Developing a Modular Architecture for Creation of Rulebased Clinical Diagnostic Criteria

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Abstract. With recent advances in computerized patient records system, there is an urgent need for producing computable and standards-based clinical diagnostic criteria. For example, constructing rule-based clinical diagnosis criteria has become one of the goals in the International Classification of Diseases (ICD)-11 revision. However, few studies have been done in building a unified architecture to support the need for diagnostic criteria computerization. In this study, we present a modular architecture for creation of rule-based clinical diagnostic criteria leveraging Semantic Web technologies. The architecture consists of two major modules: one is an authoring module that utilizes a standardsbased information model and the other is a translation module that utilizes Semantic Web Rule Language (SWRL). In a prototype implementation, for the authoring module, we developed a diagnostic criteria upper ontology that integrates ICD-11 content model with Quality Data Model (QDM); for the translation module, we developed a transformation tool that converts QDM-based diagnostic criteria into Semantic Web Rule Language (SWRL) representation. We evaluated the domain coverage of the upper ontology model by annotating 20 randomly selected diagnostic criteria. We also tested the transformation algorithms using 6 QDM templates for ontology population and 15 QDM-based criteria data for rule generation. In summary, our efforts in developing and prototyping a modular architecture provide useful insights into building a scalable solution to support diagnostic criteria representation and computerization.

Keywords: Diagnostic Criteria, Ontology, ICD-11, QDM, SWRL

1 Introduction

Diagnostic criteria are one of the most valuable sources of knowledge for supporting clinical decision-making and improving patient care [1], [2], [3], [4]. The clinical informatics research community has been seeking a solution to standardize and computerize clinical diagnosis criteria for all clinical domains. Diagnostic criteria are usually scattered over different media such as medical textbooks, literatures and clinical practice guidelines mostly in textual formats. Many studies have been conducted

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in integrating and formally expressing diagnostic rules from free-text-based clinical guidelines and diagnostic criteria into computerized decision support system to improve clinical performance and patient outcomes [5], [6]. However, very limited research has been done on building a unified architecture to support the goal of diagnostic criteria formalization. In particular, the lack of a standards-based information model has been recognized as a major barrier for achieving computable diagnostic criteria[7]. Diagnostic criteria are usually described in different narrative style, granularity, term usage and inner logic. There is a need to develop a clear information model specification and a standard architecture to support the diagnostic criteria modeling and representation, and thereby enabling computerization. To achieve a unified architecture, the following aspects should be considered: a) an information model that supports standard representation of diagnostic criteria; b) the semantic interoperability and expressivity of a knowledge representation language; c) the rule-based reasoning capability over the fact knowledge; and d) a standard exchange format for different layers of the architecture.

Current efforts in the development of international recommendation standard models in clinical domains have laid the foundation for modeling and representing computable diagnostic criteria. The notable examples include the International Classification of Diseases (ICD)-11 content model [8], [9] and National Quality Forum (NQF) Quality Data Model (QDM)¹. The content model of ICD-11 is a structured framework that defines "a classification unit" in ICD in a standard way in terms of its components that allows computerization. Under the definition of the content model, each ICD entity can be seen from different dimensions and there are currently 13 defined main dimensions in the content model. One purpose of the ICD-11 content model is to use different settings of these dimensions or parameters to construct different sets of diagnostic criteria, so different elements in the content model come together to define the diagnostic criteria of a particular ICD category. As the ICD-11 content model depicts a big picture of diagnostic criteria computerization and it has achieved consensus among the ICD Revision Group, we consider it a viable framework on which to build our Diagnostic Criteria Upper Ontology (DCUO).

