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Semantic interoperability and pattern classification for a service-oriented architecture in pregnancy care

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HIGHLIGHTS

- A comparative analysis of standards used as pattern reference model for CDSSs.
- OpenEHR Performance and its compatibility keeping semantics interoperability of HISs.
- Archetypes to support the identification of high-risk situations in pregnancy.
- Proposed semantic model performance of a SOA for gestation related chronic diseases.

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ABSTRACT

Semantic interoperability represents one of the main challenges in health information systems. The development of novel interoperability models should promote the integration of heterogeneous information in the acquisition and semantic analysis of complex data patterns, which are typically used in clinical information. The purpose of this study is to develop a knowledge-based decision support system that uses ontologies for integrating data related to hypertensive disorders in pregnancy. This model allows, when dealing with new cases, inferring from a knowledge base and predicting high-risk situations that could lead to serious problems during gestation in both pregnant women and fetuses. Results demonstrate that the use of ontologies to address semantically acquired patterns from different electronic health records has the potential to significantly influence a service-oriented architecture implementation for clinical decision support systems.

1. Introduction

The integration of distributed and heterogeneous health data has become an essential requirement for health institutions. This integration represents the challenge of reducing the high costs and increasing the quality of the services provided. The development of different database architectures has increased the necessity for data integration significantly. With the advent of the Web, novel proposals have been developed to solve complex interoperability issues [1]. The main challenges for interoperability among different knowledge sources must be resolved at both the technical and information levels. Thus, distributed data must not only be accessed but also integrated and processed by other systems. The restrictions that occur due to the heterogeneity of these data are mainly related to the heterogeneity among database management systems (DBMSs) and structural, syntactic, and semantic heterogeneity [2,3]. Recently, the use of ontologies has emerged as a potential solution to solve the complex problem of semantic data heterogeneity. The reason is that an ontology can provide a shared common understanding of an application field, in a consensual manner, with the meaning of the terms and their relationships

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to the modeled domain. That is, this methodology provides interoperability among health information systems (HISs) in such a fashion that users have no preoccupation regarding the data source or its storage method [4]. For heterogeneous data sources, the use of ontologies can make distributed processing understandable for a computer by describing entities and relationships among these data sources, as well as integrity rules for the domain. In this sense, an ontology can be used to define an overall system, serving as a fundamental basis for the data integration process.

The merging of clinical information is one of the most significant challenges in health informatics [5]. Once a patient receives additional or new care at a different healthcare institution in his lifetime, his information is distributed in different HISs, which typically execute on different hardware and software platforms. The difficulty of integrating heterogeneous databases for knowledge sharing does not only occur in healthcare systems [6]. This primary issue has been the subject of study for many years [7,8]. One of the most implemented techniques to address this problem is the development of ontologies to represent the knowledge domain [9]. An ontology is a description of concepts and relationships that can exist among these concepts in a given domain. For there to be knowledge sharing, there must be a standardized method to represent this knowledge. Novel patterns have been developed for this representation, making the possibility of semantic information sharing a reality [10,11].

Maternal mortality is an indicator of the status of women, their access to healthcare systems, and the adequacy of these systems to respond to their requirements [12]. The leading causes of maternal deaths are related to complications during and after pregnancy and childbirth. The principal complications are severe hemorrhage (27.1%), infections (10.7%), hypertension during pregnancy (14.0%), childbirth complications, and unsafe abortion (7.9%) [13]. High blood pressure accounts for 14% of the total number of deaths. To improve maternal health, according to the United Nations (UN) Millennium Development Goals (MDGs), difficulties that limit access to maternal health services must be identified and addressed at all levels of HISs [14]. In this context, efforts have been undertaken to provide health units with information and communication technologies (ICTs) that can contribute to improved access to information and adequate care. The development of intelligent solutions aimed at supporting health professionals in prenatal care is of fundamental importance to assist them in the search for better conditions for both pregnant women and fetuses [15]. The data generated during antenatal care constitute a significant information volume, being of fundamental importance for the identification of gestational risk factors. Thus, these data can provide an improved control throughout the gestation, contributing to the early diagnosis of possible complications. The development of methods for predicting risk situations through the use of knowledge-based decision support systems (DSSs) is essential to mitigate the difficulties inherent in gestational monitoring [16]. These models, when used with semantic integration, can cooperate to obtain excellent results in the prediction of risks related to pregnancy. This work presents the development of an intelligent system, based on ontologies, to predict pregnancy diagnosis risk levels. This model is integrated into a semantic platform supporting health professionals in prenatal care monitoring. The use of intelligent approaches to gestation monitoring allows that the data generated during the prenatal period can be processed automatically and, thus, can infer a pre-diagnosis autonomously, generating alerts for risk situations and providing valuable information for health professionals, anytime and anywhere. The contribution of this study to the literature is twofold. First, this work presents a knowledge-based model that links semantic interoperability to data analytics capabilities in real-time. Concerning other approaches, the proposed model offers a novel perspective to complement the data semantic acquisition, providing a comprehensive understanding of how data analytics in real-time can facilitate the decision-making process for the monitoring of chronic diseases. Secondly, the elements of a smart DSS are extracted from a real-world context and applied in different health care scenarios, providing new perspectives for healthcare practitioners. Thus, the main contributions of this paper are as follows:

- A comparative analysis of the leading standards used as information models and their compatibility in maintaining semantics in electronic health (e-health) environments;
- Development of archetypes based on the openEHR standard to recognize high-risk situations during pregnancy;
- Performance assessment of the proposed semantic model, which can serve as the basis for the development of a service-oriented architecture (SOA) for healthcare.

