Dietary Management Software for Chronic Kidney Disease: Current Status and Open Issues

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Abstract. Chronic kidney disease (CKD) affects about 10% of the population worldwide. Millions of people die prematurely from CKD each year. Dietary restrictions can slow the progression of CKD and improve outcomes. In recent years, introduction of new technologies has enabled patients to better manage their own dietary intake and health. Several dietary management software tools are currently available providing personalized nutrition and diet management advice for CKD patients. In this paper, we provide an overview of these software tools and discuss some open issues and possible solutions, in hope of stimulating future research in consumer health informatics for CKD.

Keywords: Chronic kidney disease · dietary management software · consumer health informatics

1. Introduction

Chronic kidney disease (CKD) is characterized by a slow, progressive loss of kidney function over a period of time [1]. CKD is defined by abnormalities in kidney function or albuminuria (increased protein in the urine) persisting for at least three months. CKD encompasses a broad range of disease severity and significant heterogeneity in the risk of progression to end-stage renal disease, morbidity, and mortality [2]. Kidney function can be assessed using the estimated glomerular filtration rate (eGFR) computed based on serum creatinine. CKD has five stages, with stage 1 (eGFR $\geq$ 90 mL/min/1.73 m^2) being the mildest and stage 5 (eGFR < 15 mL/min/1.73 m^2) being the most severe [3]. Stage 5 CKD, or end-stage renal disease, requires renal replacement therapy such as dialysis or kidney transplantation to maintain life. Current evidence suggests that a low eGFR increases the risk for complications including anemia, cardiovascular disease, and mineral and bone disease [3].

According to Medicare, 10% of the Medicare population has recognized CKD accounting for more than 20% of Medicare's total costs in 2013 [4]. Most of these costs were spent on renal replacement therapy. Since CKD is not reversible, interventions can only slow its progression and help prevent complications.

Besides the treatment and control of hypertension, albuminuria, diabetes, and metabolic acidosis, dietary factors play an important role in the progression and outcomes of CKD. A growing body of evidence suggests that precision care provided by a dietitian can help CKD patients maintain their health, slow disease progression, and reduce complications [5]. Although it is expensive to see a dietitian, nutrition therapy provided by the dietitian can delay the need for dialysis or kidney transplant and be cost-effective for patients. However, most CKD patients have an insufficient understanding of their disease and dietary requirements [6]. Few patients receive dietary counseling before developing end-stage renal disease. According to the 2010 United States Renal Data System annual data report, only 3.9% of CKD patients saw a dietitian for more than one year before starting dialysis [7].

CKD patients have complex dietary needs and ideally should continually monitor their protein, sodium, phosphorus, potassium, and fluid intake. However, patients often have difficulty determining whether food items consumed in unfamiliar environments (e.g., restaurants) conform with their dietitians' recommendations. When shopping for fruits and vegetables in grocery stores, absence of food packaging and nutrition labels can make it difficult for patients to identify their purchases' nutritional content. Further, it is cumbersome for patients to manually track meals, snacks, and drinks consumed throughout the day, calculate their nutrient levels, and compare them to dietitians' recommendations. By helping CKD patients manage their diet, computer-based interventions can fill many of these gaps. In this paper, we discuss the current status and open issues of dietary management software for CKD, with the hope of stimulating future research in consumer health informatics for CKD.

The rest of this paper is organized as follows. Section 2 describes current dietary recommendations for CKD patients. Section 3 shows evidence on existing dietary management software's efficacy for improving diets in the general population. Section 4 gives an overview of existing dietary management software tools for CKD patients. Section 5 presents some open issues and possible solutions. We conclude in Section 6.

2. Current Dietary Recommendations for CKD Patients

Kidneys help maintain fluid and electrolyte balance in the body, as well as remove metabolic wastes from the body. A diet appropriate for healthy people can be problematic for CKD patients as their kidney function declines. In CKD patients, over-consumption of certain nutrients can cause hyperkalemia (high blood potassium), hyperphosphatemia (high blood phosphorus), high blood pressure, fluid volume overload, and accumulation of uremic toxins. On the other hand, sarcopenia (muscle loss associated with the aging process) and decreased nutrient intake could contribute to protein-energy wasting [8]. Thus, appropriate nutrition is an important component of CKD management for minimizing complications. A well-balanced diet aims to balance electrolytes, minerals, and fluids in the body and provides appropriate energy to maintain body functions.

