

An Ontology-Based Clinical Decision Support System for the Management of Patients with Multiple Chronic Disorders

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Abstract

Decision support systems, as means of disseminating clinical practice guidelines, are powerful software that may lead to an improvement of medical practices. However, they are not always efficient and may suffer from limitations among which are lack of flexibility and weaknesses in the integration of several clinical practice guidelines (CPGs) for the management of patients with multiple chronic disorders. We propose a framework based on an ontological modeling of CPG contents as rules. The ontology provides the required flexibility to adapt patient data and enable the provision of appropriate recommendations expressed at various levels of abstraction. To solve decisional conflicts that occur when combining multiple sources of recommendations, we proposed a method based on the subsumption graph of the patient profiles corresponding to the rules. A prototype CDSS implementing this approach has been developed. Results are given on a clinical case to illustrate the assets of ontological reasoning in increasing the number of issued recommendations and thereby the reliability of decision support.

Keywords:

Practice guidelines as topic; Knowledge bases; Ontology; Clinical decision support systems; Medication therapy management.

Introduction

Delivering optimal quality of care for all is one of the major challenges of modern medicine. Unwarranted variations of medical practices should be reduced [1], and improvement of care based on solid evidence should be promoted. Health agencies and medical professional societies develop clinical practice guidelines (CPGs), which are textual documents that synthesize the state of the art on the management of medical disorders. CPGs are expected to provide decision support for certain clinical situations, being one instrument of the promotion of evidence-based medicine. So far, their implementation remains insufficient. The challenge consists in a clear understanding of the reasons that prevent the use of CPGs [2], and the development of interventions to increase their implementation [3].

Clinical decision support systems (CDSSs) are considered as an efficient vector of CPG implementation. CDSSs rely on formalized knowledge bases and are usually integrated to electronic patient records to assist the clinician in her everyday practice. The integration of CPGs in CDSSs requires

a preliminary formalization step of CPG contents [4]. CPG knowledge may be represented as a set of decision rules where each rule consists in the description of a given patient profile and its associated recommendation. Therefore, CPGs are modeled as clinical patient profiles for which recommendations are provided. Guideline-based CDSSs yield patient-specific recommendations by pairing the description of the actual patient with related CPG patient profiles. Despite their promise, several studies reported discrepancies between CDSS expectations and their effectiveness in promoting best practices, illustrating the existence of obstacles to their widespread use in routine [5, 6].

CPGs generally focus on a specific medical disorder, eg. Hypertension, Asthma, Obesity, etc. But, actual patients often present multiple pathologies and the management of multi-morbidity can be a real challenge for the clinician [7]. Indeed, this requires identifying CPGs related to the patient state, to gather every relevant recommendation, and to combine them accordingly [8]. Competing CPGs and their potential decisional conflicts are identified as a reason of non-adherence with CPGs [2]. Future CDSSs should account for the integration of multiple CPGs [9].

Clinical descriptions of theoretical patient situations are often not detailed in the same way depending on CPGs. Indeed, CPGs are usually written in free text by different consortia, sometimes in different languages. Therefore, the same concept might be described using different terms, and with stylistic variations. A standardized description is then required for representing CPG knowledge. Depending on CPGs, some patient characteristics may be described at different levels of abstraction, which requires the tacit knowledge that link them. For instance, kidney disease is mentioned as a co-morbidity in diabetes CPGs, whereas more specific precisions in terms of renal failure are considered in hypertension CPGs. This lack of normalization makes the identification of appropriate patient states complex. It may lead to an incomplete or bad characterization of the patient and consequently to the production of conflicting recommendations, incorrect recommendations, or even no recommendation. Indeed, it happens that guideline-based CDSSs are not able to match patient data with the premisses of recommendations, which can result in a problematic silence when the system does not provide any recommendation to the user. This may cause a loss of confidence and usually ends up with an abandonment of such systems.

While developing biomedical applications, ontologies (domain conceptualizations for representing CPG knowledge) can efficiently be used as a stable framework [10]. Our

assumption is that they could provide solutions to the seamless consideration of multiple CPGs within CDSSs.

We have developed a method based on ontologies to give CDSSs the flexibility needed to deal with patients with multiple pathologies. The aim of this paper is to describe the framework we developed where ontological reasoning is used to enrich the patient description at different levels of abstraction and thereby increase the number of appropriate recommendations. The approach allows to solve decisional conflicts exploiting the subsumption of CPG-based patient profiles in order to provide the most relevant recommendations. We have implemented a prototype CDSS applied to CPGs on hypertension (HT) and type 2 diabetes (T2D). We used an example to illustrate the impact, on the quality of the recommendations provided, of taking into account the ontological reasoning.

