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An interoperable clinical decision-support system for early detection of SIRS in pediatric intensive care using openEHR

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ABSTRACT

Background: Clinical decision-support systems (CDSS) are designed to solve knowledge-intensive tasks for supporting decision-making processes. Although many approaches for designing CDSS have been proposed, due to high implementation costs, as well as the lack of interoperability features, current solutions are not well-established across different institutions. Recently, the use of standardized formalisms for knowledge representation as terminologies as well as the integration of semantically enriched clinical information models, as openEHR Archetypes, and their reuse within CDSS are theoretically considered as key factors for reusable CDSS.
Objective: We aim at developing and evaluating an openEHR based approach to achieve interoperability in CDSS by designing and implementing an exemplary system for automated systemic inflammatory response syndrome (SIRS) detection in pediatric intensive care.
Methods: We designed an interoperable concept, which enables an easy integration of the CDSS across different institutions, by using openEHR Archetypes, terminology bindings and the Archetype Query Language (AQL). The practicability of the approach was tested by (1) implementing a prototype, which is based on an openEHR based data repository of the Hannover Medical School (HaMSTR), and (2) conducting a first pilot study.
Results: We successfully designed and implemented a CDSS with interoperable knowledge bases and interfaces by reusing internationally agreed-upon Archetypes, incorporating LOINC terminology and creating AQL queries, which allowed retrieving dynamic facts in a standardized and unambiguous form. The technical capabilities of the system were evaluated by testing the prototype on 16 randomly selected patients with 129 days of stay, and comparing the results with the assessment of clinical experts (leading to a sensitivity of 1.00, a specificity of 0.94 and a Cohen's kappa of 0.92).
Conclusions: We found the use of openEHR Archetypes and AQL a feasible approach to bridge the interoperability gap between local infrastructures and CDSS. The designed concept was successfully transferred into a clinically evaluated openEHR based CDSS. To the authors' knowledge, this is the first openEHR based CDSS, which is technically reliable and capable in a real context, and facilitates clinical decision-support for a complex task. Further activities will comprise enrichments of the knowledge base, the reasoning processes and cross-institutional evaluations.

1. Introduction

1.1. Knowledge-based systems for clinical decision-support

Medical practice is characterized by a wide variety of different, complex decision-making problems that have to be solved by medical staff continuously throughout their clinical routine ("*medical practice is medical decision-making*" [1]). The quality of decision-making highly depends on the availability of a broad knowledge-base, which comprises domain, explicit, factual and tacit knowledge. A medical expert is able to handle the complexity of these knowledge-intensive tasks. However, clinical routine includes a high pressure of time, a high amount of parallel tasks and many interruptions. This can lead to healthcare decisions with a lower quality than aspired [2,3]. Besides, the implicit knowledge of an expert is personally bound and not accessible permanently [3].

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Clinical Decision-Support Systems (CDSS) are described as *"(…) any computer program designed to help healthcare professionals to make clinical decisions"* [1]. They are often referred to as a key element to enhance patient safety and quality of care [4,5]. By processing, analyzing, summarizing and representing crucial information, medical staff can be supported. This can lead to better informed healthcare decisions [3]. CDSS can be designed as *knowledge-based systems,* which represent the expertise, knowledge and inference procedures a human expert applies while dealing with knowledge-intensive decision tasks [1,6]. Knowledge-based systems are characterized by a functional decomposition of a knowledge base and an inference engine, and can be used in different contexts as diagnosis, prognosis, configuration or monitoring [6–8]. Currently, knowledge-based CDSS are mainly used to support diagnosis, medication tasks, mechanical ventilation or monitoring processes in intensive care settings [9]. However, although there are many other use cases for CDSS, these systems are often not extensively adopted in clinical routine or shareable across institutions.

1.2. Semantic interoperability in CDSS

The lack of CDSS adoption might be due to different factors, e.g., legal, ethical and financial challenges, the inadequate integration in the clinician's workflow [7] or insufficient quality of data, domain and inference knowledge [10]. Apart from these, a very well-known bottleneck is the challenge of providing easy integration with local systems (e.g., hospital information systems) [7]. Often, CDSS are designed as stand-alone systems without interfaces to electronic health records. Hence, redundant data acquisition is needed, which might hinder routine use of CDSS [7].

As one of the best known approaches, addressing this issue in the context of clinical knowledge representation, the *Arden Syntax* allows the alignment with local data repositories in specific sections of the *Medical Logic Modules (MLM)* (called *data sections*). By using curly braces ["{}"], site-specific mapping clauses to local environments are defined in sections, which are separated from the logic rules. Here, it is often referred to the 'curly braces problem' because each reuse of MLMs requires an adaption of local mappings [11–14]. Although different approaches for the evaluation of mappings exist (e.g., within Arden2ByteCode compiler [14]), CDSS based on MLMs are not extensively shared. Furthermore, by providing this 'implementation defined' gap, it cannot be semantically assured that the data is representing the data set, which is required for the reasoning task (e.g., because different meanings of clinical concepts exist). If the semantic of the data elements, which are processed in knowledge-based systems, is not defined, the inference procedure might lead to weak results.

