Creating personalised clinical pathways by semantic interoperability with electronic health records

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\section*{ABSTRACT}

Objective: There is a growing realisation that clinical pathways (CPs) are vital for improving the treatment quality of healthcare organisations. However, treatment personalisation is one of the main challenges when implementing CPs, and the inadequate dynamic adaptability restricts the practicality of CPs. The purpose of this study is to improve the practicality of CPs using semantic interoperability between knowledge-based CPs and semantic electronic health records (EHRs).

Methods: Simple protocol and resource description framework query language is used to gather patient information from semantic EHRs. The gathered patient information is entered into the CP ontology represented by web ontology language. Then, after reasoning over rules described by semantic web rule language in the Jena semantic framework, we adjust the standardised CPs to meet different patients’ practical needs.

Results: A CP for acute appendicitis is used as an example to illustrate how to achieve CP customisation based on the semantic interoperability between knowledge-based CPs and semantic EHRs. A personalised care plan is generated by comprehensively analysing the patient’s personal allergy history and past medical history, which are stored in semantic EHRs. Additionally, by monitoring the patient’s clinical information, an exception is recorded and handled during CP execution. According to execution results of the actual example, the solutions we present are shown to be technically feasible.

Conclusion: This study contributes towards improving the clinical personalised practicality of standardised CPs. In addition, this study establishes the foundation for future work on the research and development of an independent CP system.

\section*{1. Introduction}

Clinical pathways (CPs), as standardised treatment processes, play an important role in the treatment quality and efficiency of healthcare organisations [1–3]. However, in clinical environments, the status of a patient is complex and variable, likely resulting in the termination of CPs. Consequently, personalising treatment plans is one of the main challenges when implementing CPs [4].

The European Pathway Association (EPA) performed their first international survey on the use and dissemination of CPs in 23 countries in 2006 [5]. As reported, most countries only use CPs for a few cases; they are mainly used in the treatment of acute hospital diseases. Approximately 21–40\% of the patients in Estonia, Singapore, and America received pathway-based treatment in the past two years, while 11–15\% of the patients in Australia, Canada, and England received such treatment. Other countries claimed that less than 10\% of the patients received pathway-based treatment. According to the EPA, practical CP execution is not optimistic.

In the last decade, researchers have proposed various approaches to improve CP compliance and user acceptance in an attempt to implement personalised CPs and improve CP practicality [6–11]; some of these approaches are a part of an implementation system within a clinical environment [12]. By analysing and summarising related studies, this paper proposes a novel approach of semantic interoperability between ontology-based CPs and patient clinical information to solve the aforementioned problem. To achieve semantic interoperability, both the CP knowledge and patient information must be semantically represented. Obviously, CP knowledge represented by an ontology-based method is semantic; however, patient information may not be semantic. Therefore, the source of this information is vital for achieving semantic interoperability.

The rapid increase in the adoption and implementation of electronic health records (EHRs) by many healthcare institutions provides new opportunities to create semantic interoperable healthcare applications and solutions for personalised treatment...
Clinical treatment and research is becoming increasingly dependent on the analysis of patient data [15]. However, the heterogeneous data in EHRs must be normalised into a comparable, consistent representation to construct a sharable knowledge base [16]. A secondary use of EHRs is facilitating other medical applications. Prior research has indicated that semantic web tools and technologies provide a feasible solution for modelling clinical knowledge, querying data and inferring new knowledge [17]. Semantic technology has been widely used to obtain clinical data from EHRs and represent it as useful knowledge that comprises the semantic EHRs.

The semantic interoperability between semantic EHRs and knowledge-based CPs allows for the automatic creation and orchestration of personalised CPs. Notably, ontology-based CPs automatically adjust to create personalised care plans according to the patients’ clinical information from their semantic EHRs before CP execution. The semantic patient information mainly includes allergies to medications, such as aspirin; disease history, such as hypertension; and results of laboratory tests and medical radiation examinations. Furthermore, the personalised care plan makes real-time and dynamic modifications independently when an exception situation occurs during treatment execution.

