ON THE SEMANTIC ISSUES OF ELECTRONIC HEALTH RECORDS FOR VIRTUAL PHYSIOLOGICAL HUMAN INFRASTRUCTURES

Milan Zdravković[1], Miroslav Trajanović[1]
[1]***Faculty of Mechanical Engineering, University of Niš***

Abstract *- In this position paper[1], we discuss about the semantic issues of the existing formal or non-formal models of Electronic Health Records (EHR). The discussion synthesizes the relevant conclusions from the literature, related to the expanded scope of EHR, namely, its use in cross-boundary medical workflows and diagnosis, prediction and treatment of diseases, in the context of its integration with Virtual Physiological Human (VPH) models. Based on this discussion, we propose the guidelines for the development of the corresponding semantic infrastructure.*

1. INTRODUCTION

The current state of the implementation of Electronic Health Records (EHR) is often characterized by the proprietary, vendor-specific formats or at least, a low level of adoption of existing medical vocabularies. Moreover, it seems that EHR focuses exclusively on improving the efficiency of the medical workflow, while the potential of usage of its data sets in the diagnosis and treatment processes is underrated by the vendors. One of the reasons for this may be the lack of the large knowledge bases and associated computational tools for decision support in above processes. These databases and tools will be provided by the Virtual Physiological Human (VPH) infrastructures.

Current fragmentation of health science and medical care along traditional boundaries is considered [1] as artificial and inefficient with respect to many scientific hypotheses that establish the correspondences between the concepts from the different disciplines. This fragmentation occurs in the contemporary patient management which is often inefficient due to very few bridges between the clinical specialties (such as cardiology, neurology, etc.). It can be considered at modeling level, where reductionist approach (modeling on a particular dimensional scale, such as organ, tissue, cellular and molecular) dominates over the systemic one [2]. The fragmentation is also evident in academia where inter-disciplinary research is often under-rewarded comparing to efforts within the particular scientific disciplines (such as biology, physiology, molecular biology, bio-engineering). It is argued [1] that a more effective approach must be applied. It is foreseen that this approach will integrate the different relevant areas according to the focus of the particular problem, unconstrained by scientific discipline, anatomical subsystem and temporal or dimensional scale [3], with ultimate challenge to understand human biological function [1].

The VPH [1] is intended to provide a unifying framework that enables and practically benefits from the integration of inter-disciplinary data (multi-scale models, from molecule to organ systems) and observations about human's biology. These observations may be collected, organized and shared across the laboratories and hospitals, so that clinical and non-clinical experts can collaboratively interpret, model, validate and understand the data. Thus, the unifying framework is expected to facilitate: 1) integration of physiological processes across different length and time scales; 2) integration of descriptive data with predictive models; and 3) integration across disciplines [4]. Then, this integration will eventually lead to the practical benefits of the future healthcare system: 1) personalized care solutions; 2) reduced need for experiments on animals; 3) more holistic approach to medicine; and 4) preventative approach to treatment of disease [4]. The impact of the VPH on industry will first be felt in the medical device and pharmaceutical industries, but in time will inevitably spread beyond these key areas [1].

VPH resembles of multi-scale, multi-disciplinary computer models of a human and data processing tools for predictive and preventative treatment of disease. One of the main issues of VPH is establishment of the logical correspondences (based on the scientific hypotheses) between all these models so that a holistic perspective to the treatment of diseases can be achieved. However, the correspondences between VPH multi-scale models and EHR data must also exist in order to become possible to assess the patient-specific data against the common medical knowledge and make accurate diagnostic and treatment decisions in specific cases. Accurate and complete mapping between the concepts of different knowledge domains, models and data formats will facilitate the semantic interoperability of the systems that are using them and, consequently, their integrated processing.

In this paper, we discuss the issues of using the existing, common formal medical knowledge for expansion of de-facto current scope of EHR. Expansion of scope is directed towards EHR's use in cross-boundary medical workflows and its use in diagnosis, prediction and treatment of diseases (in the context of integration with VPH models infrastructures). This discussion focuses on the semantic issues of the relevant models from the literature, technical and research reports and industry

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experiences. Thus, it involves relevant domain ontologies, as well as common conceptualizations, used by the relevant EHR standards.

2. ELECTRONIC HEALTH RECORDS (EHR)

Health Information Management Systems Society's defines EHR as follows: "The Electronic Health Record (EHR) is a longitudinal electronic record of patient health information generated by one or more encounters in any care delivery setting. Included in this information are patient demographics, progress notes, problems, medications, vital signs, past medical history, immunizations, laboratory data, and radiology reports."

