increased risk of kidney stones[24]. The differential effects of various fluids on stone risk highlight the importance of not only increasing overall fluid intake but also choosing fluids that provide additional protective benefits[25].

Citrate is a potent inhibitor of stone formation, and low urinary citrate levels (hypocitraturia) are a significant risk factor for the development of calcium stones[25]. Dietary strategies to increase urinary citrate excretion, such as consuming citrus fruits like lemons and oranges, have been shown to be effective in reducing stone risk[25]. Citrate binds to urinary calcium, reducing the availability of free calcium to form crystals[26]. Additionally, citrate can inhibit crystal growth and aggregation, further preventing stone formation[26]. Studies have demonstrated that patients with hypocitraturia who increase their intake of citrate-rich foods or supplements experience a significant reduction in stone recurrence[26]. However, the effectiveness of citrate supplementation may vary depending on individual metabolic factors, and further research is needed to determine optimal dietary sources and amounts[27].

Magnesium plays a protective role in kidney stone prevention by forming soluble complexes with oxalate, reducing the concentration of free oxalate available to bind with calcium[27]. This reduces the risk of calcium oxalate stone formation[27]. Clinical studies have suggested that higher dietary magnesium intake is associated with a lower risk of stone formation, particularly in populations with low baseline magnesium levels[28]. Although the evidence is still emerging, magnesium supplementation could be considered as part of a dietary strategy to prevent stone formation in high-risk individuals[28]. The role of magnesium in stone prevention may also be modulated by other factors, such as the presence of other dietary components that influence magnesium absorption and metabolism[28].

The formation of uric acid stones is closely linked to the metabolism of purines, which are found in high concentrations in certain foods, such as red meat, shellfish, and some types of alcohol[29]. Hyperuricosuria, characterized by elevated levels of uric acid in the urine, can promote the formation of uric acid stones, particularly in individuals with acidic urine[29]. Studies have shown that a diet low in purines can reduce urinary uric acid levels and decrease the risk of uric acid stone formation[29]. Furthermore, alkaline diets, which help to increase urinary pH, can enhance the solubility of uric acid and reduce the likelihood of crystal formation[30]. These findings underscore the importance of dietary management in patients with or at risk of uric acid stones, with a focus on reducing purine intake and promoting an alkaline urinary environment[30].

Carbohydrates, particularly refined carbohydrates and sugars, may influence kidney stone formation through their effects on insulin resistance, obesity, and urinary excretion patterns[30]. High intake of refined sugars, such as fructose, has been associated with increased urinary calcium, oxalate, and uric acid excretion, which are all risk factors for stone formation[31]. Moreover, diets high in simple sugars can exacerbate metabolic conditions like obesity and insulin resistance, which are themselves risk factors for kidney stones[31]. Conversely, diets rich in complex carbohydrates and dietary fiber have been shown to reduce the risk of nephrolithiasis, likely due to their beneficial effects on weight management, glycemic control, and gut health[31]. These findings suggest that a diet emphasizing complex carbohydrates and limiting refined sugars may be beneficial for stone prevention[32].

Dietary fiber, especially from fruits, vegetables, and whole grains, appears to have a protective effect against kidney stone formation[32]. Fiber can modulate the gut microbiota and reduce the intestinal absorption of oxalate, thereby decreasing urinary oxalate excretion[32]. High-fiber diets are also associated with lower body weight and improved metabolic profiles, which may further reduce the risk of stone formation[33]. Clinical studies have shown that individuals with higher dietary fiber intake have a lower incidence of kidney stones, particularly calcium oxalate stones[33]. These findings support the inclusion of high-fiber foods in dietary recommendations for individuals at risk of nephrolithiasis[33].

The impact of specific foods and beverages on kidney stone risk is complex and influenced by multiple factors, including individual metabolic responses, genetic predispositions, and overall dietary patterns[34]. For example, while coffee and tea have been associated with a reduced risk of stone formation due to their diuretic properties, high intake of these beverages can also lead to increased urinary excretion of calcium and oxalate in some individuals[34]. Similarly, alcohol consumption has shown both protective and harmful effects depending on the type of alcohol and the amount consumed[34]. These findings highlight the need for personalized dietary recommendations that take into account individual risk factors and metabolic responses[35].

Recent studies have also explored the role of dietary patterns, such as the DASH (Dietary Approaches to Stop Hypertension) diet, in kidney stone prevention[35]. The DASH diet, which emphasizes fruits, vegetables, whole grains, and low-fat dairy products while limiting sodium, red meat, and sweets, has been associated with a reduced risk of kidney stones[35]. This protective effect is thought to be due to the diet's high content of calcium, potassium, and magnesium, which promote a favorable urinary environment for preventing

stone formation[36]. However, the effectiveness of the DASH diet may vary depending on individual dietary adherence and baseline risk factors[36].