Hence, the use of standardized formalisms to represent logic and knowledge is a key factor for interoperability of CDSS. A semantic enrichment of data elements provided to the inference engine of a CDSS is to assure that there is a common, shared meaning of data *(semantic interoperability*). Within the context of EHR systems, Martinez-Costa et al. [15] distinguish the aforementioned levels of semantic interoperability in *models of use* (generic information and clinical models) and *models of meanings* (ontologies and terminologies). These insights are also acknowledged more frequently in recent work on semantic interoperability in CDSS. The focus is shifted towards the use of clinical information standards as HL7 V3 RIM, openEHR, HL7 CDA/CCR, HL7 VMR or Intermountain CEMs in combination with guideline representation formalisms, ontologies and terminologies [16].

In the context of openEHR, most recently Marcos et al. [17] described a concept on linking CDSS to heterogeneous EHRs by using openEHR Archetypes. A prototypical CDSS implementation for supporting the patient recruitment in clinical trials for colorectal cancer screenings was evaluated on simulated data sets. Another approach, which focuses on the integration between openEHR Archetypes and non-knowledge based systems, was presented by Marco-Ruiz et al. [18]. Here, the presented meta-architecture was not tested practically because neither a prototype was implemented nor an evaluation in a realistic clinical scenario was carried out. Hence, to the best of our knowledge, recent approaches have not presented openEHR based CDSS to the extent as we do: (1) with the design of a prototype, which works on real data sets originating from patient data management systems, (2) by selecting an exemplary use case of high importance for pediatric intensive care and (3) by conducting a first pilot study for evaluating the technical practicability of the approach.

1.3. Use case

In this work, we aim at investigating an openEHR based approach to achieve semantic interoperability in CDSS. The practicability of the described approach is examined by designing, implementing and assessing a system for a knowledge-intensive task as pediatric SIRS detection in pediatric intensive care.

SIRS was first introduced in adults to describe a nonspecific systemic inflammatory process in the absence of infection [19]. In case of positive blood culture or suspected infection with response to antibiotic treatment, SIRS becomes sepsis. For the pediatric population, SIRS criteria for adults were incorporated and modified with age-specific norms for children by the IPSCC [20]. SIRS in children is manifested by the presence of at least two out of four criteria, one of which must be an abnormal temperature or leukocyte count: a) hyperthermia or hypothermia, b) tachycardia c) tachy- or bradypnoea or d) leukocytosis or leukopenia [20] (see Tables A1 and A2 in Appendix A). The problem for the pediatrician in charge lays in the complexity of the definition, with differentiation in six age groups and the resulting widespread age-specific normal values for heart rate, respiratory rate and leukocyte counts. Some very young patients (newborn babies) even change twice the underlying age group whilst being on the PICU. Patient data management software is able to visualize all data on screen but often there is a certain time delay between the fulfilling of the different types of criteria for SIRS and sepsis (e.g., laboratory values, vital signs, automated transferred data, annotations of the nursing staff). The resulting complexity of the diagnostic process makes it very difficult for the clinician to recognize SIRS or sepsis early in the clinical routine. But SIRS and sepsis have a relevant impact on the clinical outcome of pediatric ICU patients [21,22]. Especially in the septic patient, different studies proved that any delay in the treatment directly leads to an increase in morbidity and mortality [23]. Moreover, the occurrence of SIRS predispose patients to organ failure and frequently determines the clinical outcomes [19]. Mortality and morbidity of severe non-infectious SIRS did not differ from severe sepsis, as shown in a multicenter trial in 3500 patients in adult intensive care units [24]. SIRS on admission determined mortality and length of stay of critically ill adult trauma patients [25]. Pathophysiological mechanisms of SIRS and sepsis are similar but the management of SIRS is typically non-specific [26]. However, an early detection of SIRS and sepsis may help to prevent organ dysfunction or organ failure, and contribute to a better outcome of intensive care patients.

1.4. Objectives

1 Both, the design of interoperable CDSS and the development of CDSS in pediatric SIRS-settings are still active fields of research. With our work, we investigate an openEHR based approach to achieve semantic interoperability in CDSS by using Archetypes and AQL. The goal is to evaluate the technical practicability of this approach, to gain first insights on the feasibility and to identify possible bottlenecks.
2 In matters of the selected use case, the detection of SIRS and sepsis in pediatric intensive care settings is a time-consuming, complex and knowledge-intensive task because of the wide variety of disease patterns, age-specific characteristics and personal experiences of clinical staff as well as implicit knowledge assets, which need to be