

An Ontology-based Application in Heart Electrophysiology: Representation, Reasoning and Visualization on the Web

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ABSTRACT

Computational technologies have been increasingly explored to make biomedical knowledge and data more accessible for human understanding, comparison, analysis and communication. In this context, ontology has been recognized in the bioinformatics literature as a suitable technique for advancing knowledge and data representations in Biomedicine. Moreover, automated reasoning and visualization mechanisms can favor in providing support for human comprehensibility as well as in dealing with the complexity inherent to this domain. This paper elaborates on the application of ontology for heart electrophysiology representation, reasoning and visualization on the web. The ontology-based application we propose can be used to offer support for interactive learning in heart electrophysiology.

Categories and Subject Descriptors

H.3.5 [Information Storage and Retrieval]: Online Information Services – *Web-based services*; I.2.1 [Artificial Intelligence]: Applications and Expert Systems – *Medicine and Science*.

General Terms

Design, Languages, Standardization.

Keywords

Biomedical ontology, Heart electrophysiology and ECG, OWL DL + SWRL, Web animations, Medical education.

1. INTRODUCTION

Biomedical data has been ever more available for computing as far as the use of information systems in Biology and Medicine becomes widespread. An example of daily useful biomedical data is the electrocardiogram (ECG), which is the most frequently applied test for measuring heart activity in Cardiology. The ECG was probably the first diagnostic signal to be studied with the purpose of automatic interpretation by computer programs [5]. Such an interest in computing ECG records is because the analysis of the ECG waveform can help to identify a wide range of heart illnesses, which are distinguished by specific modifications on the ECG elementary forms. Although the ECG data can be presented either through sound, text or chart image, the latter is the most used for exhibiting it. The reason is that the

heart beat patterns can be better recognized (by humans) visually in a graphical chart.

While vital signs such as the ECG are usually former exams, other sorts of biomedical data have called attention on account of more recently developed technologies. Advanced imaging, for instance, is a valuable resource for supporting diagnostic nowadays. Besides, human body computer models have increasingly served as virtual environments for organ level surgical simulation (e.g. [3]), contributing then to aid learning in Medicine. However, while mathematical models are suitable for simulating biological structures and phenomena, there is a growing need for fostering philosophic- and logic-based representations capable to support in dealing with the size and complexity of biomedical knowledge and data (e.g., consider clinical terminologies). In face of this, in recent years several research initiatives have promoted ontology as a formalism to represent (parts of) the biomedical domain (e.g. [11], [19], [20]). In this context, the Open Biomedical Ontologies (OBO) foundry [18] has gathered many ontologies as attempts to represent a clearly bounded subject-matter. So far, OBO comprises over 60 ontologies concerning knowledge and data from the biomedical domain [18]. These ontologies have been used not only for human understanding, comparison, analysis and communication, but also for (tractable) information retrieval.

This paper elaborates on the application of the *Ontology of Heart Electrophysiology (OHE)* [6] for reasoning and visualization on the web. This ontology-based web application is a prototype that exploits user-interaction by processing clicks either on an ECG chart or on heart-like image whereby heart phenomena are illustrated via animations. A reasoning engine then draws (ontology-based) logical inferences as a result, by taking into account the mapping from the ECG to the heart electrophysiology. The facts either asserted (drawn by user input) or inferred (by reasoning results) are made explicit by means of (i) short text written in a log box, (ii) the animation that simulates (an abstraction of) the heart electrical system, and (iii) the emphasized part of the ECG chart. The remainder of this paper stands for a discussion in Section 2 of the methods used (educational animations and ontology); the introduction (in Section 3) of the application proposed here, which is followed by a performance evaluation carried out in Section 4; finally, we discuss related work and conclude the paper.

2. METHODS

2.1 Ontology of Heart Electrophysiology

A domain ontology can serve properly in representing a picture of the reality as long as it is based on philosophical theories of parts, wholes, types and instantiation, identity, dependence, unity, etc.

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The call for philosophically well-founded representations is especially remarkable in dealing with complex domains such as Biomedicine [11], [13], [20]. In developing OHE, we have tackled many non-trivial philosophical issues. Some examples are: (i) how to represent that although the electrical impulse that triggers a ventricular contraction is the sinoatrial (SA) impulse, the atrioventricular (AV) impulse also contributes (sometimes indispensably) in such a contraction; (ii) how to state that the heart's role as a blood pump is continually played as long as ventricular contractions are continually performed as a result of subtle bioelectric phenomena; or (iii) how to interconnect bioelectric phenomena to ECG waveform patterns measured by means of a recording device. As introduced by Guarino and Welty [7], the modeling decisions that are to address such issues should not result from heuristic considerations but instead should be motivated and explained in the basis of principled *ontological distinctions*.