In this paper, we propose a novel approach to achieve semantic interoperability between knowledge-based CPs and semantic EHRs to create personalised CPs. To construct a knowledge-based CP model, we use web ontology language (OWL) to represent medical concepts and relationships in CP knowledge and employ semantic web rule language (SWRL) to describe clinical procedure rules during CP execution. To construct semantic EHRs, we present a specific semantic web framework by summarising and generalising previous research. Interoperating with semantic EHRs, personalised care plans are created by the knowledge-based CP model. By gathering real-time patient information from semantic EHRs and reasoning over rules that have been described by SWRL in the CP model, every clinical activity in a treatment procedure will be efficiently monitored, and automatic error-checks by the reasoning results could improve treatment schemes by dynamically adjusting the clinical procedure. In this paper, a CP for acute appendicitis is used as an example to illustrate how personalised treatment procedures are adjusted based on the interaction of CPs and semantic EHRs. The execution results of the personalised CP for acute appendicitis indicate that this approach is technically feasible for the creation of personalised care plans and improves the dynamic adaptability of CPs.

2. Methods

2.1. Knowledge-based CP model

With the development of semantic technologies in a knowledge-based system, ontology has begun to play a more important role in building the domain model. It is now widely acknowledged that ontology can make a significant contribution to the design and implementation of information systems in the medical field [18–20]. This study generalised the CP modelling process [21] and summarised four modelling phases using ontology methodology: (1) knowledge base of identification; (2) knowledge extraction; (3) knowledge representation; and (4) model evaluation, as shown in Fig. 1.

2.1.1. Knowledge base of identification

A knowledge base of identification of CPs is the basis for knowledge extraction. Obviously, the source identification of CP knowledge is crucial to build a CP knowledge base. We analyse CP knowledge based on three types of knowledge sources: (1) existing CPs in use at healthcare organisations, including the electronic CPs adopted in Miyazaki University Hospital and paper CPs established by the ministry of health [22]; (2) the clinical experience of domain experts, which is difficult to specify and interpret; and (3) published literature on CPs [23–26]. In this phase, healthcare professionals cooperate with knowledge engineers to establish the knowledge sources of CPs and analyse treatment procedures, applicable diseases and the input and output criteria of CPs.

2.1.2. Knowledge extraction

Knowledge extraction is the process that culls tacit knowledge in documents on the basis of information extraction. CP knowledge extraction includes the extraction of CP semantics based on ontology, combined with knowledge technologies and natural language processing techniques [27], and focuses on the identification and extraction of concepts and relationships between concepts. CP terminology knowledge and rules are extracted from existing electronic CPs or paper CPs used in healthcare organisations and CP-related literature. With the help of clinicians, we have analysed the content and structures of approximately 140 CPs used by the Miyazaki University Hospital and found 19 super classes, 98 subclasses and 48 common relationships using meta-ontology approach [21].
2.1.3. Knowledge representation

After the initial two phases, we obtain the required domain knowledge for CP modelling including terminology, individuals, and rules. In this phase, we describe the method of representing CP knowledge semantically. OWL is adapted to represent CP terminology, and SWRL is introduced to represent CP rules [28].

OWL is the standard language used to represent web ontology and was launched by the W3C in 2004. According to W3C specifications, OWL facilitates machine interpretability of web content better than extensible markup language (XML), resource description framework (RDF) or RDF Schema (RDFS) by providing additional vocabulary in addition to formal semantics. OWL is categorised into three increasingly expressive sublanguages: OWL Lite, OWL DL and OWL Full. OWL Lite, with minimum expressiveness, is usually adopted for simple implementations. OWL Full is designed for users who need maximum expressiveness, but do not need computational guarantees. OWL DL provides higher expressiveness while retaining computational completeness [29]. Through comprehensive consideration of expressivity and reasoning support, we adopt OWL DL to declare classes, properties, and individuals of CP knowledge.