The QDM is an information model that describes clinical concepts in a standardized format to enable electronic quality performance measurement in support of operationalizing the Meaningful Use Program of the Health Information Technology for Economic and Clinical Health Act. It allows quality measure developers and many clinical researchers or performers to describe clearly and unambiguously the data required to calculate the performance measure. As the purpose, QDM allows electronic health records (EHR) and other clinical electronic system to share a common understanding and interpretation of the clinical data. To describe different part of the clinical care process, QDM defines many datatypes to specify the context in which each category is used. It has been proved that the extension of QDM could support a number of relevant areas. As a standard format, Health Quality Measure Format (HQMF) [10] formally defines a quality measure (data elements, logic, definitions,

¹ http://www.healthit.gov/quality-data-model

etc.) to support consistent and unambiguous interpretation. HQMF has been accepted as a format to define eMeasures in the HL7 standard.

While formalizing the inner logic for diagnostic criteria is complex, Semantic Web technologies provide a homogeneous framework that enables an ontology-based modeling with the Web Ontology Language (OWL)² and supports rule-based reasoning with the Semantic Web Rule Language (SWRL) [11]. In a semantic web environment, OWL is a W3C recommendation for ontology description and modeling and SWRL is a rule language to formalize and represent rules to support knowledge reasoning. In the present study, we evaluate OWL and SWRL-based representation languages for formalizing diagnostic criteria.

The objective of the present study is to describe our efforts in developing a modular architecture for creation of rule-based clinical diagnostic criteria leveraging Semantic Web technologies. We prototyped and evaluated a number of key components of the architecture, including an upper ontology and a transformation tool. We select a collection of QDM datatypes that are commonly used in describing diagnostic criteria and then integrated them into ICD-11 Content Model to build a schema for a diagnostic criteria upper ontology. We perform our data translation and interaction following the HQMF standard format and propose extensions where needed.

2 Materials & Methods

2.1 Materials

WHO ICD-11 content model: WHO developed a content model to present the knowledge that underlies the definitions of an ICD entity [8]. The content model is composed of three layers: a foundation layer, a linearization layer, and an ontological layer. The foundation layer is the core product of the ICD-11 revision that stores the full range of knowledge of all classification units in ICD.

Each ICD entity can be seen from different dimensions. The content model represents each one of these dimensions as a parameter. Currently, there are 13 defined main parameters in the content model to describe a category in ICD-11, for example, Manifestation Properties, Causal Properties, Treatment Properties. "Diagnostic Criteria" is one of the main parameters for describing an ICD category.

NQF Quality Data Model (QDM): QDM consists of two modules: a data-model module and a logic module. The data-model module includes the notions of category (e.g., Medication), datatype (e.g., Medication, Administered), attribute (e.g., information about dosage, route, strength, and duration of a medication), and value set comprising concept codes from one or more terminologies. The logic module includes Logic Operators, Functions, Comparison Operators, Temporal Operators, Subset Operators. As mentioned above, the HQMF provides a standard format to render the QDM-based criteria (i.e., instance data) in XML format using a collection of templates [10]. In a previous study [12], we evaluated the feasibility of using QDM for representing diagnostic criteria through a data-driven approach and suggested that the

² http://www.w3.org/TR/owlfeatures/

common patterns informed by QDM are useful and feasible in building a standardsbased information model for computable diagnostic criteria. In this study, we reference the common patterns and selected a collection of QDM datatypes and attributes for developing an upper ontology.

2.2 Methods

The overall system architecture for creation of rule-based clinical diagnosis criteria is shown in Figure 1.



Fig. 1. Overall System Architecture for Creation of Rule-based Clinical Diagnosis Criteria

The system architecture contains two major modules: one is an authoring module that utilizes a standards-based information model and the other is a translation module that utilizes SWRL. The first module of the architecture contains an upper ontology that supports the organization of diagnostic criteria. We integrated a collection of selected ICD-11 content model elements and QDM elements manually informed by the analysis of real-world diagnostic criteria. The first module also contains a unified web user interface that supports collecting and authoring diagnostic criteria from clinicians or experts. All collected data elements, value sets and logic expressions of diagnostic criteria are formalized using QDM-based HQMF template. Standard QDM model serves as a foundation layer for all following automatic parsing and reasoning work. The second module of the architecture contains a rule translation engine that converts diagnostic criteria ontology and a set of rules using SWRL. The rule translation engine supports further diagnostic inference on patient data. In the following subsec-

tions, we mainly focus on describing the core parts that we prototyped and developed in detail.