The remainder of this paper is organized as follows. Section 2 elaborates on the related work regarding this topic, focusing on semantic interoperability and its application in healthcare. Section 3 describes the use of ontology for pattern recognition in predicting hypertensive disorders in pregnancy. A performance evaluation, comparison of different methods, and analysis of the results of the proposed approach are presented in Section 4. Finally, Section 5 concludes the paper and suggests further works.

2. Related work

The increasing incorporation of informatics in health services has favored agility in the production, organization, and sharing of information. With the interoperability among HISs, information exchange among electronic health records (EHRs) has facilitated longitudinal patient monitoring, enabling improvements in their care, reducing errors and duplications, and minimizing the high costs of unnecessary diagnostic investigations [17]. The most important characteristic of EHRs is the sharing of information among systems. However, this requires the resolution of several problems related to functional interoperability [18], which represents the ability of systems to share information with each other. An archetype set involves complex tools for storing, indexing, and sharing information among HISs. Its vast diversity and scope represent one of its primary characteristics, for example, in epidemiological studies, the notification of diseases and reimbursement of health service providers [19,20].

The development of an EHR must consider health criteria because it contains complex information and the requirement of strict confidentiality. These records must also consider the recent reference models. Among the current models most used in the literature, the clinical document architecture (CDA) [21] and virtual medical record (vMR) [22], both developed by Health Level Seven, Inc. (HL7), and the model based on archetypes proposed by the openEHR foundation [23] are noteworthy.

2.1. HL7 CDA: an XML-based electronic pattern for clinical document exchange

The HL7 CDA is an extensible markup language (XML)-based standard that specifies the structure and semantics of clinical documents for information exchange. CDA aims to provide a model for clinical documents such as hospital discharge, clinical history, and transfers, advancing the healthcare industry closer to an EHR accepted by all. The use of XML by the HL7 reference information model (RIM) allows the use of clinical codes such as the systematized nomenclature of medicine — clinical terms (SNOMED CT) and the International Classification of Diseases, Tenth Revision (ICD-10) [24]. Thus, the CDA standard provides documents readable by both computers and users because of the ease of analyzing the content and process the contained information represented by codes. CDA documents can be used by the majority of common Web browsers and wireless devices [25] such as mobile phones.

In [26], for precise information exchange, Khan et al. suggested a data interoperability mediation system for collaboration among HISs compliant with different healthcare patterns. This model stores the semantic information of the different standards using ontology. This work also presented a performance comparison related to the transformation process of medical records between CDA and vMR standards. The conversion process achieved an excellent degree of accuracy between the CDA and vMR standards, improving the global communication process among HISs. Lee et al. discussed issues related to the deployment costs and adoption of interoperable HISs in health organizations [27]. These problems involve mainly difficulties of managing scattered CDA format documents. The authors proposed an open application programming interface (API) service for CDA document generation and integration using cloud computing concepts. This solution represents a low-cost service for hospitals that provides interoperability among HISs and improved information management. Similarly, Wu et al. presented a cloud-based EHR exchange approach using the HL7 CDA standard [28]. This study discussed four scenarios to determine the feasibility and effectiveness of the suggested model. The results demonstrated that the EHR exchange was satisfactory under the studied scenarios. A performance comparison among the proposed EHR-exchanging mechanisms and conventional electronic medical record exchange systems was also conducted. The proposed model presented the best results related to response time.

A model based on the HL7 CDA standard can assist the process of clinical information transfer among different HISs, from the department or place where the first delivery of medical care occurs to the patient's discharge. This characteristic is the main difference from other standards and systems that are more centralized.

2.2. HL7 vMR: a standardized EHR data model designed to support interfaces compatible with SOA for CDSSs

HL7 vMR is an object-oriented data model where there is no dependency on specific classes or tables. This standard enables an abstract representation of the inputs and outputs of clinical information that can be exchanged among the clinical decision support system (CDSS) mechanism and HISs. This reference model represents a standardized interface for heterogeneous EHR systems, allowing access to data structures of different formats with the same code.