The following examples show that the class Patient is defined directly, and the defined class Patient declares the individuals PatientA and PatientB.

```xml
<owl:Class rdf:ID="Patient"/>
<Patient rdf:id="PatientA"/>
<Patient rdf:id="PatientB"/>
```

An OWL property connects two items. Datatype properties describe the relationship between individuals of classes and RDF literals or XML Schema datatypes; object properties describe the relationship between individuals of two classes. The following OWL ontology fragment depicts that individual PatientA has a datatype property hasAge, the range of which is 'xsd:int', and an object property hasFather, the value of which is the individual PatientB.

```xml
<Patient rdf:id="PatientA">  
  <hasAge rdf:datatype="&xsd;int">7</hasAge>  
  <hasFather rdf:resource="#PatientB"/>
</Patient>
/owl:DatatypeProperty rdf:id="hasAge">  
  <rdfs:domain rdf:resource="#PatientA"/>
  <rdfs:range rdf:resource="&xsd;int"/>
</owl:DatatypeProperty>
/owl:ObjectProperty rdf:id="hasFather">  
  <rdfs:domain rdf:resource="#PatientA"/>
  <rdfs:range rdf:resource="#PatientB"/>
</owl:ObjectProperty>
```

SWRL is a semantic web rule language based on OWL DL and OWL Lite that applies the Unary/Binary Datalog RuleML sublanguages of the Rule Markup Language. SWRL provides the expressivity that OWL does not support while maintaining compatibility with OWL syntax; a high-level abstract syntax is provided that extends the OWL abstract syntax. In this syntax, a rule axiom is composed of an antecedent and a consequent. A rule is informally defined as follows: if the antecedent is true, then the consequent must also be true [30]. The SWRL abstract syntax has the advantage of being easy for people to read and understand. Thus, we adopt the SWRL abstract syntax to describe the required rules in the CP knowledge base.

Tetracyclines can induce liver and kidney damage and influence the growth of the infant skeleton. Therefore, tetracycline is forbidden in children less than eight years old. The corresponding SWRL abstract syntax is depicted as follows.

```xml
Patient(?p) ∧ hasAge(?p, ?age) ∧ swrlb:lessThan(?age, 8)  
  → hasTetracycline(?p, False)
```

variable declaration:

?p – an individual of Class Patient;

?age – value of age;

2.1.4. Model evaluation

This paper applies a task-oriented model evaluation method [31]. We build the CP model of acute appendicitis based on previous models and computerise the procedures of the CP for acute appendicitis. Then, we observe whether the computerised acute appendicitis CP embedded in electronic medical records (EMR) systems can create personalised care plans according to patient information extracted from the semantic EHRs. We also observe whether the computerised CP can dynamically adapt itself based on patient status during CP implementation. By analysing the observed result, we establish the advantages and disadvantages of the CP model and can subsequently improve the CP model.

2.2. Semantic EHRs

Numerous studies have noted the problem of extracting the patient information from EHRs [32]. Zillner et al. mapped patient data onto relevant ontology fragments and inferred that ontological structures should be used as a basis for improving patient data visualisation, comparison, and analysis [15]. To search for specific patients for clinical trials, TrialX was developed as a tool to obtain patient information from personal health records [33]. Tao et al. obtained useful patient information from EHRs and represented the clinical knowledge and data using semantic web technologies [16]. Serbanati et al. proposed a virtually centralised, longitudinal patient record called the virtual healthcare record (VHR) for regional sharing [34]. The process of extracting semantic patient information from EHRs, based on previous studies, is shown in Fig. 2. Patient data has two sources: patient data in various healthcare organisations and existing related ontologies. Semantic web techniques are applied to clinical knowledge and data representation; existing related standards such as HL7, ICD, and SNOMED CT are employed to normalise the conceptual model of patient data. We normalise these two parts of patient data and store the normalised data in the form of RDF triples. The normalised patient data, including past medical records, current health status and past patient response to certain treatments and medications, can be shared with other applications, such as evidence-based medicine and decision supporting systems.

Privacy and security are significant issues when using sharable EHRs. Patient data accessibility depends on individual patients’ preferences. Limits of authority may restrict data extraction from sharable EHRs and influence personalised CP generation and exception management. In this study, we presume that the required data in EHRs are authorised and accessible. Standardised patient information stored in RDF triples constitutes a sharable knowledge base. Simple protocol and RDF query language (SPARQL) is a query language based on the RDF triples data format. Thus, the semantic patient information can be extracted from the patient knowledge base by SPARQL so that the CP model can create personalised care plans.