Methods

Our goal is to address the management of multiple CPGs, expressed at various levels of abstraction, within a functional CDSS. The approach relies on the use of ontological representation and reasoning. The first step deals with the construction of the knowledge base from multiple CPGs. The second focuses on the exploitation of the knowledge base and the processing of patient data to deliver patient-specific recommendations. The proposed framework aims at increasing the number of patient-specific recommendations while managing potential conflicts.

Hypertension and type 2 diabetes CPGs

Considering the management of cardiovascular risk in general practice, we first chose to consider HT and T2D. We used contemporary CPGs authored in 2014 by Vidal, a French company that markets a drug database and original medical content whose quality has been certified by the medical profession. CPGs include graphical clinical pathways that illustrate the process of care. Each step of the trees are then detailed by synthetic textual sections. CPGs also deal with particular cases (eg. HT and Pregnancy) and provide indications and contraindications of recommended drug classes.

Construction of the knowledge base

In a previous study [11], we performed a formalization of HT and T2D CPGs by manually extracting and conceptualizing the decision rules. As illustrated in Figure 1, decision rules are built on the IF-THEN model with the conditional combination of patient criteria in the IF-part and the recommended actions in the THEN-part. The IF-part corresponds to a patient profile described in CPGs. We obtained two rule bases: one for the HT CPGs and one for the T2D CPGs.



with Patient Profile = Criterion 1 \wedge ... \wedge Criterion n

ex. : HT \wedge Renal failure \rightarrow Prescribe ACEi

Figure 1 - Formalisation of decision rules

Decision criteria and actions were encoded in a single custom ontology. This ontology was inspired from the existing OntoUrgences developed for the management of emergencies [12]. Concepts relevant to cardiovascular risk management

were extracted from this emergency ontology, and supplemented by CPG-specific concepts required by our decision rules. We encoded the ontology in OWL. Concepts are related by subsumption, equivalence, and disjunction links so that every inference is valid. Figure 2 illustrates an extract of the custom ontology under the "Pathology" concept.

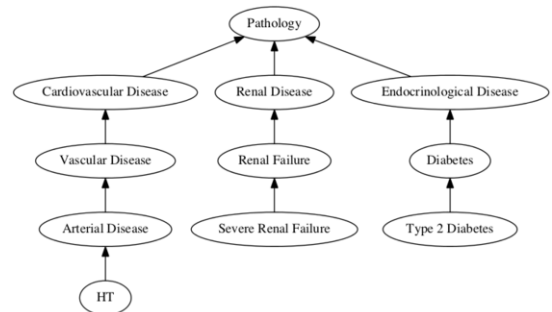


Figure 2 - Extract of the Pathology subgraph of the custom ontology

Generation of the graph of patient profiles

The patient profiles described in the IF-part of the rules are conjunctions of concepts from the ontology. Patient profiles correspond to new defined concepts and are consequently linked within the subsumption hierarchy of the ontology, some being more specific than the others. Following the ontological framework, there are two kinds of specificity: (i) the conceptual specificity which comes from the subsumption of atomic concepts (eg. "HT" is more specific than "Arterial Disease") and (ii) the logical specificity derived from defined concepts (eg. "HT \wedge Diabetes" is more specific than "HT"). The classification of patient profile/rules is performed automatically by an ontological reasoner. This yields a subsumption graph of patient profiles where the root is the least specified profile and the leaves are the most detailed ones. Figure 3 illustrates an extract of the profile subsumption graph for patient profiles of both HT and T2D rule bases.

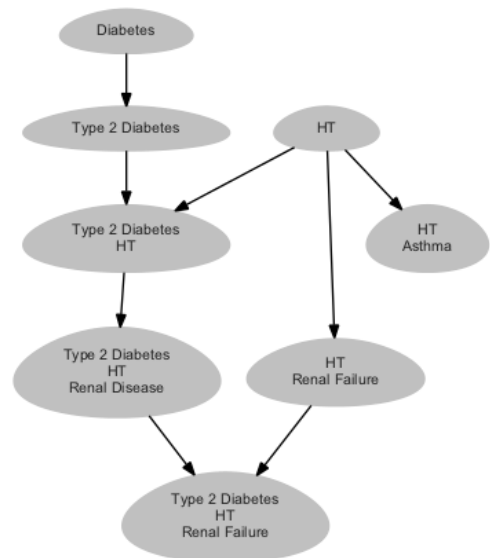


Figure 3 - Extract of the subsumption graph of profiles from HT and Type 2 Diabetes CPGs

Matching of decision rules

When an actual patient's clinical case is considered, patient data is first translated to match the concepts of the ontology. The actual patient description is then a conjunction of ontological criteria. The initial description of the patient is then enriched through the ontology. For instance, a patient described by "HT \wedge Diabetes" will be characterized by "HT \wedge Arterial Disease \wedge Vascular Disease \wedge Cardiovascular Disease \wedge Endocrinological Disease \wedge Pathology". In this framework, finding which decision rules apply for the patient consists in identifying all the CPG-based patient profiles that subsume the actual patient profile.