Hussain et al. presented an intelligent CDSS that receives data from several sources including health experts, to generate pattern-based personalized recommendations [29]. This work included an interface based on the HL7 vMR standards for submitting data to the clinical system for generating the recommendations. The performance assessment used data from diabetic patients to evaluate the proposal. The system performed the set of syntax rules using a cloud infrastructure, achieving a reasonable performance regarding computational time. Similarly, González-Ferrez and Peleg performed a comparison of several data standards to solve the issue regarding interoperability in knowledge-based DSSs through the integration of several data sources in an EHR [30]. This study identified important criteria to this evaluation using a case-study methodology. The results indicated the main advantages/disadvantages of each approach, concluding that the HL7 vMR standard demonstrated the best conceptual model in an evaluation curve. Among the key characteristics identified in this specification were the ease of use of its query mechanisms and significant support in clinical vocabulary integration. Zhang et al. suggested a framework based on ontology to integrate clinical data, medical knowledge, and rules for patient evaluation regarding diabetes mellitus [31]. This CDSS used automatic selection and adaptation of standard evaluation protocols to assess the patient's clinical conditions. For this research, the authors adopted the SNOMED CT standard for terminology regarding semantic interoperability. As standard schema for syntactic interoperability, this work used the HL7 vMR standard. The results demonstrated that this approach could contribute to an improvement in the integration of medical decision support services related to chronic diseases classification.

2.3. OpenEHR: Integration of heterogeneous HISs using the openEHR reference model and its archetype-based methodology

The changes provided by the openEHR standard have the potential to expedite the information technology (IT) development in healthcare [32]. Its impact affects the rapid evolution and updating of novel EHRs, as well as the development of CDSSs adapted to different clinical guidelines. openEHR represents a set of specifications and open tools. This combination facilitates the development of clinical records in modules according to the necessity and, therefore, is capable of performing operations among them. The primary objective of this open standard is to expand interoperability and computability in e-health systems [33]. The main focus is on enabling the construction of EHR systems that can communicate with each other without content meaning loss, *i.e.*, semantically interoperable systems.

In [34], Pahl et al. discussed the adequacy of the openEHR reference model, its archetypes, and templates for digital representation of obstetric clinical data. Furthermore, this work elaborated a modeling for HISs using the openEHR standard based on a regional level of hospital management into a major logical infrastructure. Results indicate that the openEHR standard represents a suitable tool for complex data processing in healthcare. Demski et al. suggested a model-driven DSS, using standardized clinical information, for the development of interoperable EHR systems [35]. This system considered several schemes for data exchange, automated generation of input forms, and platforms for executing the models directly, based on the openEHR standard usage. The results confirmed that the use of the openEHR standard could assist the development of innovative smart health applications for interoperable SOAs. Ulriksen et al. discussed the developing process of the archetypes as an infrastructure for interoperable EHR systems based on the openEHR standard [36]. This work also presented the main gaps in the infrastructure of a large-scale user-driven standardization focused on healthcare. The results indicated that the development of archetypes represents the backbone for novel EHR implementations.

OpenEHR archetypes provide a significant advantage over HL7 standards because data can be specified understandably for both healthcare and IT professionals. This approach represents an efficient manner of managing data specifications to be shared among HISs. Table 1 presents a comparison between the HL7 and openEHR standards.

3. Use of ontologies for the representation of archetypes in pregnancy care

The approach of this study is based on the dual model architecture. This architecture is based on the ontological separation between the information model, developed by IT professionals, and the knowledge model, built by health experts. The ontology provides the basis for the reference model classes. The reference

Table 1
Comparative analysis of HL7 standards and openEHR archetypes.

Advantages	Disadvantages
HL7 CDA	
· Supports the XML format; · Presents a well-defined reference model e.g., the HL7 RIM; · Uses a coded vocabulary and has a standardized and straightforward structure; · Is sufficiently flexible to be read on any platform and by any application.	· Implies a thorough understanding of RIM for the schematization of the structure; · Overly flexible; · In certain situations can be overly complex; · Information can be encoded in fields other than those that would be expected; · Occurrence of the same information in several fields and/or segments.
HL7 vMR	
· Reduces data and terminology divergencies in CDSSs; · Identifies restrictions that can be made to existing HL7 data models to simplify · CDSSs development; · Allows clinical decision support through a consistent set of standardized data inputs and outputs; · Encourages clinical decision support at the point of care, reducing costs and response time.	· Presents difficulties in representing, abstractions or high-level concepts.
OpenEHR	
· Clinical information can be created and modified at any time; · Allows defining a common knowledge shared by all actors involved in the service process; · Access to data can be controlled; · Allows the use of a knowledge base for automatic processing, such as DSSs; · Allows the definition and control of knowledge in healthcare at the level of concepts.	· Data structures may not have sufficient information to be well represented in an entity; · Challenges in the construction of the graphical interface; · Requirement for a terminology service that does not lose its semantic portability; · Costs for the technical team in the development of templates because there are no free editors.

model is generic and allows raw information registry, without the semantic specification of the particular clinical concepts, which are dynamic to be modeled a priori. The knowledge model is based on archetypes and specifies constraints on the constituent elements of the reference model, i.e., this model represents particular clinical concepts. Archetypes are external, as opposed to the reference model, which is part of the software. The former is expressed as constraints imposed on the information model. The information model is characterized by its stability, containing the semantic base that remains unchanged. Conversely, the knowledge model is susceptible to changes that occur in the application domain. The separation of these models allows future modifications in the HISs, without the requirement for changes in the software code because their construction is based on the information model, resulting in higher interoperability. The openEHR standard is object-oriented and incorporates types of robust data to represent health information and is based on an ontology of concepts represented by archetypes.

