Validation and Calibration of Dietary Intake in Chronic Kidney Disease: An Ontological Approach

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Abstract. This study develops a pilot knowledge-based system (KBS) for addressing validation and calibration of dietary intake in chronic kidney disease (CKD). The system is constructed by using Web Ontology Language (OWL) and Semantic Web Rule Language (SWRL) to demonstrate how a KBS approach can achieve sound problem solving modeling and effective knowledge inference. In terms of experimental evaluation, data from 36 case patients are used for testing. The evaluation results show that, excluding the interference factors and certain non-medical reasons, the system has achieved the research goal of CKD dietary consultation. For future studies, the problem solving scope can be expanded to implement a more comprehensive dietary consultation system.

Keywords: Knowledge-based system · Chronic kidney disease · Ontology · Semantic rules

1 Introduction

The care for patients with chronic kidney disease (CKD) is closely related to the patient‘s daily diet management. The type, quantity, and nutrient content of the patient’s food intake need to be strictly controlled [2]. However, dietary management involves complicated interactions among various factors. This complexity not only reduces the quality of dietary management, but can also consume medical resources if the patients are to have constant dietary consultation. As a result, CKD patients often do not receive enough professional guidance in dietary control, which can lead to disease progression, low life quality, and even malnutrition. Traditional CKD dietary consultation requires dietitians to perform a series of steps, such as collecting patient physical profile and biomedical examination data as baseline information; calculating patient’s clinical CKD stage, nutrient baselines, and suggested servings from each food group; comparing the patient’s actual diet to the suggested servings for dietary adjustment. These consultation steps involve intensive knowledge from different sources. The dietitian then considers the complicated logical relationships between the patient’s conditions and the various knowledge-intensive sources in order to provide dietary guidance.

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This study employs an ontological engineering approach with focus on the construction of knowledge models and knowledge reasoning with logical rules. Ontology has been widely adopted in various fields of study to model and construct taxonomies for domains of interest [7]. Over time, ontology is seen as a synonym of "conceptual model" [8]. In information science research, especially in the areas of artificial intelligence, ontologies are created with properties and relationships to enable knowledge inference. In knowledge-based systems (KBS), concepts are used not just as terms, but also as computable objects with logical definitions, which enable knowledge for inductive and deductive reasoning [9]. The W3C recommended the OWL (Web Ontology Language) as a formal specification for ontology representation [10]. In terms of development tools, Protégé is a prevalent platform created by the Stanford Center for Biomedical Informatics Research for OWL-based ontology development, OWL-based problem solving modeling, and KBS execution [11]. In addition to conceptual representation of ontology, SWRL (Semantic Web Rule Language) can be used to develop semantic rules in the instance layer of the ontology to enable reasoning using rule inference engines [12, 13].

This study is collaboration between dietitians and knowledge engineers. The first task in knowledge engineering is to decompose and reassemble professional knowledge content in order to analyze the concepts and data required for modeling. Through this process, the nature of the problem, the scope of the knowledge domain, and the logical relationship between concepts are clarified. Then, the task is followed by the construction of a conceptual taxonomy of the domain and by the definition of conceptual properties for inference. Last, semantic rules are developed to create an "instance layer" for knowledge inference. The major knowledge-based elements designed in this process include: (1) using generalized knowledge sources to construct a domain ontology that consists of common constructs, concepts, and instances with super-subordinates and inheritance created using the "*is-a*" hierarchical relationships; (2) to enable problem-solving, the development of an objective-oriented task ontology with a "*has-a*" expression to describe the logical relationship of subsumption and composition aggregation among concepts; and (3) definition of the problem-solving steps in the instance layer with semantic rules to infer implicit knowledge based on known factual knowledge.