We can capture all relations of the individual PatientA mentioned above using the following SPARQL fragment. The query results are shown in Table 1, where the predicate rdf:type indicates...
that PatientA is an individual of the class Patient. Additionally, the individual PatientA has two properties: the datatype property hasAge with its value ‘7’ and the object property hasFather with its value PatientB.

![Diagram of EHRs and SPARQL](Fig. 2. Process of extracting semantic patient information from EHRs.)

### 2.3. Personalised CPs

After building the CP model and constructing the semantic EHRs, we present an approach for combining the CP knowledge base with the semantic EHRs to create personalised CPs and dynamically adjust treatment procedures. The semantic interoperability between the CP knowledge base and semantic EHRs can be divided into two parts: (1) capture the patient information from the semantic EHRs by SPARQL according the practical demand and (2) execute the CP rules based on the obtained information. Using this interaction method, we show two examples of the detailed procedure: creation of personalised care plans and dynamic self-adaption.

When an electronic CP is applied to a patient in a current healthcare organisation, clinicians must determine if the CP is applicable to the patient according to the patient's clinical status. Then, if the CP is applicable, clinicians must modify items, such as orders, in the CP to meet the patient's specific needs. As a patient's clinical data becomes more complex, the number of items in the CP that require modification may increase, diminishing the efficiency of implementing CPs. In this paper, the CP knowledge base automatically creates the personalised care plans using patient information obtained from the semantic EHRs.

The ability to dynamically self-adjust effectively improves the practicality of CPs. During CP execution, there is constant monitoring of patient clinical data in the semantic EHRs and recognition of exceptional situations. For instance, a patient may be in danger if his/her pulse rate is not within the normal range. Thus, if the pulse rate drops below a defined minimum, it is important to give clinicians a variance warning and stop the path. The SPARQL fragment below shows the capturing of the pulse rate value of PatientA. Reasoning over the following SWRL rules, the variance is reported to the clinicians.

<table>
<thead>
<tr>
<th>Table 1: Query results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicate</td>
</tr>
<tr>
<td>rdf:type</td>
</tr>
<tr>
<td>hasAge</td>
</tr>
<tr>
<td>hasFather</td>
</tr>
</tbody>
</table>

For example, the CP for Lobectomy Pulmonalis (LP) is applicable to patients who have a key disease, i.e., bronchiectasis. However, LP cannot be used with patients who have hypertension. In the semantic EHRs, every patient has two object properties: hasKeyDisease, for the current key disease, and hasDiseaseHistory, for personal disease history. Both of these properties have a range of diseases normalised by the international statistical classification of diseases and related health problems 10th Revision (ICD10). The value of hasKeyDisease is unique, whereas hasDiseaseHistory can have several values. Two patients named PatientA and PatientB both have the key disease bronchiectasis, but PatientB has hypertension. The following SPARQL query fragments capture the values (?object) of the two properties for each patient from the semantic EHRs. After consulting the subsequent rules pertaining to the information entered into the CP model, we can establish that the CP for LP is applicable to PatientA, but not to PatientB.

```sparql

SELECT ?object WHERE { :PatientA :PatientB :hasKeyDisease ?object
SELECT ?object WHERE { :PatientA :PatientB :hasDiseaseHistory ?object

Patient(?p) × ClinicalPathways(?cp) × 
hasKeyDisease(?p, Bronchiectasis) × usedForDisease(?cp, Bronchiectasis) × 
hasDiseaseHistory(?p, ?dh) × hasICD10Code(?dh, ?dhc) × 
hasICD10Code(Hypertension, ?hc) × swrlb:notEqual(?dhc, ?hc) × 
→ hasCP(?p, ?cp)

valuable declaration:
?cp – an individual of Class ClinicalPathways;
?dh – an individual of current diseases of ?p;
?dhc – ICD-10 code of ?dh;
?hc – ICD-10 code of the disease Hypertension;
```
2.4. Technical architecture

The technical architecture of the implemented prototype is presented in Fig. 3. The execution procedure of the personalised CP model is composed of four major components. These four major components are described in full detail in the following section.