Archetypes are key specifications of shareable clinical information necessary for the provision of quality healthcare. These specifications have been formally accepted as standard. Each archetype represents a complete, discrete, and most inclusive specification, always regarding the openEHR reference model. Fig. 1 displays an example of the `openEHR-EHR-EVALUATION.pregnancy_summary.v0` archetype for pregnancy evaluation. The application of several concepts inherent to knowledge organization systems is found in this architecture. Archetypes are classified into several categories such as observation, evaluation, instruction, and action; at the same time, they are hierarchically structured into sections, namely, data, protocol, state, events, and description, forming a clinical information ontology. This archetype includes all the data and information inherent to the clinical pregnancy concept, such as data regarding pregnancy outcome, childbirth onset, and induction method, as well as the pregnant woman's clinical condition. The occurrence of events is registered in this section. The protocol section presents the methods, equipment, and medication. Finally, the description section provides a complete description of the archetype, such as author, date, and function.

Templates are used to group archetypes, defining a clinical or demographic form. From these models, it is possible to develop an input interface for data that can be customized according to the specialty and/or necessity. Fig. 2 presents a detailed clinical model that uses templates for the grouping of archetypes.

Archetypes use ontologies, which are sets of concepts belonging to a specific field of knowledge. Ontologies describe complex information structures that indicate how information is to be expressed, what is mandatory or optional, and what are the sensitive values for each data, while defining usage rules that must be expressed. This work sought the entry archetype development called `CEN-EN13606-ENTRY.HypertensiveDisorders.v1` and its modeling, which contain a cluster object called "List of hypertensive disorder" and another named "Illness". This second object includes two elements, "Hypertensive disorders classification" and "Observations". For this model presentation, this archetype is divided into three sections, namely, header (identification and description), definition, and ontology. Next, the details of the archetype definition language (ADL) code referring to each of these mentioned sections is presented.

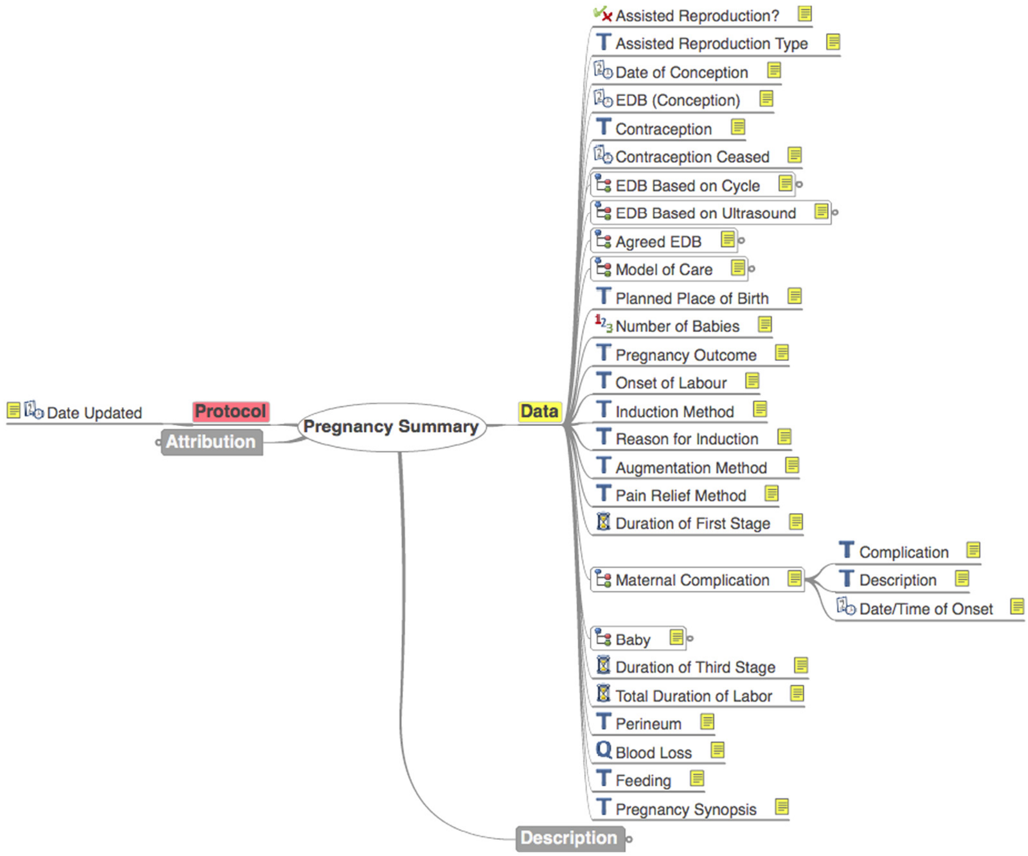

Fig. 1. Mind map representation of pregnancy evaluation archetype.