2 Problem Analysis

Chronic kidney disease is caused by the biomedical abnormalities in the kidneys [3]. The function of the kidneys is to metabolize nitrogenous waste (such as uric acid) in order to maintain the body's balance of minerals (sodium, potassium, phosphorus, etc.) and to assist in blood pressure control and blood cell production [4]. The generally accepted operational definition of CKD is kidney damage and the kidneys' inability to filter blood as measured by Glomerular Filtration Rate (GFR) [1]. The clinical CKD stages are then defined by plotting the estimated GFR (eGFR) [5, 6] as shown in Table 1. In the calculation of eGFR, the Modification of Diet in Renal Disease (MDRD) equation is widely adopted by organizations such as the United States NKF.

Table 1. Clinical stages of chronic kidney disease.

Stage	Description	GFR
1	Kidney damage with normal or increased GFR	≥90
2	Kidney damage with mild decrease in GFR	60 ~ 89
3	Moderate decrease in GFR	30 ~ 59
4	Severe decrease in GFR	15 ~ 29
5	Kidney failure	<15

Common CKD knowledge sources used in clinical dietary consultation include clinical stage definition, stage estimation equation, and nutrient restriction. Nutrient knowledge, as a concept, includes at least food groups and the nutrient composition of each food item. The food group includes the categorization of food items and their recommended daily servings in different conditions. Case patient data work as a trigger to interact with the knowledge sources to create dietary suggestions. To implement the problem scenarios analysis, dietitians and knowledge engineers have participated as consultants for verifying knowledge sources and problem scenarios from the beginning. They formalized the problem solving into two groups of non-logical axioms as follows:

1. Examining suggested food group servings against a patient's food combination: The first step is calculating suggested food group servings by individual conditions. Equation (1) is the general equation for the suggested servings $FS_{(p, i, s)}$ in food groups by case (p), calorie level (i), and CKD stage (s) to find the suggested corresponding servings in each food group. The second step is calculating the case patient's food combination intake in each food group. Equation (2) is by case (p) $FSI_{(p)}$ to find the intake corresponding servings in each food group. The last step is calculating the difference between Eqs. (1) and (2) (i.e. of $FSI_{(p)}$ - $FS_{(p, i, s)}$). Equation (3) examines the differences in food group servings between the case patient's food combination and the suggested values. For example, $f_{(i,\ grains,\ servings)}$ denotes the number of grain servings in food item i.

$$FS_{(p,\ i,\ stage)} = \left(S_{grains}, S_{meat}, S_{milk}, S_{vegetable}, S_{fruit}, S_{oil\ \&nuts}\right) \tag{1}$$

$$\left(\begin{array}{l} \sum_{i=1}^{n}\left(f_{i,grains,servings}\right), \sum_{i=1}^{n}\left(f_{i,meat,servings}\right), \sum_{i=1}^{n} f_{i,vegetable,servings}), \sum_{i=1}^{n}\left(f_{i,Potassium} * s_i\right), \\ \sum_{i=1}^{n}\left(f_{i,fruit,servings}\right), \sum_{i=1}^{n}\left(f_{i,oil\&nuts,servings}\right) \end{array}\right) \tag{2}$$

$$Case_{(p,food\_group)} = \begin{pmatrix} (\sum_{i=1}^{n}(f_{i,grains,servings}) - S_{grains}), (\sum_{i=1}^{n}(f_{i,meat,servings}) - S_{meat}), \\ (\sum_{i=1}^{n}(f_{i,vetetable,servings}) - S_{vegetable}), (\sum_{i=1}^{n} f_{i,milk,servings}) - S_{milk}), \\ (\sum_{i=1}^{n}(f_{i,fruit,servings}) - S_{fruit}), (\sum_{i=1}^{n}(f_{i,oil\&nuts,servings}) - S_{oil\&nuts}) \end{pmatrix} \quad (3)$$

2. Examining suggested key nutrient intakes against a patient's food combination: The first step is calculating suggested key nutrient restrictions $NR_{(p)}$ by individual conditions. CKD patients require sufficient calories, but have to restrict the intake of certain key nutrients: proteins, phosphorus, potassium, and sodium. Equation (4) is a general equation for calculating the patient's suggested key nutrient intakes. The second step is calculating the case patient's food combination intake in each key nutrient. Equation (5) is by case (p) $NI_{(p)}$ to find the intake corresponding amounts in each key nutrient. The last step is calculating the difference between Eqs. (5) and (4) (i.e. of $NI_{(p)}$ - $NR_{(p)}$). Equation (6) examines the differences of key nutrient intake between the patient's food combination and the suggested key nutrient intakes. For example, $f_{(i,Calories)}$ denotes the calorie intake per serving of food item i. The value is then multiplied by the number of intake servings (s_i) to obtain the total calories, and then subtracted by the suggested $N_{Calories}$ to calculate the difference.