Management of potential conflicts

By using the subsumption of patient profiles, more rules than those that solely match patient data are, logically, considered for execution, whatever their level of abstraction, and whatever their originating CPG in case multiple rule bases from different CPGs have been merged. Potential conflicts may then be revealed and should be managed. We used the ontological representation of rule actions to detect such conflicts. When comparing every pair of matching profiles, we identified three possible cases:

1. No action conflict. Recommended actions are complementary and can be suggested without causing any decisional conflict. For instance, "Prescribe Anti-HT treatment" and "Monitor hypoglycemia" are two recommended actions of different nature and can thus be suggested together to the user.
2. Action conflict and profile subsumption. Recommended actions are conflicting and subsumption exists between the profiles from which actions have been extracted. The priority is given to the recommendation attached to the most specific profile. For instance, betablockers are recommended for patients suffering from HT, but contraindicated for patients suffering from HT and Asthma. Thus, the contraindication of betablockers overrides their recommendation in the case of a patient matching the "HT \wedge Asthma" profile.
3. Action conflict but no profile subsumption. In this case, recommended actions are conflicting but the originating profiles cannot be compared since there is no subsumption link between them. Without additional encoded knowledge to solve this conflict, we cannot solve it automatically, and we chose to let the clinician decide what recommendation (if any) is the most relevant for his patient. For instance, for hypertensive patients, thiazide diuretics are recommended for diabetic patients but contraindicated for patient with renal failure. In the case of a patient characterized by "HT \wedge Diabetes \wedge Renal Failure", the system is unable to discriminate between the recommendations.

Analysis of the role of ontological reasoning

To assess the benefits of the ontological reasoning when merging several CPGs, we compared the results provided by the CDSS with the results of the same system when the ontological reasoning was disabled. To illustrate this, we used a simulated patient case profile which has to be a realistic situation of a patient suffering from multiple pathologies among which at least HT or Diabetes. Then, we executed the system and compared the characterization of the patient including inferred findings, triggered decision rules, and the recommendations of drug prescription.

Results

The custom CPG ontology built for HT and T2D CPGs is made of 500 concepts and includes 96 disjunction declarations. It is divided into two main parts: concepts related to the patient or decision variables (i.e. characteristics, pathologies, clinical signs) and those related to the clinical management or actions (i.e. treatment, goals, medical actions).

The rule bases contain 180 different rules for HT CPGs, and 94 different rules for T2D CPGs. These two rule bases share two common profiles ("Diabetes" and "HT \wedge T2D") which yields 272 different patient profiles for the unified rule base.

A CDSS has been developed to provide recommendations issued from HT and T2D CPGs. We used the JENA API for ontological reasoning, and rule inferences based on the set of patient data. A graphical user interface enables interaction with the user and the display of the recommended drug classes for each pathology as well as other recommended information (diet, prevention). Figure 4 displays a screenshot of the CDSS interface.

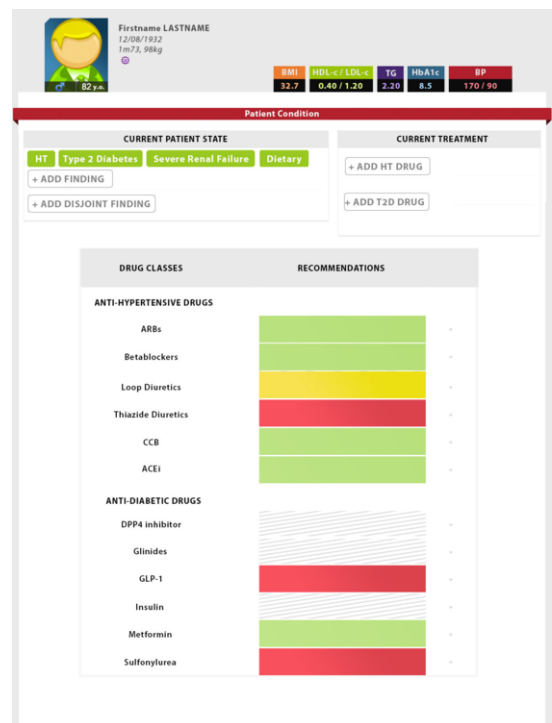


Figure 4 - Screenshot of the CDSS user interface

To illustrate how the system operates, we used the clinical case of a 83 year old male patient under dietary, with HT, T2D, and suffering from severe renal failure. His arterial pressure is 170/90 mmHg and his HbA1c rate is 8.5%. We run the system on this example patient with and without the ontological reasoning. Table 1 synthesizes the results obtained.