2.2.1 Developing a standards-based diagnostic criteria upper ontology

The purpose of this work is to integrate existing standard information models relevant to modeling of diagnostic criteria by expert review and manual editing. As mentioned in the section above, we choose the ICD-11 content model and NQF QDM as reference standards. Our work in this stage is to create a diagnostic criteria upper ontology (DCUO) through integration of ICD-11 content model and those QDM elements commonly used in diagnostic criteria. The selection of these QDM elements was informed by the results from a previous study [12]. We selected 10 QDM datatypes and 4 QDM attributes and integrated them with ICD-11 content modelbased ontology schema. Table 1 shows a list of the QDM datatypes and attributes used for the integration. We used Prot & e ontology editing environment for manually integrating these two standard information models into a diagnostic criteria upper ontology.

QDM Datatypes	QDM Attributes		
Laboratory Test, Result	Result		
Diagnostic Study, Performed	Method		
Diagnostic, Active	Reason		
Physical Exam, Performed	Severity		
Symptom, Active			
Medication, Active			
Patient Characteristic Birth Date			
Patient Characteristic Race			
Patient Characteristic Sex			
Procedure, Recommended			

Table 1. A list of selected QDM datatypes and attributes for developing the upper ontology

2.2.2 Transforming QDM templates into domain-specific diagnostic criteria ontology

To build a scalable diagnostic rule translation environment, it is important to dynamically populate a Diagnostic Criteria Domain Ontology (DCDO) for a specific disease or condition, e.g. 'DCDO for AMI (Acute Myocardial Infarction)'. We developed a parsing interface that could support data extraction from diagnostic criteria encapsulated by HQMF templates. To parse all HQMF instance data in a specific template, we developed a collection of JAVA-based XML parsing and mapping algorithms to automatically extract instance data from HQMF templates and convert them into corresponding DCDO elements. The parsing algorithms decompose HQMF XML data into different parts and populate the parsed elements into the same DCDO. The process of the ontology population consists of 2 steps: template-based XML parsing and semantic mapping. A HQMF template example and its parsing results are shown in Figure 2. The lefthand part is the template representation of QDM datatype "Laboratory Test, Result" (hqmf r1 template - 2.16.840.1.113883.3.560.1.12) [10] and the right-hand part is the elements extracted from the XML template.

<act classcode="ACT" iscriterionind="true" moodcode="EVN"> <templateid< td=""></templateid<></act>
root="{\$getTemplateOID}"/> <id root="{\$QDMElementUniqueId}"></id> <code< td=""></code<>
<pre>code="30954-2" displayName="Results" codeSystem="2.16.840.1.113883.6.1"></pre>
<sourceof typecode="COMP"> <observation <="" classcode="OBS" moodcode="EVN" td=""></observation></sourceof>
isCriterionInd="true"> <code <="" code="{\$valueSetOID}" td=""></code>
codeSystem="2.16.840.1.113883.3.560.101.1" displayName="{\$displayName}"/>
<title>"{\$datatypeName}: {\$valueSetName}"</title> <statuscode< td=""></statuscode<>
code="completed"/>

Elements of template - 2.16.840.1.113883.3.560.1.12
"30954-2"
"Results"
"2.16.840.1.113883.6.1"
"\$valueSetOID"
"2.16.840.1.113883.3.560.101.1"
"\$displayName"
"\$datatypeName"
"\$valueSetName"

Fig. 2. An XML Parsing of the HQMF template "Laboratory Test, Result" (hqmf r1 template - 2.16.840.1.113883.3.560.1.12)

And then, we created semantic mapping between the XML elements and the elements of the DCDO ontology. For example, the semantic mappings of the template - 2.16.840.1.113883.3.560.1.12 are shown in Table 2.