$$NR_p = (N'_{stage,\,Calorie} \times w_p, N_{Calorie}, N_{Protein}, N_{Phosphorus}, N_{Potassium}, N_{Sodium}) \quad (4)$$

$$NI_{(p)} = \begin{pmatrix} \sum_{i=1}^{n}(f_{i,Calorie} * s_i), \sum_{i=1}^{n}(f_{i,Protein} * s_i), \sum_{i=1}^{n}(f_{i,Phosphorus} * s_i), \\ \sum_{i=1}^{n}(f_{i,Potassium} * s_i), \sum_{i=1}^{n}(f_{i,Sodium} * s_i) \end{pmatrix} \quad (5)$$

$$Case_{(p,nutrients)} = \begin{pmatrix} (\sum_{i=1}^{n}(f_{i,Calorie} * s_i) - N_{Calorie}), (\sum_{i=1}^{n}(f_{i,Protein} * s_i) - N_{Proein}), \\ \sum_{i=1}^{n}(f_{i,Phosphorus} * s_i) - N_{Phosphorus}), \sum_{i=1}^{n}(f_{i,Potassium} * s_i) - N_{Potassium}), \\ (\sum_{i=1}^{n}(f_{i,Sodium} * s_i) - N_{Sodium}) \end{pmatrix} \quad (6)$$

3 OWL-Based KBS

This study uses ontological engineering for knowledge modeling. An ontological knowledge model is an abstract structure of concepts, in which each concept has properties and relationships to represent the knowledge connotations. Knowledge models, when extensively analyzed and defined, are robust and extensive. New factual knowledge can be stored into existing knowledge structures, and the existing logical relationships are inherited for reasoning with no data processing required. Therefore, knowledge systems are suitable for solving knowledge-intensive problems that require logical inference. Based on the guidelines proposed by researchers [8, 14–16], we design three components in the KBS including construction of domain ontology, task ontology and semantic rules.

3.1 Construction of Domain Ontology

Domain ontology consists of a general conceptual structure and instances and uses "*is-a*" relation to establish parent-child hierarchy subordination relations with the terminal concepts being further elaborated by giving instances. Therefore, domain ontology is a typological structure which does not aim for specific problems but rather base on common recognition of the domain and thus can work as definition references to other ontologies and as well as communication terminologies for sharing and reusability. As illustrated in Fig. 1, the knowledge model is edited using the Protégé user interface. The main class hierarchy is presented in the left frame. The class hierarchy is related using super- and sub-class relationships. More restrictions or definitions of classes can be formally defined using description logics expressions. Class members or instances are shown in the middle frame. An instance inherits all properties and restrictions of a class. For example, this frame lists several individual names of the "Nutrient Limitation" concept. Meanwhile, the right frame provides the individual editor for editing details. For example, the instance "restriction_stage2" contains properties such as "*has_stage*" and "*has_Protein_Limitation*".