Proteins are important building blocks of human body tissues. As kidney function declines, kidneys must work harder to remove waste products from protein metabolism. The Dietary Reference Intakes recommends a daily protein intake of 0.8 g/kg for healthy adults [9]. However, patients with stage 4 CKD are recommended to reduce their daily protein intake to 0.6 g/kg [10] because excessive protein intake can accelerate CKD.

Dietary intake of sodium, phosphorus, and potassium need to be closely monitored and continuously adjusted based on the CKD patient's kidney function, health status, and blood test results. Human body needs sodium, phosphorus, and potassium to work properly. However, as kidneys lose their function, these minerals' intake needs to be limited as kidneys can no longer remove excess minerals from the blood. Excessive sodium intake can elevate blood pressure and body fluid level leading to heart failure. High blood phosphorus level can increase risk of weakened bones and heart disease. Also, high blood potassium level can cause serious consequences such as sudden cardiac death due to arrhythmias.

Some CKD patients such as those on dialysis need to restrict their fluid intake, as their kidneys can no longer remove excess water from the blood. Excessive fluid retention in the circulatory system, body tissues, or cavities in the body cause high blood pressure, edema, and breathing difficulties.

3. Dietary Management Software for the General Population

Computer software holds great promise for delivering personalized nutrition interventions. Research has shown that personalized nutrition education tailored by computers based on survey results obtained from patients can be more effective at motivating patients to make dietary changes than providing general dietary guidelines [11]. Compared to general dietary guidelines, personalized dietary recommendations generated by computers contain less extraneous information and are cognitively processed more intensively, leading to more self-motivating cognitions.

At present, several dietary management software tools are available for weight control in the general population. By simulating face-to-face nutrition counseling and providing personalized nutrition interventions, these software tools help users monitor their eating behavior in a cost-effective way.

Carter *et al*. developed *My Meal Mate*, a mobile app tracking users' diet to help lose weight. The app allows users to set a weight loss goal and provides daily calorie allowance for achieving this goal. Users can use the app to log their food intake and physical activities and track their progress. Carter *et al*. compared the dietary data captured by the app with a duplicate 24-hour dietary recall, a gold standard for dietary assessment [12]. The results showed a moderate to strong correlation between the two measurements for calories and macronutrients (i.e., proteins, carbohydrates, and fats) [13]. In a related pilot study conducted on overweight adults, using the app for six months led to an average weight loss of 4.6 kg [14].

Software for dietitians providing hospital care can result in reduced error while saving time. Skouroliakou *et al*. developed *DIET*, a software tool that calculates personalized dietary requirements and produces daily menus for hospitalized patients [15]. Skouroliakou *et al*. evaluated *DIET* versus traditional face-to-face interventions given by dietitians for calculating dietary and nutrient intake and menu planning in 135 hospitalized patients.

Compared to manual methods, using *DIET* reduced calculation errors from 12% to 1.5%, which is clinically significant, and also decreased nutrition calculation and menu planning time by 50%. Hong *et al*. developed *NutriSonic*, a Web-based system for dietary counseling and menu management [16]. *NutriSonic* analyzes meals' nutritional content using computer-generated menus and compares it with Korean Recommended Dietary Allowance. The study showed that *NutriSonic* can not only accurately and quickly calculate users' nutritional needs, but also be used by both dietitians and the general population.

General dietary management software has great potential to improve health for the general population. However, it is not ideally suited for CKD patients for three reasons. First, unlike the general population, CKD patients need to follow a special diet limiting certain nutrients such as proteins, sodium, potassium, phosphorus, and fluids. General dietary management software does not address these special requirements. Second, general dietary management software lacks information of certain nutrient levels in its food database and hence cannot make recommendations based on such information. For instance, *MyFitnessPal*, one of the largest food databases, includes no information on phosphorus level. However, CKD patients need to carefully manage their intake of food with high amounts of phosphorus, such as dairy products, meat, nuts, and beans. Third, dietary recommendations need to be personalized for a CKD patient based on his/her CKD-related health status such as kidney function and comorbidities. General dietary management software does not capture enough health data for this purpose. In summary, general dietary management software does not meet CKD patients' special nutrition demands. CKD patients need customized dietary management software designed and optimized for their need to manage dietary restrictions.