2.4.1. CP knowledge base

The knowledge base includes the domain knowledge of the CP, mainly CP relevant terms, properties and relations represented by OWL and rules represented by SWRL. Protégé is used to represent the CP ontology and has the plug-in SWRL tab supporting rule editing. The ontologies and rules represented in Protégé are saved in OWL format.

2.4.2. Knowledge engine

This paper adopts the Jena semantic web framework as the knowledge engine. Jena is a Java framework for building semantic web applications, providing a collection of tools and java libraries to develop semantic-related applications, tools and servers. The Jena framework provides an ontology API for handling OWL ontologies and a rule-based inference engine for reasoning with OWL data sources. Additionally, it is compatible with the latest SPARQL version.

2.4.3. CP execution environment

Using the Jena framework, the electronic CPs, which were constructed based on the CP knowledge base, interact with the semantic EHRs and finally execute in EMR systems in the embedded form. The semantic EHRs promote CP customisation according to the patient’s medical history, personal clinical responses and current health status, facilitating interactions between EMR systems and the CP knowledge base. CP customisation supports physicians’ decision-making processes, remarkably improving efficiency. However, physicians are the final decision makers who can modify the customised treatment procedures if necessary and establish personalised care plans in practical clinical environments.

2.4.4. CP knowledge management

CP knowledge management is responsible for the management of the CP knowledge base, including the base maintenance and CP knowledge update. These management procedures also need a bridge of knowledge engine to help the interaction between the management interface and the CP knowledge base.

3. Results

Acute appendicitis is a common surgical emergency, with a lifetime occurrence of 7% [35]. Compared to other diseases, the treatment procedure for acute appendicitis has a clear and concise process and low exception rate. Therefore, the treatment procedure for acute appendicitis is feasible to implement as a CP. We use a CP for acute appendicitis as an example to illustrate how to create an individualised treatment plan and enhance the dynamic adaptability of CPs by semantic interoperability between the CP ontology and semantic EHRs.

3.1. Ontology modelling of the CP for acute appendicitis

The CP ontology model includes basic classes and properties. These are four major super classes: Patient, ClinicalPathways, CPElementBase and CPEventModel. As implied by the name, CPElementBase includes all the related vocabularies. CPEventModel, with subclasses named DocumentsEvents, ObservationsEvent and OrderEvent, is used for recording the detailed events of individual CPs. Every event in the CPEventModel has a corresponding vocabulary in the CPElementBase.

The reference materials used to establish the ontology of the appendectomy CP are mainly taken from the CP tables published by the ministry of health. The ontology concepts and relationships are confirmed by combining the analysis of the CP tables with suggestions from clinical experts. Based on the ontology model, we add the related individuals to the CP for acute appendicitis and construct the relationships between individuals by setting up the values of properties, such as hasOrder. With the plug-in Ontoviz tab in Protégé, the relationships of the individual Appendectomy are presented in graph form. Fig. 4 displays some important relationships of Appendectomy, such as UsedForDisease, hasDocument, and hasOrder.
To model temporal information, the SWRL temporal ontology [36] is imported for temporal reasoning and answering time-oriented queries [37]. The property \textit{hasValidTime} is used to describe the execution time of every order event, as shown in Fig. 4.

### 3.2. Creating personalised CP for acute appendicitis

When determining if a CP applies to specific patients, the input check is crucial. The necessary patient information from the semantic EHRs is captured according to the predefined input rules. Then, the input rules are used to determine whether the CP is applicable to the patient. For example, allergies to medications likely affect treatment procedures; thus, obtaining the patients’ allergy histories from the semantic EHRs and reasoning over them before CP execution is essential. Additionally, checking previous orders for patients helps prevent repeated operations and, therefore, decreases cost.

To create the personalised appendectomy CP, we define two input rules, as represented in the following SWRL rule fragments.