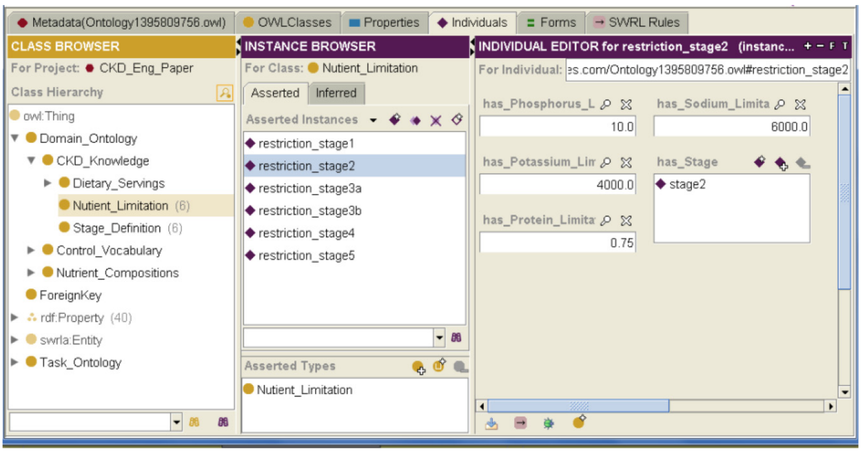

Fig. 1. Develop domain ontology construct and instances with Protégé editor.

This study constructs common terminologies into "Control Vocabulary." From the background and the known factual information of CKD and foods are constructed as initial concepts including "CKD_Knowledge" and "Food_Ingredients". In order to transfer knowledge model into format for information systems, the Protégé ontology editor is used to establish the ontological knowledge framework including classes, properties, and instances.

1. Control Vocabulary: Including 3 sub-concepts such as "Activity Level", "Calorie_Level", and "Food_Groups". Under each concept, the common terminologies are listed to provide reference, indexing, exchange and communication to other concepts and instances.
2. CKD Knowledge: Established 3 sub-concepts by the definition of CKD clinical stages, the key nutrient restrictions in each stage, and the suggested dietary serving in each food group.
3. Food Ingredients: The factual contents of food nutrient composition are adopted from a national government open data platform. However, the due to the difference in data model and the need to integrate with existing models, this study developed a pre-processing procedure for the transformation including data cleaning, relationship mapping. Some protégé plugins are utilized to assist transformation procedure such as DataMaster.

3.2 Construction of Task Ontology

A task ontology aims at solving practical problems. In addition to developing the concepts, the constituent properties of the concepts need to be planned to describe the knowledge framework for describing the problem solving process. To mark the detailed definition of the OWL-based properties, the property content values of known facts or unknown knowledge need to be firstly confirmed to separate asserted property from inferred property. Next, the domain and range of the properties need to be denoted. If a range uses basic data type, it is a data property; whereas if a range uses instances, it is an object property.

The task of this study is to solve the problem of CKD patient diet care, the background knowledge from the aforementioned domain is used to design the conceptual structure of problem solving. Five concepts designed under task ontology are as follows:

1. Personal Profile: including inference properties such as CKD clinical stages, eGFR, calorie requirement.
2. Personal Nutrient Count: including inference properties to obtain suggested amounts of protein, phosphorus, potassium, and sodium.
3. Personal Dietary: including inference properties to obtain the suggested balanced diet servings in food groups.
4. Diet Examination: including inference properties to obtain key nutrients examination and food group examination.
5. Food Selection: including properties for annotating case patient's food combinations.

3.3 Semantic Rules Development

A knowledge base represents factual knowledge in the form of instance, therefore semantic problem solving can be performed by running semantic rules in the instance layer of an ontology to infer implicit knowledge based on known factual knowledge. The ontological inference in the instance layer is performed by semantic rule language (e.g., Semantic Web Rule Language, SWRL) for rule development (Horrocks, Patelschneider, Bechhofer, & Tsarkov, 2005). Protégé platform provides such function through the SWRL Rules tab. In short, SWRL works with OWL-based knowledge bases and is able to perform the inference of implicit knowledge through a rule inference engine (Corsar & Sleeman, 2006).