4. An Overview of Existing Dietary Management Software for CKD

Over the past few years, several dietary management software tools specifically designed for CKD patients have been released, including *MyFoodCoach* by the National Kidney Foundation, *Diet Helper* by the company Davita, and *KidneyAPPetite* by the company Sanofi. These software tools have similar functions: creating personalized dietary recommendations and monitoring the user's dietary/nutritional intake. Each of these software tools has one or more of the following components: a health data input interface, a medical knowledge base and inference engine, a diet tracking system, and a diet recommender system.

4.1 Health data input interface

When a user first uses a dietary management software tool for CKD, he/she is required to enter some basic health information about himself/herself. The software tool saves these data in its database and produces personalized dietary recommendations based on these data. Typically requested data elements include demographics (e.g., age, gender, and race), anthropometric measurements (e.g., weight, height, and body mass index), kidney function (e.g., eGFR, whether the patient is on dialysis, and whether the patient has had kidney transplantation), comorbidities and complications (e.g., diabetes and hypertension), and lab test results (e.g., serum potassium levels, serum phosphorus levels, and serum calcium levels).

4.2 Medical knowledge base and inference engine

A dietary management software tool for CKD usually has a medical knowledge base and an inference engine. The inference engine uses both the medical knowledge stored in the knowledge base and the user's health information stored in the database to produce personalized dietary recommendations. Outputs are in the form of daily allowances for calories, protein, sodium, potassium, phosphorus, water, and other nutrients important for CKD patients.

Medical knowledge is usually stored in the knowledge base in the form of rules. For example, patients with stage 4 CKD ($15 \leq$ eGFR < 30 mL/min/1.73 m^2) are recommended to reduce their daily protein intake to less than 0.6 g/kg. A rule for this can be: if the patient's eGFR is < 30 AND the patient's eGFR is ≥ 15, then the patient's daily allowance for protein $= 0.6 \times$ the patient's weight (kg). As another example, fluid for CKD patients on dialysis is restricted to 1-1.5 L/day. A rule for this can be: if the patient is on dialysis, then the patient's daily allowance for water is 1.5 L.

Although some CKD patients prefer consulting a dietitian or physician for a diet prescription rather than completely relying on computer software, they still need a tool to help them manage their nutritional intake on a daily basis. Some dietary management software tools for CKD give users an option of manually inputting their dietitians' recommendations to override the nutrition allowances given by the software tool.

4.3 Diet tracking system

Many dietary management software tools for CKD have a diet tracking system and a food database. The diet tracking system allows the user to enter keywords into a search box to retrieve a list of food items having these keywords. The user selects an item from the list, enters the portion size, and adds it into the food diary. Based on the items in the food diary, the diet tracking system calculates the diet's nutritional components and compares them to the allowances produced by the software tool, in a way similar to what dietitians do when providing nutrition therapy.

On their food information page, some dietary management software tools for CKD code certain nutrients in different colors to indicate whether these nutrients exceed the user's daily allowances. For example, green means that the user's intake for a specific nutrient is within the user's allowance. Red means that the user's intake for a specific nutrient is near or over the user's allowance for that day. Some dietary management software tools for CKD provide a kidney-friendly score for each food item based on its overall nutrition composition. A high score means that the food item is safe for kidneys. A low score means that the food item should be avoided or consumed in small quantity. For example, a food item high in phosphorus can be given a low score, warning users that the food item is not good for their kidneys. This helps users adjust their eating behaviors.

4.4 Diet recommender system

Some dietary management software tools for CKD translate nutrient allowances into meal choices by generating food combinations as close to these allowances as possible in addition to displaying the values of these allowances. For example, a CKD patient can find it difficult to adhere to a dietary phosphorus limit of <1200 mg/day. While the diet tracking system can indicate that certain food items are high in phosphorus, the user may not know which food items are available as alternatives to help control his phosphorus intake. In this case, the diet recommender system can generate a complete, kidney-friendly meal plan that considers the user's dietary phosphorus limit to help him reach his nutritional goal.

5. Open Issues and Potential Solutions

Dietary management software offers the promise of dietary self-management for CKD patients. However, existing dietary management software for CKD has several limitations. In this section, we list some open issues concerning dietary management software for CKD and propose some possible solutions.

5.1 Integration with personal health records

Existing dietary management software for CKD has several shortcomings in its health data input interface. First, many existing software tools ask users to enter their health data manually. This requires labor-intensive data input and can discourage users from using the software. Second, users often lack enough medical knowledge to fully understand their health conditions and the medical terms used on the input interface. As a result, the quality of health data entered by users can be questionable. Third, many health data elements are dynamic and change over time. The user's weight can fluctuate. The user's kidney function can decline as his/her CKD progresses. Lab test results typically change on a daily basis. Thus, the database storing the user's health data needs to be updated regularly.