Elements of template - 2.16.840.1.113883.3.560.1.12	Elements of Ontology		
"30954-2"	Annotation property of "Laboratory Test, Result"		
"Results"	Annotation property of "Laboratory Test, Result"		
"2.16.840.1.113883.6.1"	Annotation property of "Laboratory Test, Result"		
"\$valueSetOID"	Annotation property of "\$valueSetName"		
"2.16.840.1.113883.3.560.101.1"	Annotation property of "\$valueSetName"		
"\$displayName"	Annotation property of "\$valueSetName"		
"\$datatypeName"	Class: Laboratory Test, Result		
"\$valueSetName"	Class: Subclass of "\$datatypeName"		

Table 2. Semantic mappings between HQMF template elements and ontology elements

2.2.3 Automatic rule composition and validation

After having a DCDO ontology populated, we developed JAVA-based algorithms using Prot & OWL API and SWRL API for automatic rule composition and rule validation, which are respectively responsible for rule assembling and rule grammar checking.

The SWRL syntax contains two parts: Body and Head. The Body is also called the antecedent and the Head part is the consequent of the rule. There are 6 atom types that can be used as the components of the Body and Head: class atom, individual property atom, same/different atom, and data valued property atom, build-in atom and data range atom.

Adhering to SWRL structure and grammar, we designed a collection of translation algorithms to automatically extract SWRL rule elements from the logic components of an HQMF XML template and then to assemble these rule elements into the SWRL syntax.

For example, Figure 3 shows the HQMF XML representation of the QDM-based criterion "Laboratory Test, Result: LDL-c (result < 100 mg/dL)". The criterion is composed by two templates: HQMF template "Laboratory Test, Result" (hqmf r1 template - 2.16.840.1.113883.3.560.1.12) and HQMF template "result comparison" (hqmf r1 comparison template - 2.16.840.1.113883.3.560.1.1019.3).

```
<!-- Laboratory Test, Result pattern -->
<templateId root="2.16.840.1.113883.3.560.1.12"/>
<id root="c5244e91-3c2e-4863-ae87-a48556b9e3ae"/>
  <code code="30954-2" displayName="Results" codeSystem="2.16.840.1.113883.6.1"/>
  <sourceOf typeCode="COMP">
    <observation classCode="OBS" moodCode="EVN" isCriterionInd="true">
       <code code="2.16.840.1.113883.3.117.1.7.1.215" displayName="LDL-c LOINC Value
       Set" codeSystem="2.16.840.1.113883.3.560.101.1"/>
           <title>Laboratory Test, Result: LDL-c (result &lt; 100 mg/dL)</title>
           <statusCode code="completed"/>
           <sourceOf typeCode="REFR">
                <observation classCode="OBS" moodCode="EVN" isCriterionInd="true">
                <templateId root="2.16.840.1.113883.3.560.1.1019.3"/>
                <code code="385676005" codeSystem="2.16.840.1.113883.6.96"
                displayName="result" codeSystemName="SNOMED-CT"/>
                    <value xsi:type="IVL PQ">
                    <high value="100" unit="mg/dL" inclusive="false"/>
                    </value>
             </observation>
           </sourceOf>
    </observation>
   </sourceOf>
```

Fig. 3. The HQMF XML representation of the QDM-based criterion "Laboratory Test, Result: LDL-c (result < 100 mg/dL)".

Our translation algorithms then automatically extract SWRL rule elements from the logic components of the two HQMF XML templates and then assemble these rule elements into following SWRL syntax.