The analysis of semantic rules starts with the concept in which the property belongs, and then chains the concept to other facts in a step-by-step manner until the objective is achieved. Each step is expressed as an atom and the rule is expressed in the form of "($atom_1$^… ^ $atom_n$) → *Consequence*" to express the cause-effect relationship. The rules below are implemented equations as designed in Eqs. (1) ~ (3). The equations can be expressed as an SWRL-based rule as follows:

1. Six rules are respectively developed to infer suggested food group servings as designed in Eq. (1). For example, the rule below infers grains servings. Rules for other suggested food group servings can be created in the same manner.

```
Personal_Dietary (?x) ∧ has_Case_Name (?x, ?p) ∧
has_Stage (?p, ?s) ∧ has_Calorie_Level (?p, ?k) ∧
Dietary_Servings (?y) ∧ has_Stage (?y, ?s) ∧
has_Calorie_Level (?y, ?k) ∧ has_Grain_Servings (?y,
?ans) → has_Grain_Servings (?x, ?ans)
```

2. The rule below is developed to infer the actual food group servings as designed in Eq. (2). The Semantic Query-Enhanced Web Rule Language (SQWRL) is used to help the arithmetic operations of rules.

```
Personal_Dietary (?x) ∧ has_Case_Name (?x, ?x1) ∧
has_Name (?x1, ?x2) ∧ has_Intake_Food (?x, ?y) ∧
Food_Selection (?y) ∧ has_Food (?y, ?g) ∧
has_Food_Group (?y, ?g1) ∧ has_Servings (?y, ?n) °
sqwrl:makeBag (?s, ?n) ∧ sqwrl:groupBy (?s, ?x, ?g) °
sqwrl:sum (?ans, ?s) → sqwrl:select (?x2, ?g1, ?ans) ∧
sqwrl:columnNames ("CSV_Name", "CSV_Food_Group",
"CSV_Servings")
```

3. The rules below examine the differences in food group servings between the case patient's diet and the suggested values as designed in Eq. (3). The rule below infers grains servings. Rules for inferring other food group serving differences can be created in the same manner.

```
Diet_Examination (?x) ∧ has_Case_Name (?x, ?x1) ∧
has_Name (?x1, ?x2) ∧ Personal_Dietary (?y) ∧
has_Case_Name (?y, ?x1) ∧ has_Grain_Servings (?y, ?y1)
∧ Servings (?z) ∧ CSV_NAME (?z, ?x2) ∧
CSV_FOOD_GROUP(?z, "Grain") ∧ CSV_SERVINGS(?z, ?z1) ∧
swrlb:subtract (?ans, ?z1, ?y1) ∧ swrlb:stringConcat
(?ans1, "Inspect Grain   standard value: ", ?y1, "
case: ", ?z1, "  overbalance : ", ?ans, " portion") →
has_Examine-on_servings (?x, ?ans1)
```

4 Experiment

The design of the data flow follows dietary consultation activities. Patients input their basic data and daily actual food combination, and the system answers with inference and estimation from the existing knowledge, similar to dietitians. The system uses Apache Tomcat as the application server to provide a Web platform to connect to the inference services provided by the rules engine (Java Expert System Shell, JESS) available from the Protégé platform. Finally, the user interfaces utilize Java Server Page (JSP) to create Web applications.

4.1 Case Study

This study has designed a patient data collection interface. For example, a case patient may input personal data as: male, height 176, age 65, weight 75 kg, Cr value 1.2, and light activity level. In the Food List block, a user needs to input the daily actual food combination. The food items and servings are added into the My Plate box.

After completing the personal data and daily food combination, the back-end rules engine infers the CKD stage, calorie baseline, suggested food group servings, and suggested key nutrient intakes. This study has devised an interface that presents the four categories that summarize the dietary consultation as described in Eqs. (1) ~ (6) and corresponding rules. Figure 2 demonstrates the results of the rule computation and inference:

1. Calculating suggested food group servings by individual conditions: in the upper left block of Fig. 2.
2. Calculating suggested key nutrient intake by individual conditions: in the upper right block of Fig. 2, the five key nutrient limitations are obtained from executing relevant rules.
3. Examining suggested food group servings against daily diet combination: in the lower left block of Fig. 2, the results are obtained from examining the differences between cases in the food group. For example, the number of servings matches the suggestion in Protein-food, Vegetables, Daily, and Oils. Half serving short in Grains and Fruits.
4. Examining key nutrient intake against daily diet combination: in the lower right block of Fig. 2, the results are obtained from examining the differences in key nutrient

ingestion between cases. For example, in “Protein Restriction”, the maximum value is 56.25 g, but the actual intake over 3.45 g. Other examinations on calories, phosphorus, and sodium also show over intake.