To overcome these shortcomings and obtain more up-to-date health data of users, the dietary management software for CKD can be integrated with personal health records. This improves the dietary management software's usability, as 1) users no longer need to input their health data and 2) this ensures data accuracy and that the most up-to-date health data are used for generating dietary recommendations. Synchronizing the dietary management software with personal health records means connecting with healthcare providers with a two-way flow of information. The dietary management software is updated with users' current clinical data. The healthcare providers' information systems can be updated with information on users' nutritional status, dietary habits, and general well-being. To perform this integration, we need to develop and implement appropriate data and messaging standards for nutrition and dietary domains to support interoperability with different personal health records. With appropriate approvals, a data store from such an integration can be repurposed for further biomedical research on CKD and nutrition.

5.2 Diet tracking system

Many dietary management software tools for CKD include a search tool for locating desired food items from a nutrition database, such as the one developed by the United States

Department of Agriculture [17]. However, many of these software tools received poor ratings on the Apple and Android app stores, as users find that the diet tracking system has limited options for inputting dietary data and is cumbersome to use. Users are required to record their dietary intake each time they eat something. This is time-consuming and labor-intensive, causing users to lose patience. Moreover, the food search and data entry processes require experience with computers and can be challenging for the elderly or patients with low education levels. Since CKD is more prevalent in the elderly [18], the diet tracking system need to be senior-friendly and provide an easier and faster approach for inputting dietary data.

To make the dietary data input system more user-friendly, several new features can be added to dietary management software for CKD. Example features include a built-in barcode scanner, photo reminder, expanded database with new food products and restaurant food, allowing users to create their own recipes, saving users' favorite food combinations, and providing an option to add food items often consumed together, such as bread and butter. Some users consider a category look-up method easier to use than the traditional search method. Besides the search function, users can be given an option to click on multi-layered food category menus to locate common food items. For example, a user can click the fruit category and then the apple category to locate gala apple in the food database.

5.3 Food sources

Nutrition information is not limited to calories and nutrient compositions. Sometimes, the food source matters. For example, proteins from plant sources are more protective of kidneys than proteins from animal sources [19]. As another example, food additives (e.g., sodium phosphate) are widely used in preparing processed foods including cheese, meat, beverages, and baked products. Phosphorus from food additives is absorbed almost completely by the human digestive tract. In comparison, only 60% of phosphorus from natural sources is absorbed [20]. Thus, phosphorus from food additives is more problematic for CKD patients than phosphorus from natural sources. Most dietary management software tools for CKD focus on nutrient compositions and overlook food sources essential for a healthy diet. Ideally, when producing the kidney-friendly score for a specific food item, the dietary management software needs to consider the food source in addition to calculating the nutrient composition. In this way, evidence-based nutrition knowledge can be better used.

5.4 Nutrition facts labels

The Food and Drug Administration requires a nutrition facts label to be included on most food packages. The nutrition facts label must detail the levels of several nutrients such as cholesterol, sodium, sugar, and protein. However, no law requires phosphorus or potassium to be listed on the nutrition facts label. Thus, phosphorus and potassium levels are usually omitted from the food databases in diet tracking systems. This causes dietary management software to often underestimate a user's dietary intake of phosphorus and potassium, which needs to be closely monitored for CKD patients.

Given limited resources, it would be difficult to analyze the phosphorus and potassium levels of each food item and to update the food database manually. Nevertheless, there are

several other ways to keep track of phosphorus and potassium. First, certain ingredients of processed food can be included in the food database. As mentioned earlier, CKD patients need to avoid food containing phosphorus additives. Food additives, including those containing phosphorus, are required by law to be listed on food ingredient labels. The diet tracking system can include phosphorus additives in the food database and warn users of their presence. Second, the diet tracking system can automatically issue a warning for whole food naturally high in phosphorus or potassium, if their values are missing from the nutrition facts label. For example, banana, yogurt, and potatoes are high potassium food (i.e., more than 200 mg of potassium per serving). If their potassium values are missing from the nutrition facts label, the diet tracking system can automatically identify them and give the user a warning.

5.5 Medications and dietary supplements

Certain medications and dietary supplements can affect overall nutrition levels, but are ignored by existing dietary management software tools for CKD. For example, some medications and dietary supplements contain high levels of phosphorus. As another example, phosphorus binders are medications that reduce the gastrointestinal tract's absorption rate of phosphates and greatly influence a patient's phosphorus level. Dietary management software for CKD needs to consider these medications and dietary supplements when producing dietary recommendations.