Rule: Patient(?x),LDL-c(?y),has_result(?x, ?y),has_value(?y, ?z),has_unit(?y, mg/dL),lessThan(?z, 100)-> has_evidence(?x,ev1)

2.2.4 Evaluation of prototyped components

First, we evaluated the domain coverage of ICD-11 content model in terms of representing diagnostic criteria. We collected 20 diagnostic criteria from different clinical topics and manually annotated them with the elements in ICD-11 content model. Second, we evaluated the translation algorithms for ontology population and rule generation. We first tested the ontology population algorithms using the 6 HQMF templates. The first author assessed whether they are correctly parsed and represented in the domain ontology, and the assessment results were verified by other three coauthors. The 6 HQMF templates are as follows.

- 1. "Laboratory Test, Result" (hqmfr1 template 2.16.840.1.113883.3.560.1.12)
- 2. "Patient Characteristic Sex"(hqmfr1 template 2.16.840.1.113883.3.560.1.402)
- 3. "Patient Characteristic Birth Date"(hqmf r1 template 2.16.840.1.113883.3.560.1.400)
- 4. "result/is present" (hqmf r1 template 2.16.840.1.113883.3.560.1.1019.1)
- 5. "result/valueset" (hqmf r1 template 2.16.840.1.113883.3.560.1.1019.2)
- 6. "result/comparison" (hqmf r1 template 2.16.840.1.113883.3.560.1.1019.3)

We then tested the rule generation algorithms using 15 QDM-based criteria represented in HQMF XML format. All the 15 criteria are selected from existing eMeasures and use the HQMF template - "Laboratory Test, Result" (hqmf r1 template - 2.16.840.1.113883.3.560.1.12). We used Prot & SWRL API to validate the syntactical correctness of the SWRL rule grammars. The first authors assessed the semantic correctness of the generated SWRL rules through comparing the HQMF XML-based logic with SWRL rule logic and the assessment results were verified by other three co-authors.

3 Results

3.1 Upper ontology DUCO development and evaluation

Figure 4 shows a screenshot of the upper ontology in Prot & e ontology editing environment. There are total 14 root classes and 21 subclasses in the ontology. In this ontology, 22 classes came from ICD-11 content model with the namespace prefix 'ICD', 10 of the classes are integrated from QDM datatypes with the namespace prefix 'QDM' and 3 classes with the namespace prefix 'DCUO' created for the need of representing diagnostic criteria.

We also evaluated the domain coverage of ICD-11 content model. Table 3 shows distribution of element annotations based on ICD-11 content model. The results showed that Investigation Findings, and Signs and Symptoms are the two most commonly used element types in diagnostic criteria description. The results are consistent with the analysis we did for QDM elements in a previous study [12].

Table 3. Distribution of element annotations based on ICD-11 Content Model

ICD-11 Content Model	Count	Examples
Investigation Findings	74	Serum triglycerides
Sign and Symptom	69	Fatigue, Headache
Title	20	Metabolic Syndrome
Causal Properties	18	Pericardial effusion
Classification	12	T71
Severity Of Subtype	10	Mind, Moderate, Severe
Body System/Structure	8	Nervous system
Specific Condition	3	Female, Pregnancy
Temporary Properties	2	Age 55, sudden



Fig. 4. The Diagnostic Criteria Upper Ontology

3.2 Translation algorithms evaluation

All 6 HQMF templates are successfully parsed and populated into their corresponding DCDO ontologies. Human-based review confirmed that the elements in the templates are correctly represented in the target ontology.

For the rule generation algorithm evaluation, in total, 15 SWRL rules were generated. Table 5 shows a list of 15 QDM/HQMF-based criteria and the validation results in terms of whether generated rules passed the validation or not. Of them, 14 rules (93.3%) passed rule validation using Prot ég é SWRL validation tool whereas one rule (6.7%) failed to pass. Human-based review analysis found that the failure was caused by an invalid expression '[copies]/mL' that contains special characters '[' and ']'. Human-based review also confirmed the semantic correctness of all 15 generated rules.