The first fragment states that if a CP order \( ?oe \) is applied to a patient \( ?p \), the CP order \( ?oe \) is mapped to the common order \( ?o \), and the patient \( ?p \) has undergone the common order \( ?o \), then a variance \( \text{OrderRepeat} \) will be added to the CP order \( ?oe \). In this SWRL fragment, \( ?oe \), \( ?o \), and \( ?o \) are variables defined in the rule. \textit{hasPatient}, \textit{hasRelatedTerm}, \textit{hasTodayOrder}, and \textit{hasVariance} are object properties defined in the CP ontology, each with their own domain and range. \textit{hasVariance}, for example, has a domain of CP orders and a range of individuals in the class \textit{Variance}. \textit{OrderRepeat} is one of the individuals in the class \textit{Variance}.

The second fragment states that (1) a CP \( ?cp \) is applied to a patient \( ?p \); (2) the CP \( ?cp \) includes a CP order \( ?oe \); (3) the CP order \( ?oe \) uses a standard injection drug \( ?drug1 \); and (4) the drug \( ?drug1 \) has an alternate drug option \( ?drug2 \). If the patient \( ?p \) is allergic to the standard drug \( ?drug1 \), then the CP order \( ?oe \) adopts the alternate drug \( ?drug2 \).

The Jess rule engine is applied to reason over the ontology and rules. We transfer the SWRL rules and relevant OWL ontology knowledge to the Jess rule engine, run the rule engine and transfer the inferred rule engine knowledge to OWL ontology. The inferred CP ontology is embedded into the EMR system [38,39] (developed by Healthcare Informatics Engineering Research Centre) via the Jena semantic web framework.

Fig. 5 describes the process of input checking the CP for acute appendicitis.

The patient information in the semantic EHRs is shown in the left rectangle, including the patient ID, patient name, laboratory history and allergy history. The patient with ID PID081603 received a blood test (complete blood count, CBC) on March 10, 2012, and is allergic to penicillin. This patient information can be captured by SPARQL. The following SPARQL fragments are used to capture the values of the object properties \textit{hasTodayOrder} and \textit{hasAllergy}.

```
SELECT ?subject ?object WHERE { PID081603:hasTodayOrder ?object }
SELECT ?subject ?object WHERE { PID081603:hasAllergy ?object }
```
The interface of 'Standard CP for acute appendicitis' shows basic information, applicability criteria information and treatment items of the standard CP. We can see that this CP executes a blood test and orders an injection of penicillin on the first day. When this standard CP is applied to the patient with ID PID081603, the pop-up input check interface appears, and the checked result is shown in the middle of Fig. 5. As shown above, two warnings occurred.

1. Order repeat. According to Rule1, this patient has already received the blood test. Thus, this warning is generated to note that this order need not be repeated.
2. Drug allergy. According to Rule2, this patient is allergic to penicillin. Thus, this warning is generated to note that levofloxacin should be substituted for penicillin.

The treatment procedure of patient PID081603 is shown at the bottom of Fig. 5. The standard CP for acute appendectomy becomes a personalised care plan as a result of input checking. The blood test order is deleted, and the injection order is modified by substituting levofloxacin for penicillin.

3.3. Dynamic adaptability of the CP for acute appendicitis

Dynamic adaptive adjustment of CPs occurs during CP execution. The principle for exception checking is similar to that of the input checking mentioned above. During CP execution, the patients’ physiological parameters from the semantic EHRs are captured by SPARQL. If the patients’ physiological parameters leave the standard range set in the rules, an exception occurs, and the CPs respond to the exception. During the execution of the personalised CP, the value of the body temperature of patient PID081603 is captured by SPARQL from the semantic EHRs. The query language is shown below. If the value of the body temperature is over 37.5 °C, then we record the variance and pause the CP, as described in the following rule.

```
SELECT ?subject ?object WHERE {
  ?PID081603 :hasBodyTemperature ?btval .
  Patient(?p) ∧ ClinicalPathway(?cp) ∧ hasCP (?cp, ?cp) ∧
  hasBodyTemperature(?cp, ?btval) ∧ swrlb:greaterThan(?btval, 37.5) ∧
  hasCPVariance(?cp, fever) ∧ hasCPStatus(?cp, pause)

valuable declaration:
?btval -- the value of body temperature;
```

The process of exception checking the CP for acute appendicitis is shown in Fig. 6.