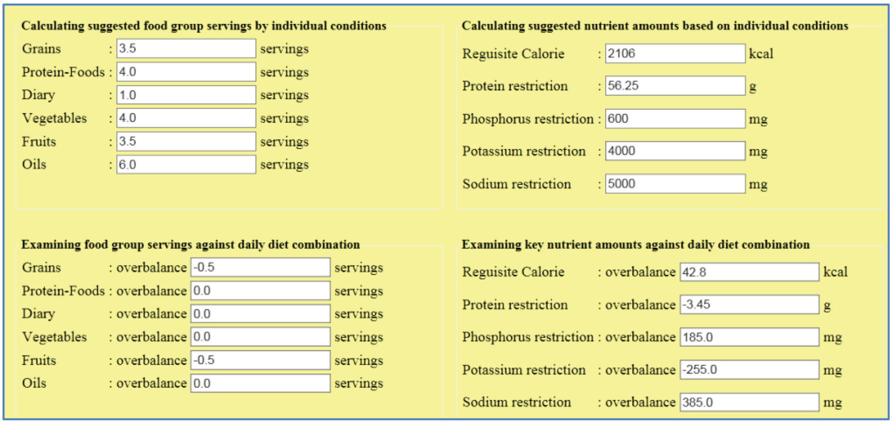

Fig. 2. Screen snapshot of inference.

4.2 Evaluation

For evaluation purpose, results of the 36 case patients’ experiments were sent to the two hospital dietitians for examination and verification of accuracy. The items verified included the evaluation of the case clinical stages, the suggested food servings, the key nutrient restrictions, and the suggested diet combinations. The accuracy is represented as the ratio of the number of identical results (between system outcome and expert examination) over the total number of case results. During the evaluation process, a number of inconsistent results were found between the system outcome and the manual estimation. This finding is similar to a previous study where the system estimation is faster and more accurate than manual estimation [17]. After correcting the manual calculation errors, both sets of evaluation are identical. As the knowledge system-inferred diet suggestions agree with those of the dietitians’, it is evidenced that the knowledge system can provide CKD patients with correct dietary consultation.

On the other hand, we compared the inference results from the KBS with the dietitian suggested food combinations. We found noticeable differences in all columns except the CKD Clinical stage. After a joint review of the researchers, it was found that some patients had comorbidity and complication (CC) and few patients had non-medical reasons. These interference factors had caused the differences. However, for the cases without the interference factors, the inference results of the KBS and the dietitians were identical.

5 Conclusion

This study aims to solve the problem of dietary consultation for chronic kidney disease patients. CKD patients are often challenged with dietary management because of the multitude of factors involved: unable to receive frequent and detailed dietary consultation, variation in illness and physical conditions, and lack of nutrient knowledge in daily food intake. This study has contributed to dietary management in the following aspects: (1) building an ontological dietary consultation system with the extensibility to include other chronic diseases in the future; (2) the integration of multiple open knowledge sources into a knowledge model; and (3) the design of task ontology with semantic rules for problem solving. We use CKD as an example domain and develop an ontological knowledge model and a knowledge base system for CKD dietary consultation.

This study uses case information from 36 CKD patients for the case experiment. The resulting dietary suggestions from the experiment are identical to those from the dietitians. This shows that the research objective was accomplished and that this knowledge system is capable of offering good dietary guidance to CKD patients. In the future, with the strengths of open knowledge integration and knowledge base extensibility, this dietary consultation system can be expanded and refined for comorbidity and complication to create a more comprehensive dietary consultation system for chronic disease patients. For future clinical deployment, given the experience from the current research, we suggest to firstly expand the knowledge model to include the closely related knowledge sources of CKD comorbidity and complication, such as specific diabetes mellitus and cardiovascular diseases. Such expansion will enable the KBS to take into account major interaction and interference factors and thus enhance its inference capacity for clinical usage.

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