Without ontological reasoning, the system missed a contraindication to thiazide diuretics for people suffering from renal failure and recommended this class of antihypertensive drugs. When the ontological reasoning was enabled, the system detected a conflict about thiazide diuretics which are recommended for T2D patients, but are contraindicated for patient suffering from renal failure. Likewise, without ontological reasoning, the system missed the indication of

loop diuretics for patients with renal failure. Other actions that differ between the two execution modes of the system are not related to drug prescription and concern the other aspects of the management (risk factors, medical appointments, monitoring). It must be noted that the recommended drug prescription for the management of T2D is the same regardless of the activation of ontological reasoning.

Table 1 - Comparison of the CDSS execution with and without ontological reasoning on the example patient

Object	Without ontology	With ontological reasoning
Patient Concepts (input/inferred)	3/0 (HT, T2D, Severe Renal Failure)	3/11 (HT, T2D, Severe Renal Failure, Arterial Disease, Vascular Disease, Cardiovascular Disease, Diabetes, Endocrinological Disease, Renal Failure, Renal Disease, Pathology)
Incompatible Concepts	0	33
Incompatible profiles	0	136
Triggered profiles	15	22
Recommended actions	42	51
Contraindicated Anti-HT classes	—	Thiazide diuretics
Recommended Anti-HT classes	ARB, ACEi, Betablockers, Calcium-channel blockers, Thiazide diuretics	ARB, ACEi, Betablockers, Calcium-channel blockers, Loop diuretics
Recommended Anti-Diabetic classes	Metformin	Metformin
Contraindicated Anti-Diabetic classes	GLP-1, Sulfonylurea	GLP-1, Sulfonylurea

On the CDSS interface (see Figure 4), the drug prescription dashboard synthesizes the recommendations about drug prescription for the two pathologies. Drug classes are written on the left of the dashboard and the associated recommendations are indicated using color codes: red when the drug class is contraindicated, green when it is recommended, yellow when it is possible, and grey when no indication is given for this drug class in CPGs.

Discussion

In this paper we presented our work concerning the integration of ontological reasoning to handle multiple CPGs represented as decisional rules. The method has been implemented as a functional CDSS. We have illustrated the functioning of the system on an example clinical case. We compared the results obtained with and without ontological reasoning.

The number of concepts implicitly added by ontological reasoning is closely related to the construction of the ontology; it depends on the number of levels of specificity chosen during the modeling step. This choice has to be made by taking into account the levels of specificity of the decision

rules. Indeed, a high number of additional concepts only has a meaning if it allows the triggering of more rules.

The CDSS with ontological reasoning provides, as expected, more recommendations than the classical approach. These additional recommendations were issued because rules of higher level of abstraction have been triggered. Decision rules used in the CDSS were indeed extracted from the text of CPGs and thus, inherited from text imperfections and inconsistency. Including ontological reasoning allowed to depart from the syntactical constraints of the text and to reduce such imperfections. By giving some flexibility in the characterization of a patient, we increased the number of triggered profiles including those that would not have been triggered by classical systems. The resulting recommendations are not only more numerous but also, thanks to our conflicts solving method, more adapted to the current patient case.

The lack of flexibility is pointed out as one of the reasons that clinicians don't keep using CDSSs. Ontologies bring the possibility to enrich the levels of abstraction in the management of patient profiles, and also to create, from static guidelines, dynamic pathways following the needs, the availability of the data and the usefulness of the recommendations. Other research works have incorporated ontologies for decision support as well as for other type of biomedical applications [13,14].

Besides content issues which are fundamental, but also apply to CPGs themselves, the usability of CDSSs and the clarity of the user interface are recognized as key factors for their adoption by health professionals. The real challenge lies in dealing with a lot of information and choosing which CDSSs to suggest to the clinician. We thus have to find a synthetic way to display the relevant provided recommendations and to highlight the most interesting ones. These aspects have to be further evaluated.

Conclusion

We propose a method based on semantic web techniques such as ontological reasoning to bring more flexibility to CDSSs and also offer the ability to deal with patients suffering from multiple pathologies by including several modeled CPGs. The method has been implemented as a prototype CDSS. In future works, we will enrich the current system with additional CPGs on the management of cardiovascular diseases (*e.g.* dyslipidemia). Then, we plan to assess the system both on the usability dimension and on the quality of the recommendations provided with a panel of general practitioners.

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