Many benefits from maintaining EHR are expected, such as automation and streamlining of the clinical workflow, evidence-based decision support for diagnosis or treatment prescription (based on accurate and complete record of a clinical patient encounter), support to other care-related activities such as billing, reporting and quality management. An EHR enables the hospital administrator to extract the billing data, the physician to assess the effectiveness of treatments, a nurse to report a reaction, and a researcher to analyze the efficiency of medications.

One of the main issues of EHR is the fact that it is not a record of all care provided to the patient in all facilities over time. It is generated and maintained within the single medical centre. Even so, one of the greatest challenges of maintaining EHR arises from the collaborative effort in collection and analysis of its data. Medical centers can be considered as complex enterprises. They typically consist of multiple healthcare facilities, such as affiliated hospitals and clinics, diagnostic and treatment centers and laboratories. Managing all of these departments implies the complex business processes, for which EHR is fully associated.

2.1. Components of EHR

In a way, EHR is the patient specific representation of a clinical workflow, combined with information (from the observations) collected in the course of this workflow. It typically connects administrative data with information from the relevant health information systems.

Registration, admissions, discharge, and transfer (RADT) data are the key components of EHRs. These data include vital information for accurate patient identification and assessment, such as name, demographics, employer information, etc. The registration portion of an EHR contains a patient identifier (Master Patient Index - MPI), which is identifiable only inside the organization in which the EHR is maintained. RADT data allows an individual's health information to be aggregated for use in clinical analysis and research.

An EHR can be considered as patient specific RADT data, integrated with respective information from Laboratory Information Systems, Radiology Information Systems, Electronic clinical documentation systems and pharmacy systems. This integration is carried out by computerized physician order entries (CPOE) which permit clinical providers to electronically order laboratory, pharmacy, and radiology services.

Laboratory Information Systems (LIS) are used to integrate orders, results from laboratory instruments (automatically, via interface), schedules, billing, and other administrative information. Radiology information systems (RIS) are used by radiology departments to integrate patient radiology data (e.g., orders, interpretations, patient identification information) and images. The typical RIS will include patient tracking, scheduling, results reporting, and image tracking functions. RIS systems are usually used in conjunction with picture archiving communications systems (PACS), which manage digital radiography studies. Electronic clinical documentation systems provide electronic capture of clinical notes; patient assessments; and clinical reports, such as medication administration records (MAR).

2.2. Standards for EHR integration

Today's EHR records often suffer from the vendor-specific realizations of patient record data sets which rarely accommodate to the controlled terminologies [5]. Obviously, the vendor dependence provides more compelling business case than the systems integration (the benefit of the standards adoption). However, the inefficiency of the clinical workflows which extend beyond the boundaries of a single medical centre is establishing EHR interoperability as one of the main requirements for health information systems.

To create interoperable EHRs, standards are needed for:

1) Clinical vocabularies, because their use decreases the risk from terminology inconsistencies which occur when data is captured at the point of care;
2) Healthcare message exchanges, to ensure correct and complete interpretation of the message content, by the interoperating systems;
3) EHR formal representations, as specifications of the correlations and correspondences, between the entities from vocabularies and messages.

Clinical vocabularies play a strategic role in providing access to computerized health information because clinicians use a variety of terms for the same concept. When a clinician evaluates a patient, the resulting documentation typically captures free text and unstructured information, such as history and physical findings. The efficiency of payment (reimbursement) processing is probably the key incentive for transforming this free text into more structured data. Some of the most commonly used clinical vocabularies today are LOINC, SNOMED and ICD.

Logical Observation Identifiers, Names and Codes (LOINC) for ordering lab tests and Systematized Nomenclature of Medicine - Clinical Terms (SNOMED-CT) for recording test results provide well-defined meanings for specific terms that can be standardized across applications. Logical Observation Identifiers, Names, and Codes (LOINC) is used to identify individual laboratory results, clinical and diagnostic study observations. It is most widely used in laboratory systems. Systematized Nomenclature of Medicine (SNOMED) is designed to be a comprehensive, multi-axial, controlled terminology, created for the indexing of the entire medical record. International Classification of Diseases (ICD) is published by the World Health Organization (WHO). It is primarily used to code data for billing purposes to identify the disease or problem for which the patient was treated.