The role of supplements, such as vitamin C and vitamin D, in kidney stone formation is an area of ongoing debate[36]. While vitamin C has been associated with an increased risk of oxalate stones due to its conversion to oxalate in the body, some studies suggest that this risk is primarily relevant at high doses[37]. Vitamin D, which enhances calcium absorption, may increase the risk of calcium stone formation in some individuals, particularly those with hypercalciuria[37]. However, the overall impact of these supplements on stone risk is likely influenced by numerous factors, including individual metabolic responses, baseline nutrient status, and concomitant dietary patterns[37]. Clinicians should carefully consider these factors when recommending supplements to patients at risk of kidney stones[38]. For instance, while vitamin D supplementation might benefit patients with vitamin D deficiency or low bone density, its use should be balanced against the potential risk of increasing urinary calcium excretion in susceptible individuals[38].

In addition to specific nutrients and foods, overall dietary patterns play a crucial role in kidney stone prevention[38]. Diets high in fruits, vegetables, and whole grains and low in processed foods, animal proteins, and sodium appear to offer the most benefit in reducing stone risk[39]. This approach is consistent with broader dietary recommendations aimed at promoting general health and preventing chronic diseases, including hypertension, diabetes, and cardiovascular disease[39]. Moreover, encouraging patients to adopt a balanced, diverse diet may improve long-term adherence and reduce the need for restrictive or complex dietary regimens[39].

The role of hydration cannot be overstated in the context of kidney stone prevention[39]. Patients are generally advised to maintain a high fluid intake, sufficient to produce at least 2 to 2.5 liters of urine daily[40]. This level of hydration helps dilute the urine, reducing the concentration of stone-forming solutes such as calcium, oxalate, and uric acid[40]. While water is the preferred fluid, some studies suggest that certain beverages, like citrus juices, may offer additional benefits due to their citrate content[40]. Nonetheless, patients should avoid excessive consumption of sugary beverages, which have been linked to an increased risk of stone formation[41].

The interplay between various dietary factors underscores the complexity of developing effective dietary guidelines for kidney stone prevention[41]. For instance, while reducing sodium intake can lower urinary calcium excretion, it may also affect potassium and magnesium levels, which play protective roles against stone formation[41]. Similarly, increasing dietary calcium can help bind oxalate in the gut, reducing its urinary excretion, but may simultaneously raise concerns about the potential impact on cardiovascular health[42]. Therefore, personalized dietary counseling, which takes into account individual risk factors, comorbidities, and lifestyle preferences, is essential for optimizing prevention strategies[42].

Emerging research continues to explore novel dietary components and their potential effects on kidney stone formation[42]. For example, studies are investigating the role of phytochemicals, such as polyphenols found in tea, coffee, and certain fruits, which may influence stone risk through their antioxidant properties and effects on urinary pH[43]. Similarly, ongoing research aims to clarify the potential benefits of probiotics in modulating the gut microbiota to reduce

oxalate absorption and excretion[43]. As the understanding of these factors evolves, new opportunities may arise for developing more targeted and effective dietary interventions for kidney stone prevention[43].

CONCLUSION

The formation of kidney stones is a multifactorial process influenced by a complex interplay of dietary, genetic, and metabolic factors. Among these, diet emerges as a key modifiable risk factor, with substantial evidence supporting the role of various dietary components in both promoting and preventing stone formation. Adequate dietary calcium intake appears to play a protective role against calcium oxalate stones by reducing intestinal oxalate absorption, while excessive consumption of animal protein and sodium is consistently associated with increased stone risk due to their effects on urinary chemistry. Dietary oxalates, fluid intake, citrate, magnesium, and purines are also critical factors that can either exacerbate or mitigate the risk of stone formation, depending on their levels and the presence of other dietary and metabolic conditions.

Current research underscores the need for individualized dietary recommendations that consider a patient's unique metabolic profile, genetic predispositions, and comorbid conditions. While general dietary guidelines, such as adequate hydration, reduced sodium intake, and balanced consumption of proteins and carbohydrates, are beneficial, they must be tailored to each patient's specific risk factors to maximize their effectiveness in preventing stone recurrence.

The role of specific foods and beverages, such as citrus fruits, coffee, and tea, in stone prevention remains an area of active investigation, with evidence suggesting both potential benefits and risks depending on individual circumstances. The development of dietary strategies to prevent kidney stones should focus not only on limiting harmful components but also on promoting protective dietary factors such as citrate, magnesium, and dietary fiber.

Further research is necessary to elucidate the complex interactions between diet, metabolism, and stone formation, particularly in relation to less well-understood factors such as carbohydrates, fiber, and specific food components. Advancing our understanding of these relationships will enable the development of more precise and effective dietary guidelines tailored to individual risk profiles, ultimately reducing the global burden of nephrolithiasis. In clinical practice, dietary counseling should be an integral part of the management strategy for patients with a history of kidney stones, with a focus on personalized approaches that account for the multifaceted nature of this condition.

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