Table 5.	A list of	15 (DDM/HC	OMF-based	criteria	and the	validation	results
			<					

QDM/HQMF-based Criteria Using HQMF Template - "Laboratory	If passed	
Test, Result" (hqmf r1 template - 2.16.840.1.113883.3.560.1.12)	rule syntax	
	validation?	
Laboratory Test, Result: INR (result >= 2)	Yes	
Laboratory Test, Result: Hospital Measures-Neutrophil count (result <	Yes	
500 per mm3)		
Laboratory Test, Result: High Density Lipoprotein (HDL) (result < 40	Yes	
mg/dL)		
Laboratory Test, Result: Hepatitis A Antigen Test (result: 'Seropositive')	Yes	
Laboratory Test, Result: Hepatitis B Antigen Test (result: 'Seropositive')	Yes	
Laboratory Test, Result: HIV Viral Load (result < 200 copies/mL)	No	
Occurrence A of Laboratory Test, Result: High Density Lipoprotein	Yes	
(HDL) (result $< 60 \text{ mg/dL}$)		
Occurrence A of Laboratory Test, Result: LDL Code (result < 100	Yes	
mg/dL)		
Occurrence A of Laboratory Test, Result: LDL-C Laboratory Test (result	Yes	
< 100 mg/dL)		
Laboratory Test, Result: Macroalbumin Test (result: 'Positive Finding')	Yes	
Laboratory Test, Result: Mumps Antigen Test (result: 'Seropositive')	Yes	
Laboratory Test, Result: Prostate Specific Antigen Test (result <= 10	Yes	
ng/mL)		
Laboratory Test, Result: Measles Antigen Test (result: 'Seropositive')	Yes	
Laboratory Test, Result: Rubella Antigen Test (result: 'Seropositive')	Yes	
Laboratory Test, Result: High Density Lipoprotein (HDL) (result < 40	Yes	
mg/dL)		

4 Discussion

In this study, we developed a modular architecture, with a prototype implementation and evaluation, to support the authoring and formalization of diagnostic criteria knowledge leveraging Semantic Web OWL and SWRL technologies. The diagnostic criteria upper ontology and domain ontology are all represented in OWL that is built on formalisms of description logic (DL). And the rules extracted from QDM HQMFbased criteria are formalized and represented in SWRL, which leverages the full reasoning power of OWL DL when invoking a rule engine. There are two main contributions in this study. First, the design rationale of the architecture is to enable extensive support for representation and computation of diversified diagnostic criteria. Second, the architecture supports reuse of existing standards from the perspectives of information model, terminology services and technical interface. There are a number of limitations in this study since our pilot study in this paper is mainly focused the feasibility of our proposed architecture. First, the DCUO (Diagnostic Criteria Upper Ontology) was reviewed for consensus and quality assurance only by a relatively small group (i.e., four authors). In the future, a rigorous ontology evaluation by a panel of experts from relevant domains will be useful in achieving consensus in terms of the vocabulary, syntax, structure, semantics, representation and context of the DCUO. We plan to use ontology evaluation methods as described by Vrandečić [13]. Second, we have not considered all complex conditions and details in the modeling of diagnostic criteria. For instance, the following problems need to be further considered.

- In the QDM model, the semantics of some templates are not expressed explicitly. For example, the QDM element 'Patient Characteristic Birth Date' is used to represent the numeric value comparison of the variable "Patient Age" (e.g. <low value='18' unit='a' inclusive='true'/>), assuming the value of the variable "Patient Age" could be derived from the 'Patient Characteristic Birth Date'.
- In the preliminary study, we have implemented the translation algorithms only on a limit number (n=6) of HQMF templates and the preliminary evaluation demonstrated that the translation performed is reasonably well. However, in total, there are 186 HQMF templates from diverse domains and the HQMF templates are updated continuously, so maintaining the transportability and reusability of the translation algorithms will be a challenge.
- For the diagnostic criteria rules generation using SWRL, the inclusion criteria are well supported by built-in rule grammars, such as: comparison, mathematical functions, Booleans, string and Date/Time. We understand that some of exclusion criteria could not be explicitly expressed in SWRL because negated atoms or disjunctions are not supported in SWRL.