There are three main organizations that develop and maintain standards related to EHR messages: Health Level Seven (HL7), Comite Europeen de Normalization – Technical Committee (CEN TC) 215, and the American Society for Testing and Materials (ASTM) E31. HL7 develops the most widely used healthcare-related electronic data exchange standards in North America. CEN TC 215 is the preeminent healthcare IT standards developing organization in Europe. Both HL7 and CEN collaborate with the ASTM, which is mainly used by the commercial laboratory vendors. Recently, the research community interest was brought to the OpenEHR open standard specification in health informatics. In contrast to HL7 and CEN's EN 13606 standards, which are strictly concerned with exchange of data between EHR systems, OpenEHR describes management and storage, retrieval and exchange of health data from EHRs.

3. DISCUSSION

The use of different standards affects the heterogeneity of the clinical information systems, which are using EHRs based on these standards. This heterogeneity is even increased when the growth of proprietary, vendor dependant, custom EHRs is considered. Direct mapping of the different standards in their native forms is not sustainable because of significantly decreased scalability of such mappings, namely, because of needed high maintenance efforts.

The clinical vocabularies and healthcare messaging standards are mature and widely used in a clinical practice. However, the lack of models which establish correlations between those two is evident. This lack does not affect significantly the main purpose of EHR records, that is, support to clinical workflows, mainly related to administration of the medical data. However, it is considered as one of the main barriers for extended use of EHR records in diagnosis and treatment.

The description above may be generalized to the common problems of the systems interoperability: 1) there is a need to make two or more different representations of the same reality, equivalent or same, so identical conclusions can be drawn (computed) by using each of these representations. Or, 2) different representations of the different realities may be interrelated, so extended conclusions about the world can be made (computed) from within a single reality. Today, this kind of problems is being resolved by using ontologies.

3.1 Ontologies

The notion of ontology comes from the domain of philosophy. Angeles [6] defines the ontology as "that branch of philosophy which deals with the order and structure of reality in the broadest sense possible". Bateman [7] argues that "the general programme of ontology relies on it being possible to uncover properties that could not fail to be as they are for the world to exist". Guarino [8] is more specific and defines philosophical ontology as "the study of organization and the nature of the world independently of the form of our knowledge about it". This definition separates ontology from epistemology and hence implies independence among those two.

In computer science, ontology is considered [9] as a (partial) specification of the semantic structure which is defined by the conceptualization process. It is a logical theory that explicitly expresses the conceptualization in some language. Thus, ontology is a specification used for making ontological commitments, where this commitment is an agreement to use a vocabulary (i.e., ask queries and make assertions) in a way that is consistent (but not necessarily complete) with respect to the theory specified by an ontology. Different specifications may be used to implement one conceptualization.

The ontology is increasingly used to reconcile multiple representations of reality (data, processes, etc.) stored inside the systems, or actual representations and reality itself – systems' users and their perception of reality [10]. Hence, it facilitates not only interoperation or information exchange, but also correct and complete (in cases where interoperability requirements are defined at the level of concept) reasoning on the meaning of the information which is exchanged between two systems.

3.2. On the semantic issues of EHR for VPH infrastructures

Based on the review of the relevant literature, the following key semantic issues of EHR, in context of their use in VPH infrastructure, are identified:

1) Detachment of messaging standards from vocabularies;
2) Inconsistent approaches to conceptualization;
3) Performance of semantic reasoning;
4) Completeness and accuracy of the semantic models.

Practical benefits of VPH multi-scale infrastructures occur in the biomedical and clinical workflows, where individual patient data (encoded in EHR) is linked (on demand) with VPH knowledge infrastructure or, in specific with the vocabularies. Then, the computational tools are used to infer the diagnosis, treatment or prediction of disease development. There is a clear need to uniquely identify and link all VPH components [1], including ontologies dealing with anatomy, physiology and molecular/cellular biology, as well as EHR models.

One of the key issues of the current state of the art is that terminologies are not bound to messaging and EHR standards. Rector et al [11] used ontology (of conditions) to bind HL7 messages to SNOMED-CT codes. However, the semantic reconciliation of HL7 and SNOMED-CT is still an ongoing effort and thus, semantic interoperability between the respective systems which are using the above standard is still an issue. For example, while HL7 treats birth date of the patient as "observation", SNOMED-CT is considering it as a "demographic attribute of a person". A special project of HL7 initiative is continuously working on resolving the issues related to the interface between HL7 information models and terminologies (SNOMED-CT).