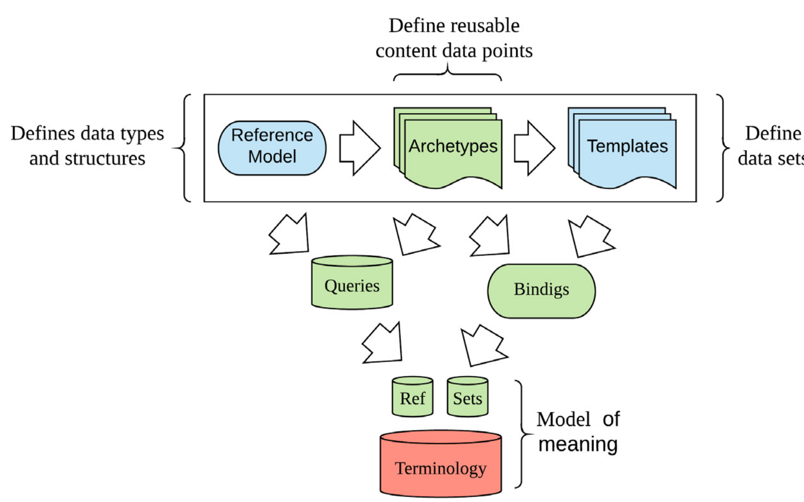

Fig. 2. Structured grouping of archetype sets through templates to originate to a clinical record.

3.1. Header: archetype, concept, language, and description sections

The ADL part of the header refers to the archetype, concept, language, and description sections. This section includes the identification of the archetype, if this archetype was based on another archetype, its original language, authorship information, life cycle, purpose, and intended use. Fig. 3 displays the ADL code corresponding to this part of the code. This structure indicates the subsections of the header. The archetype subsection consists of the code defined in use. The concept defines the central idea represented by the archetype, *i.e.*, every archetype represents a real-world conception. The language indicates the original language and all translations that have occurred in the archetype. This subsection must be written in the ADL data (dADL) language. The description subsection presents information regarding the archetype and what can be used to retrieve it from a repository. This subsection includes author data, archetype status, purpose, and intended use, among other information.

```
Archetype (adl_version=1.4)
    CEN-EN13606-ENTRY.HypertensiveDisorders.v1
concept
    [at0000]
language
    original_language = <[ISO_639-1::en]>
description
    original_author = <
        ["date"] = <"20170927">
        ["name"] = <"Mário W. L. Moreira">
        ["organization"] = <"University of Beira Interior ">
    >
    lifecycle_state = <"Draft">
    details =
        ["en"] = <
            language = <[ISO_639-1::en]>
            purpose = <"This archetype defines the semantics of the data elements of entry Illness.">
            keywords = <"Hypertension">
            copyright = <"Maternity School Assis Chateaubriand">
            use = <"Descriptive archetypes of the central repository - UFC/CE - version 1.0">
        >
    >
```

Fig. 3. First part of ADL code sample.

3.2. Definition: formal constraints of the archetype

In the definition section, this paper presents the main formal constraints of the archetype, written in the ADL constraints (cADL) language. Fig. 4 displays part of the ADL code for this section, explaining the restrictions in cADL code necessary for the formation of the tree structure of the "Illness" archetype, as displayed in Fig. 1.

Each code entry identifies an object. The `ENTRY` object, for example, is identified by `at0000`, at line 25. The assertions `occurrence matches` {1..1} restrict its structure such that it is necessarily present in the generated instances. The `Items` attribute, line 26, represents an association between the `ENTRY` and `ITEM` classes. This is an attribute of the container type. The assertion `existence matches` {0..1} indicates that the `items` attribute, in this case, is optional. The empty case could indicate, in conjunction with other attributes of the reference model, an `ENTRY` exclusion transaction. The assertion `cardinality matches` {1..1} indicates that although the attribute is a container, it cannot receive more than one instance of the `CLUSTER` object. The `ELEMENT` object is defined in line 31 and receives the `at0011` code. At line 33, the `CV` object (`datatype`) is defined as mandatory. At line 34, the `codevalue` attribute is related to the constraint code `ac0001`. This code is defined in the ontology/`constraint_binding` section. The `codingscheme` attribute, line 35, defines the ICD-10 code of the terminology in use. The `codingschemename` attribute, line 36, defines the name of the terminology (in this case, an internal reference to the archetype).

3.3. Ontology section

This section describes, in dADL, the object codes present in the archetype, translations, constraints on terms, and references to terminologies. The ADL language separates the descriptions and terminologies (dADL) from the constraint code (cADL) to facilitate the maintenance of the archetype. Fig. 5 displays part of the ADL code for this section.

The assertive `terminologies_available` defines the terminologies used in the archetype. The assertive `term_definitions` describes all term codes employed in the archetype. The codes are indexed considering the language, in this case `["en"]`, which allows a multilingual archetype. The assertive `constraint_definitions` allows the detailing of all the constraint codes used in the archetype. Although empty in this example, the `term_binding` part is used to define the descriptive terminologies that explain the semantics of the subjective terms utilized in the archetype. Finally, the `constraint_binding` part defines the external terminologies related to each constraint code and the location where they are available.