Following the rationale of the ICD-11 content model, the full range of different values for a given parameter is predefined using standard terminologies and ontologies. In this study, the QDM-based criteria used the predefined "value set" in NIH Value Set Authority Center (VSAC). The architecture will support the extension of value set definitions.

In the future, we plan to prototype a web-based application with the functionalities as follows. 1) DCUO display and update; 2) Diagnostic criteria authoring by clinicians and domain experts, including value set services invoking and semi-automated workflow for criteria editing; 3) integration of rule engine functions, including DCDO enrichment, rule generation and computerized criteria display and execution.

5 Conclusion

In this pilot study, we demonstrated the feasibility of prototyping a number of key components of our proposed architecture for diagnostic criteria knowledge modeling and reasoning. It remains a very complex field to explore and more semantic and syntactic features dealing with complexity of diagnostic criteria need to be further studied. We believe that our efforts provide useful insight into developing a scalable, semantic-oriented and standards-based solution to support diagnostic criteria formalization and computerization.

Acknowledgments

This work is supported in part by funding from: caCDE-QA (1U01CA180940-01A1), PhEMA (R01 GM105688) and a Mayo-WHO Contract 200822195-1.

References

1. Yager, J., Mcintyre, J.S.: DSM-5 Clinical and Public Health Committee: Challenges and Considerations. American Journal of Psychiatry 171, 142-144 (2014)

2. Haug, P.J., Ferraro, J.P., Holmen, J., Wu, X., Mynam, K., Ebert, M., Dean, N., Jones, J.: An ontology-driven, diagnostic modeling system. Journal of the American Medical Informatics Association : JAMIA 20, e102-110 (2013)

3. Donfack Guefack, V., Bertaud Gounot, V., Duvauferrier, R., Bourde, A., Morelli, J., Lasbleiz, J.: Ontology driven decision support systems for medical diagnosis - an interactive form for consultation in patients with plasma cell disease. Studies in health technology and informatics 180, 108-112 (2012)

4. Bertaud-Gounot, V., Duvauferrier, R., Burgun, A.: Ontology and medical diagnosis. Informatics for health & social care 37, 51-61 (2012)

5. Trivedi, M.H., Kern, J.K., Marcee, A., Grannemann, B., Kleiber, B., Bettinger, T., Altshuler, K.Z., McClelland, A.: Development and implementation of computerized clinical guidelines: Barriers and solutions. Method Inform Med 41, 435-442 (2002)

 Lloyd, T.E., Mammen, A.L., Amato, A.A., Weiss, M.D., Needham, M., Greenberg, S.A.: Evaluation and construction of diagnostic criteria for inclusion body myositis. Neurology 83, 426-433 (2014)

7. Richesson, R.L., Krischer, J.: Data standards in clinical research: gaps, overlaps, challenges and future directions. Journal of the American Medical Informatics Association : JAMIA 14, 687-696 (2007)

8. Jiang, G., Solbrig, H.R., Chute, C.G.: Using Semantic Web technology to support icd-11 textual definitions authoring. J. Biomedical Semantics 4, 11 (2013)

9. Organization, W.H.: ICD-11 Alpha Content Model Reference Guide, 11th Revision. World Health Organization, Geneva, Switzerland (2011)

10. Forum, N.Q.: HQMF Templates for QDM December 2013.

11. Horrocks, I., Patel-Schneider, P.F., Boley, H., Tabet, S., Grosof, B., Dean, M.: SWRL: A semantic web rule language combining OWL and RuleML. W3C Member submission 21, 79 (2004)

12. Jiang, G., Solbrig, H.R., Pathak J., Chute, C.G.: Developing a Standards-based Information Model for Representing Computable Diagnostic Criteria: A Feasibility Study of the NQF Quality Data Model. MedInfo (in press) 2015

13. Vrandečić, D.: Ontology evaluation. Springer (2009)