The variety and diversity of already used medical ontologies, developed with different conceptualization approaches makes the possible mappings between these ontologies very difficult. Two approaches in their development can be identified as: 1) bottom-up formalization of the vocabularies or standards; 2) semantic analysis of the clinical care process and development of facilitating ontologies. The first approach is dominant in the research community. Driven by the specific problem or need for specific competence, research community developed a significant number of biomedical ontologies, with coverage of different standards, sub-domains, scientific disciplines, etc. Many of these ontologies are hosted at BioPortal, a web repository for biomedical ontologies and data resources [12]. In addition to hosting ontologies, BioPortal is also used for defining relationships among these, as well as between the ontologies and hosted online data resources, for evaluation and evolution, etc.

In contrast to using the reference models, coding systems and clinical or scientific domains as a basis, Beale and Heard [13] argue that the starting point of a successful model must be an ontological analysis of the process of clinical care delivery. This kind of analysis is considered as bottom-up approach to ontology development. It includes induction of the main concepts of clinical care delivery (typically, specialized terms, sometimes even implicit) and then, a synthesis of the aggregates. CIR Ontology [13] is developed on the basis of semantic analysis of information recorded during healthcare process and is used for OpenEHR information model design. CIR identifies five main types of information: observation, opinion (inferences of the investigator based on observations), instruction (directly executable by investigator), action (meaning, a record of actions that have occurred) and administrative event (a record of business event, such as admission, booking, discharge, etc.).

EHR reference models define the high-level logical models for any kind of EHR and hereby enable syntactic interoperability. Archetypes, a concept integrated in most of the before-mentioned standards (HL7 uses the synonym "templates"), provide a fundamental means of semantic indexing of the structural organization of EHRs. They build a logical interface for richer systems of concepts, such as ontologies. An EHR archetype is an agreed, formal and interoperable specification of the data and their interrelationships that must or may be logically persisted within an electronic health record for documenting a particular clinical observation, evaluation, instruction or action [14]. An openEHR/EN 13606 archetype represents this specification as a set of constraints, expressed in a standardized form, for instantiating a particular EHR Reference Model. Hence, a two-level modeling approach is implemented, where a reference model and its specializations (through archetypes) are clearly distinguished. The reference model consists of a core representation which is assumed to be stable over time and across organizations, while archetypes are used to build representations for which this is not the case.

Inconsistency of the conceptualization approaches in development of medical ontologies, mostly due to the fragmentation of the research efforts is not necessarily the weakness. Bottom-up approaches and narrow scopes are characterized by the decreased development time and thus, they contribute to the commoditization of the semantic technologies in a medical sector. The resulting difficulties of integrating such ontologies (caused by the implicitness) can be resolved by using upper ontologies. Schulz et al [15] addressed logical and ontological issues of SNOMED. They re-arranged its upper levels according to standard upper ontology (BFO, Dolce) and proposed other modifications which are implemented in ontology, developed by using Description Logics. Furthermore, the well-known Ontology of Biomedical reality [16] is, in fact developed as a result of the process of vertical integration of upper ontology (Basic Formal Ontology - BFO) and domain ontology (FMA).

Besides the representational requirements (e.g. scalability, maintainability, etc.), when EHR ontology is developed, it is very important to take into account also run-time requirements, because of the large amount of involved data and corresponding computational complexity. Partionining of ontologies (using modular design) can help with regard to this matter [17]. In this case, relevant reasoning can include only relevant ontologies. Rector et al [11] are advocating decoupling of the coding system from the model of meaning, so that reasoning about the model of meaning and model of coding system is always separated. The first and obvious argument for such an approach is the performance issue of the computational infrastructure (medical ontologies are typically extremely large data sets). In the second argument, since existing coding systems and information models contain many errors, this decoupling allows developers to compensate for these failings without compromising the underlying models. This division corresponds to distinguishing between so-called ontologies of reality and ontologies of information. As information is a part of reality, this division should be considered very carefully, especially in correlating what is recorded in a process of medical care (information) to a meaning (type, structure and properties) of the recorded information. Obviously, the semantic issues of conceptualization approaches are tightly related to the performance of reasoning.

The prediction challenges of VPH directly depend on the completeness and accuracy of the correspondences between different relevant models at different scales and in different disciplines. Obviously, they are indirectly related to the quality and accuracy of these models. For example, much of the biological data has its origins in instruments/models that introduce their own assumptions and artifacts into the data. In addition, the interpretation of data (the characterization of normal and pathological behaviors) is patient-specific. Both arguments have a significant impact on the approach to modeling of VPH knowledge. The greatest legal challenge of VPH relates to patient ownership of clinical data. For this reason, sometimes semantic reasoning is based on the incomplete data. The way of VPH data processing raises many legal and ethical issues. Some of the identified circumstances are moving medical data out of the medical networks or even around the computing grid (during simulation or analysis). The legal challenges imply the need for setting an approach to data anonymization. This must be taken into account in the respective knowledge modeling process.