Addressing the security issue, this study considered the ISO 13606 standard, which presents a basic set of rules that can be used as a minimum access policy specification for an EHR system [37]. This standard presents information structures to exchange an access policy as objects of the `EHR_EXTRACT` class, describing a methodology to specify the level of privilege required to access data from an EHR system, in alignment with the information model. The `EHR_EXTRACT` class is used to represent part or all the information extracted, share data with another system (or repository), and certify the faithful transmission of the data.

The next section describes the performance assessment of the ontological rules used for classification of the data integrated semantically.

4. Performance evaluation and results analysis

This study considered 133 participants diagnosed with a hypertensive disorder during pregnancy. The data were collected during May and September of 2017, after approval of the project by the research ethics committee at the Maternity School Assis Chateaubriand (from the Federal University of Ceará, Fortaleza, CE, Brazil) under the certificate of presentation for ethical appreciation, number 66929317.0.0000.5050, and receiving assent with protocol number 2.036.062.

This work also considered the clinical knowledge manager (CKM) and national health service (NHS) eLearning repositories for the modeling process. Table 2 provides a list of archetypes that

```
Definition
  ENTRY[at0000] occurrences matches {1..1} matches { -- Illness
    items existence matches {0..1} cardinality matches {1..1;
unordered; unique} matches {
      CLUSTER[at0001] occurrences matches {1..1} matches { -- List of
Hypertensive Disorders
        parts existence matches {0..1} cardinality matches {1..*;
unordered; unique} matches {
          CLUSTER[at0004] occurrences matches {1..1} matches { --
Illness
            parts existence matches {0..1} cardinality matches {1..2;
ordered; unique} matches {
              ELEMENT[at0011] occurrences matches {0..1} matches { -
- Hypertensive disorders classification
                value matches {
                  CV[at0023] occurrences matches {1..1} matches { --
CV
                    codeValue matches {[ac0001]}
                    codingscheme matches {"2.16.840.1.113883.13.88"}
                    codingSchemeName matches ["Illness"]
                  }
                }
              }
              ELEMENT[at0014] occurrences matches {0..1} matches { -
- Observations
                value matches {
                  SIMPLE_TEXT[at0024] occurrences matches {1..1}
matches { -- SIMPLE_TEXT
```

Fig. 4. Second part of ADL code sample.

```
Ontology
  terminologies_available = <"ILLNESS", ...>
  term_definitions = <
    ["en "] = <
      items = <
        ["at0000"] = <
          text = <"Illness">
          description = <"Illness">
…
    constraint_definitions = <
      ["en"] = <
        items = <
          ["ac0001"] = <
            text = <"Hypertensive disorders classification of UFC/CE">
            description = <"Hypertensive disorders classification
referring to version 1.0 of the B-EHR. September 2017">
          >
        >
      >
    >
    term_binding = <
    >
    constraint_binding = <
      ["Illness"] = <
        items = <
      ["ac0001"] =
<http://termiologies.EBSERH.ufc.br/hypertdisordersMSBRA.xml>
        >
```

Fig. 5. Third part of ADL code sample.

specify the medical concepts involved in the hypertensive disorders expertise. These archetypes are divided into four classes, Composition, Section, Entry.Evaluation, and Entry.Observation. Some of these archetypes were reused directly, with minimal or no change; others were extended or specialized. Thus, the development of archetypes was required to complete the diagnosis process of

Table 2
List of archetypes used to specify hypertensive disorder concepts.

Classes	Archetypes	Type of use
Composition	Encounter	Reuse
	Problem_list	Reuse
	Report	Extension
	History	Specialization
Section	Conclusion	Reuse
	Diagnostic_report	Extension
	Simple_object_access_protocol	Extension
	Physical_exam	Specialization
	Family_history	Extension
Entry.Evaluation	Pregnancy	Extension
	Problem_diagnosis	Extension
	Checklist_condition_history	Specialization
Entry.Observation	Body_weight	Reuse
	Global_assessment	Extension
	Notification	Extension
	Patient_record_notes	Specialization
	Blood_pressure	Reuse
	Urine_protein_loss	Specialization
	Hemolysis	Extension
	Elevation_of_liver_enzymes	Specialization
	Thrombocytopenia	Specialization
	Edema	Specialization
	Hyperreflexia	Specialization
	Headache	Extension
	Epigastric_pain	Specialization
	Nausea_vomiting	Specialization
	Vision_blurring	Specialization
	Dizziness	Specialization
	Oliguria	Specialization

hypertensive disorder in pregnancy. The achieved result presented a high degree of EHR interoperability.

The ontology used in this model was created under the open-source ontology editor and framework Protégé. This ontology is a formulation in the Web language ontology (OWL) of the well-known international classification of diseases, ICD-10. Table 3 presents the main hypertensive disorders in pregnancy and their description according to the ICD-10 medical coding reference.

Table 4
Evaluation results of the proposed method, using the performance indicators obtained through the confusion matrix, for the classes related to hypertensive disorders in pregnancy according to the ICD-10 codes.