The changing curve of the body temperature of patient PID081603 occurring during the CP execution is shown in the dotted rectangle in Fig. 6. When the value of the body temperature is 38.2 °C (greater than 37.5 °C), an exception occurs by reasoning over the above rule, and the pop-up exception dialogue box appears. By clicking the letters in the exception dialogue box, we can see the exceptional information details, as shown in the bottom rectangle. In the meantime, the CP is paused, and the clinicians can choose to address the exception or ignore the exception to continue the CP.

4. Discussion

In Section 3, the CP for acute appendicitis is taken as an example to illustrate the process of CP customisation, especially input
checking and exception checking. This case is simple with few decision branches. However, unpredictable challenges could be encountered in proving our approach against a more complex CP, which will be addressed in future work. Another limitation in this study is the inadequate consideration of privacy and security of patient data in the semantic EHRs. The patient, as the owner of his/her medical data, has the right to determine whether his/her medical records are sharable and what types of medical information are sharable. If access to certain medical information is unauthorised, the CP systems may miss essential information to accurately generate personalised CPs or handle exceptional situations. Similar legal and economic issues restricted practical implementation and quantitative evaluation of the system. Nevertheless, this study provided feasible technical solutions to improve the practicality of CPs by constructing the technical architecture and primary applications for implementation.

Our previously published paper [21] has proposed an ontology-based method to model CPs, concentrating on the extraction and representation of CP domain terms and rules. Following that research, this study aims to improve the practicality of CPs by using semantic interoperability between knowledge-based CPs and semantic EHRs. We have accomplished three main tasks: (1) supplement and amend the CP model represented by the previous paper; (2) construct semantic EHRs; and (3) achieve semantic interoperability between CPs and EHRs, which is the key innovation of this study.

Serbanati et al. have performed excellent work on the regional digital health ecosystem. The VHR was proposed as a complete and authoritative representation of patient data, which has a native function to monitor clinical information and support CP customisation [34]. However, the specific process of CP customisation based on the characteristic of VHR is seldom mentioned. In this study, we propose a different viewpoint that considers knowledge-based CPs and semantic EHRs as two separate components and focus on the interpretation and implementation of the interactive process between them.

With the development of semantic technology, the semantic interoperability between the CP knowledge base and semantic EHRs is not a technical problem. The main challenge is the construction of the CP knowledge base. CPs refer to many treatment procedures, and ontology modelling lacks effective building standards. These shortcomings delay the implementation and popularisation of CPs. However, the development of other medical ontologies is helpful in describing CP treatment procedures; reusing existing medical ontologies will help build the CP knowledge base.

Implementing CPs takes into account both standardised care plans and personalised treatment procedures. Although they contradict each other, both are needed to balance the other to maximise the effectiveness of CPs. Personalised treatment procedures change according to the clinical status of different patients, improving the individuality of standardised CPs. Furthermore, by generating personalised care plans for every patient, medical costs could be estimated and controlled before hospitalisation. Moreover, it is helpful to promote and complement the implementation of diagnosis related groups (DRGs).

Many studies describe how to extract semantic patient information from EHRs and construct a sharable knowledge base. Capturing the patient clinical data from semantic EHRs strengthens the reuse of patient data, avoids repeated medical actions such as laboratory tests, and is beneficial with respect to conserving resources and decreasing medical costs.

The CP knowledge base constructed by semantic technology is independent and sharable. Notably, patient information, which is used to create personalised CPs, is extracted from EHRs instead of EMR systems. This eliminates the dependence of CP knowledge on EMR systems, which is conducive to the design and development of an independent CP system. Currently, EMR systems have been widely used in medical organisations; however, only some of them have adopted electronic CPs, which are implemented as an integral part of EMR systems [21, 40]. It is expensive and inadvisable to replace the entire EMR system to increase CP function. Thus, an independent CP system is in high demand. In this paper, we apply the Jena framework to embed the inferred independent CP knowledge base into the EMR system developed by our laboratory. By embedding the CP knowledge base into a familiar EMR system, we establish the interface data between CPs and EMR systems, laying the foundation for future work on the research and development of an independent CP system.

5. Conclusion

Healthcare information systems (HIS), such as EMR systems and EHRs, have been widely used in medical institutions and
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