3.3. Semantic EHR-based frameworks for VPH infrastructures

Even if all semantic issues of the underlying semantic framework are resolved, this framework can be used only within the unifying infrastructure that collates, classifies, integrates and ultimately leverages different modeling efforts (and corresponding heterogeneous data) and standards [18]. This infrastructure must be neutral of the conceptualization level or approach, modularity approach, even of the level of completeness or accuracy. In other words, the scalability and flexibility of such an infrastructure must be such to consider the vast diversity and variety of the current and future biomedical and functional (e.g. clinical workflow) ontologies. Fig. 1 illustrates the proposed approach to development of such an infrastructure with an example. The development approach follows the principles below. The approach is based on the previously developed method for making two information systems semantically interoperable [19]. Semantic applications (e.g. $SemApp_1$, $SemApp_2$) that exploit the ontological framework are developed for reasoning about the specific problem. They can infer the relevant facts or facilitate assertion of the new facts to the knowledge framework (through interaction with human).

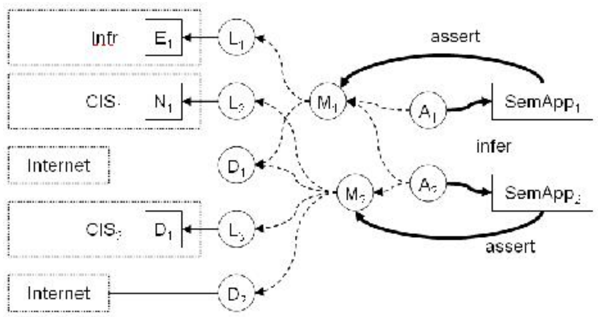

Fig.1. Illustrative example of the VPH infrastructure

The problem is formalized by using the application or problem ontologies (A_1, A_2). These ontologies are developed: 1) on basis of the desired competency (of semantic applications) and; 2) by using the relevant knowledge from imported mapping ontologies. In a way, mapping ontologies (M_1, M_2) synthesize needed (where this need is related to the assumed competence of the application ontologies) knowledge by importing the domain and local ontologies and by storing the logical correspondences between their concepts. These concepts may be explicit definitions in the domain ontologies (e.g. D_1, D_2) or in the local ontologies (L_1,L_2,L_3), as implicit representations of the terms from the relevant standards, e.g. EHR (E_1), CIS databases (D_1) and native files (N_1).

4. CONCLUSIONS

Not only that linking messaging standards to vocabularies, or more complex domain theories is expected to have the most profound impact on the development of the semantic reasoning platforms for VPH; it will also contribute to resolution of all remaining semantic issues of EHR for VPH infrastructures. First, establishment of the logical correspondences between the relevant ontologies makes the conceptualization approach and detail irrelevant, as it extends the semantic environment to needed application domains. Second, it affirms the modular approach and thus, it creates the opportunities for modular and partial reasoning, hereby addressing performance issues. Third, by involving multiple ontologies, it contributes to completeness of reasoning and increases the validation opportunities. Approach to the linking is not considered as important. Whether upper ontologies or approaches of direct logical correspondences between the concepts from the mapped ontologies are used, as long as these correspondences are accurate and complete, the reasoning will be accurate and complete, which is indeed the bottom line.

When the infrastructure for realizing the VPH infrastructure is considered, the key challenge in further development of the framework are mapping ontologies. In the near future, it is our opinion that the research work in making existing biomedical ontologies correspondent is of crucial importance. This expectation is based on the assumption that diversity and variety of the biomedical ontologies will continue to grow, both in the horizontal and vertical direction. While horizontal direction spans scientific and clinical domains and functional perspective (e.g. clinical workflow), the vertical one diversifies levels of conceptualization or explicitness. Thus, it classifies implicit, local and application (problem) ontologies on one hand and explicit, domain ontologies, on another. All these ontologies, especially mapping ones, which interrelate their concepts are considered as a bridge between conventional clinical information systems, which are used to collect and maintain this information and semantic applications, which will be used to infer about this information. The semantic applications will be developed on a basis of a very specific problem (such as diagnosis or treatment suggestion, in specific cases), but they will be enabled to use whole ontological framework for achieving their competence.

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