Precision	Recall	F-measure	Class
1.000	0.600	0.750	O10
0.880	0.846	0.863	O11
0.000	0.000	0.000	O12
0.739	0.944	0.829	O13
1.000	0.375	0.545	O14.0
0.844	0.982	0.908	O14.1
1.000	0.714	0.833	O14.2
0.714	0.714	0.714	O15
0.000	0.000	0.000	O16
0.847	**0.842**	**0.827**	**Weighted Avg.**

The performance evaluation employed a confusion matrix, which is widely used in the assessment of classification models [38,39]. The confusion matrix of a hypothesis provides an effective measure of the classification model by proving the number of correct classifications versus the classifications predicted for each class over a set of examples. The elements that form this matrix are true positives (TP), *i.e.*, the pregnant woman has a certain hypertensive disorder, and the model correctly classifies it; and true negatives (TN), where the pregnant woman does not present a certain hypertensive disorder and the model classifies it correctly as negative. In false positives (FP), also known as false alarms, the patient does not present a certain hypertensive disorder; however, the ontological model classifies it as positive for this gestational complication. In false negatives (FN), the input case is positive, that is, the pregnant woman suffers from a certain disease; however, the system incorrectly classifies this condition. Table 4 presents the result for the confusion matrix of the model proposed in this work.

Precision represents the number of cases classified as belonging to a determining class, which truly are of that class (TP), divided by the sum of this number and the number of examples classified in this class, yet belonging to others (FP). Recall represents the number of cases classified as belonging to a determining class,

Table 3
Hypertensive disorders related to pregnancy, childbirth, and puerperium, according to the international statistical classification of diseases and related health problems (ICD-10).

Code	Hypertensive disease related to pregnancy, childbirth, and puerperium	Observations
O10	Pre-existing hypertension complicating pregnancy, childbirth, and puerperium	Incl.: the listed conditions with pre-existing proteinuria Excl.: those with increased or superimposed proteinuria (O11)
O11	Pre-existing hypertensive disorder with superimposed proteinuria	Incl.: Conditions in O10 - complicated by increased proteinuria Superimposed pre-eclampsia
O12	Gestational [pregnancy-induced] edema and proteinuria without hypertension	
O13	Gestational [pregnancy-induced] hypertension without significant proteinuria	Incl.: Gestational hypertension Mild pre-eclampsia
O14	Gestational [pregnancy-induced] hypertension with significant proteinuria	Excl.: superimposed pre-eclampsia (O11) O14.0 Moderate pre-eclampsia O14.1 Severe pre-eclampsia O14.2 HELLP syndrome O14.9 Preeclampsia, unspecified
O15	Eclampsia	Incl.: convulsions following conditions in O10-O14 and O16 eclampsia with pregnancy-induced or pre-existing hypertension
O16	Unspecified maternal hypertension	

Table 5
ROC area for classes related to hypertensive disorders in pregnancy according to the ICD-10 codes.

TP rate	FP rate	ROC area	Class
0.600	0.000	0.960	O10
0.846	0.028	0.863	O11
0.000	0.000	–	O12
0.944	0.052	0.973	O13
0.375	0.000	0.948	O14.0
0.982	0.128	0.966	O14.1
0.714	0.016	0.976	O15
0.714	0.000	0.992	O14.2
0.000	0.000	0.931	O16
0.847	**0.066**	**0.968**	**Weighted Avg.**

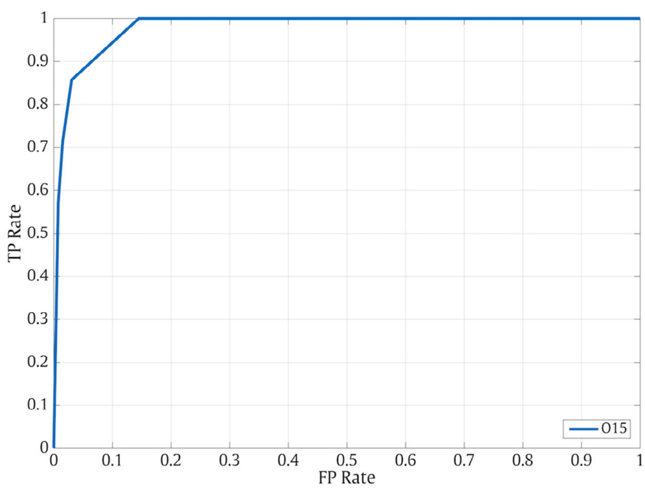

Fig. 6. ROC curve for O15 class, which is related to the hypertensive disease in pregnancy that causes the majority of deaths worldwide, *i.e.*, the eclampsia.

which truly belong to that class, divided by the total number of cases belonging to this class, even if they are classified into another class, *i.e.*, TP divided by total positives. The *F*-measure is a harmonic average between precision and recall. Eqs. (1), (2), and (3) present the mathematical model for these metrics.

$$Precision = \frac{TP}{TP + FP} \quad (1)$$

$$Recall = \frac{TP}{TP + FN} \quad (2)$$

$$F\text{-}Measure = 2 \times \frac{Recall \times Precision}{Recall + Precision} \quad (3)$$

The area under the receiver operating characteristic (ROC) curve is an interesting metric for tasks with disproportionate classes. In this indicator, the area under a curve (AUC) formed by the graph is calculated between the TP rate and the FP rate. The main advantage concerning the *F*-measure indicator is that the ROC curve measures the model performance at different cut-off points, not necessarily assigning examples with probability greater than 50% for the positive class, and lower for the negative class. Table 5 presents the results for this indicator.