5.6 Nutrition education

Most dietary management software tools for CKD assume that users have at least some knowledge about CKD and nutrition, and provide no additional information beyond a nutritional goal. However, many users, especially those with newly diagnosed CKD, are unfamiliar with CKD. Even if they have nutritional goals, they do not know how to change their diets to achieve these goals. By providing concrete examples of what they can eat, a dietary management software tool can be more useful for them. For example, the software tool can suggest a user to limit his/her protein intake to less than 80 grams per day. However, with no background in nutrition, the user has no idea what 80 grams of protein look like. In this case, the software tool can provide some concrete examples such as "You will consume 80 grams of protein if you eat 2 eggs, 4 ounces of lean fish, 4 ounces of lean beef, 1/2 cup of tofu, and 1 cup of milk."

CKD self-management education can improve clinical outcomes [21]. Nutrition education tends to be more effective when actionable strategies are made explicit to help people achieve their targeted behaviors [22]. The dietary management software for CKD can educate patients about why their lab test results matter, common food sources, vital nutrients, and how to estimate portion sizes and read nutrition facts labels. For example, patients with stage 4 CKD and high serum potassium levels would benefit from education about common foods high in potassium that need to be avoided. A Web-based dietary management software tool can display education materials in a text box when the user positions the cursor on a relevant term.

Ideally, a dietary management software tool for CKD should personalize patient education based on the patient's specific needs. For example, some CKD patients need to follow a diet high in protein and low in phosphorus. Most high protein foods (e.g., meat and eggs) are also high in phosphorus. This makes it difficult for patients to adhere to appropriate diet. In this case, the dietary management software can give users tips on increasing their protein intake without over-consuming phosphorus. Examples of such tips include avoiding organ and processed meat, choosing non-enriched rice milk instead of regular milk, and consuming vegetable protein rather than animal protein.

5.7 Sharing meal plans

Some CKD patients need to follow a highly restricted diet, making it difficult for them to find foods they enjoy eating. For example, consider stage-4 CKD patients who also have hypertension and high serum potassium and phosphorus levels. To reduce damage to their kidneys and avoid various complications, these patients need to follow a diet low in proteins, phosphorus, sodium, and potassium. Their dietitians may have given them a long list of food items that they should avoid. This list informs them what they cannot eat, but not what they can eat. With all the restrictions, these patients can have difficulty finding foods they enjoy. Hence, they often completely abandon their diets.

To address this issue, the diet recommender system can automatically generate food combinations meeting the patient's nutritional goals. For example, the dietary management software tool can check each recipe in its database against all dietary restrictions. However, having too many restrictions can prevent the software tool from finding a solution acceptable to the user. To solve this problem, the software tool can allow patients to share their food diary or meal plans with those having similar dietary restrictions. By communicating with each other, patients can find new cookbooks and recipes giving more dietary options.

5.8 Evaluation of dietary management software for CKD

To our best knowledge, no research has been published evaluating dietary management software for CKD. Existing dietary management software tools for CKD vary in their development process, theoretical framework, and knowledge base accuracy. To provide high-quality health information, qualified healthcare professionals including nephrologists, dietitians, and nutritionists should be involved in compiling and reviewing knowledge stored in the knowledge base. Also, the dietary management software tool's efficacy should be evaluated through controlled clinical trials with CKD patients.

5.9 Senior-friendly user interface

A major issue in using health information technology for dietary management among CKD patients is the digital divide. The digital divide refers to the economic or social gap between those who have access to modern technologies and those who do not or are unaware of them. CKD is correlated with old age and low socioeconomic status [18]. When developing a dietary management software tool for CKD, the developer needs to consider the fact that many users will have little experience with computers. The software tool's graphical user

interface needs to be senior-friendly and intuitive. Also, mobile apps for CKD patients need to include an option for larger fonts, adjustable contrast, and an interface with simple prompts such as “yes” and “no.”

6. Conclusion

Computer-based interventions can be cost-effective if they can reach sufficiently large populations and confer discernable health benefits [23]. Using medical knowledge to automatically provide users with personalized nutrition care, dietary management software holds great promise for improving health and reducing costs for CKD patients. This paper provides an overview of existing dietary management software for CKD and identifies several open issues. In addition, we propose some possible solutions to these open issues in the hope of benefiting future research.

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