Fig. 6 displays the ROC curve for the O15 class, *i.e.*, eclampsia, which is responsible for the majority of maternal deaths worldwide. The ROC curve permits evaluation of classification models for which there is more significant optimization of sensitivity (TP rate) as a function of the specificity (TN rate), that corresponds to the point where it is closest to the diagram upper left corner because the TP rate is one and the FP rate is zero.

Table 6
Performance comparison among recent similar works related to pregnancy care.

	Method	TPR	FPR	Prec.
Moreira et al.	Ontology	0.842	0.066	0.847
Paydar et al. [40]	RBF	0.533	0.206	0.714
	MLP	0.800	**0.059**	**0.909**
Pereira et al. [41]	GLM	**0.890**	0.709	0.586
	SVM	0.856	0.721	0.621
	DT	0.883	0.200	0.839
	NB	0.843	0.370	0.747

To demonstrate the feasibility of the proposed semantic model, Table 6 compares similar approaches, used recently in the literature for pregnancy care, using the metrics of the confusion matrix.

The performance evaluation indicates that, concerning classification, the proposed ontology-based model is equivalent to algorithms based on artificial neural networks (ANNs), *e.g.*, radial basis function (RBF) network, multilayer perceptron (MLP), and support vector machine (SVM). The approach proposed in this work also presented accuracy close to decision tree-based algorithms, *e.g.*, decision tree (DT) and statistically based models, *e.g.*, the naïve Bayes (NB) classifier. Thus, regarding the use of rules and constraints, using the OWL language in the Protégé framework, it is possible to classify the hypertensive disorders of pregnancy correctly through information clustering.

5. Conclusion and future work

An SOA is based on a conjunction of services that communicate with each other, transmitting valuable information. This architecture can be involved in the cooperation of several activities, anywhere and anytime. However, an SOA implementation can consist of a combination of different technologies including resources, applications, and platforms. This combination presents a series of challenges to be solved, with the interoperability, at the technical level and the semantic and syntactic levels, representing the main issue.

Interoperability represents innovation and progress in healthcare, and its users increasingly perceive its benefits; these are essential to attain excellence in the use of this technology, to offer the best possible services to the patient, generating lower costs for institutions. Several standards for reference models of health information and for the exchange of information among EHR systems have been established in the international scenario. Among these, the openEHR standard is noteworthy. The use of standards to ensure the semantic interoperability of EHRs is not a trivial issue. The challenge that remains is to broaden the research community to build a library of archetypes capable of identifying patterns to improve the medical care. Today, knowledge combined to define patterns at the ideal level of granularity, specificity, quality, and to classify these for broad adoption, represents the leading challenge.

In this regard, this work sought a solution based on the development and integration of archetypes necessary to solve the problems related to semantic interoperability among EHRs. The second contribution of this research was to use rules based on ontology for pattern classification from data acquired in the previous stage. The results confirmed that the proposed semantic model was efficient for the acquisition and classification of data on hypertensive disorders of pregnancy. As a proof-of-concept, this research strongly suggested that recent state-of-the-art approaches based on openEHR data representation are not sufficient for representing all pregnancy-related data. Therefore, this paper extended the openEHR through new gestational related data and also complemented those previously developed. Moreover, this novel study developed different archetypes, which represents a contrasting view to studies published by other research groups related to pregnancy care [34]. Thus, the conventional archetypes were adequate for this study through domain-specific modifications.

Obstetric/gynecologist physicians from the health unit of the Maternity School Assis Chateaubriand and information-modeling experts assessed the content of the archetypes used to represent the information contained in the forms provided by this health unit. The CKM collaborative system provided some of the archetypes to represent part of specific data. All archetypes and templates presented the requirements for the pregnancy data modeling. Regarding technical semantic and syntactic interoperability requirements, this study used the ADL Workbench and CKM application through multiple iterations of the review process. This study used the LinkEHR-Ed Archetype Editor for modification of the archetypes. This graphical application developed the syntactically correct ADL code automatically. This study also developed technical approaches to associate archetypes using the International Classification of Diseases and health-related problems, ICD-10. The second part of this study resulted in a single template, equivalent to a single broad archetype, built through the semantic data capture, presenting an associated generic XML schema. The semantic rules were developed in OWL language as part of the ontology where they were created. Regarding classification, the rules and their parts were represented internally by the Protégé framework as individuals belonging to one or more classes and having properties that relate them to each other.

Further work would involve using other types of standards to acquire data semantically. This work strongly supports the development of more archetypes aimed at the care of pregnant women. Developing an SOA that can be accessible in remote locations is also a challenge to be addressed. Other approaches to classifying and clustering data also require further study.

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