The OHE has been developed along these lines, i.e., OHE is specified in an ontologically well-founded UML profile [8] based on the Unified Foundational Ontology (UFO) [9]. As a result, it can be argued that OHE is a specification that makes a clear and precise description of the domain elements for the purposes of communication, learning and problem-solving. However, in order to exploit the benefits of ontology-based reasoning in a computational application, OHE has to be implemented in some codification language, say, one based on Description Logic [1]. This ontology implementation ought to afford a practical performance for automated reasoning and information retrieval. We have adopted OWL DL + SWRL [12] as a codification language. This allows us to take advantage of a number of off-the-shelf semantic web technologies (viz., Java APIs). Indeed, the Ontology Engineering approach employed in this work, as in any engineering process, and in line with [10], comprises the phases of analysis, design and implementation. However, a detailed description of how we have applied it to implement OHE falls out the scope of this paper and can be found elsewhere [21].

Aside from serving as an application-independent domain theory, OHE is useful for (cf. discussion in Section 5): reasoning about complex entities of heart electrophysiology as well as reasoning about individual data, say, a specific ECG record acquired from a specific patient. OHE fits well for such purposes since it models the mapping from ECG concepts, say, the P wave, to the real correlated bioelectric phenomenon, namely, the SA electrical impulse (see Figure 1). This has been exploited in the ontology-based web application introduced here for supporting learning in heart electrophysiology. The parts of OHE which are used in the application are the sub-ontologies of (i) heart, (ii) bioelectric phenomena and (iii) ECG. As traditionally in Ontology Engineering, the scope and competence of OHE is defined by means of competence questions (CQ). By taking the end-application requirements into account, the following CQs (cf. [21]) are to be addressed.

CQ1. What conditions must be satisfied for the heart to play the role of a blood pump?

CQ7. What does the P wave represent in the ECG waveform?

CQ8. What does the QRS complex represent in the ECG waveform?

CQ1 is addressed by the first-order logic formulae A1, A2 and A3:

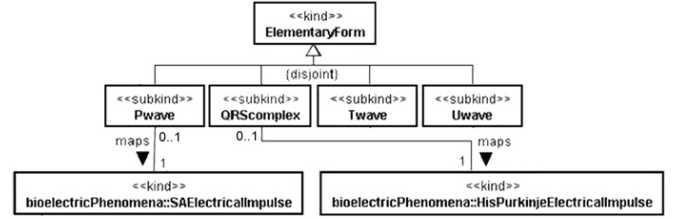


Figure 1. Mapping of ECG concepts and bioelectric phenomena.

(A1) $\forall x (\text{leftVentricleAsAPump}(x) \leftrightarrow \text{leftVentricle}(x) \wedge \exists y, z (\text{purkinjeElectricalImpulse}(y) \wedge \text{lvContraction}(z) \wedge \text{mediates}(z, x) \wedge \text{mediates}(z, y)))$

(A2) $\forall x (\text{rightVentricleAsAPump}(x) \leftrightarrow \text{rightVentricle}(x) \wedge \exists y, z (\text{purkinjeElectricalImpulse}(y) \wedge \text{rvContraction}(z) \wedge \text{mediates}(z, x) \wedge \text{mediates}(z, y)))$

(A3) $\forall x (\text{heartAsPump}(x) \leftrightarrow \text{heart}(x) \wedge \exists y, z (\text{leftVentricleAsAPump}(y) \wedge \text{isPartOf}(y, x) \wedge \text{rightVentricleAsAPump}(z) \wedge \text{isPartOf}(z, x)))$

The formula A1 states that a left ventricle works as a pump if and only if there exists a purkinje electrical impulse triggering the contraction of this left ventricle. Similarly, A2 enunciates the necessary and sufficient conditions for a right ventricle to work as a pump. Finally, A3 states that a heart works as a pump if and only if it has both the left and right ventricles working as pumps. A3 is implemented in OWL DL as follows.

```
<owl:Class rdf:ID="HeartAsPump">
  <owl:equivalentClass>
    <owl:Class>
      <owl:intersectionOf rdf:parseType="Collection">
        <owl:Restriction>
          <owl:onProperty rdf:resource="#heart;hasLeftVentricle"/>
          <owl:someValuesFrom rdf:resource="#LeftVentricleAsPump"/>
        </owl:Restriction>
        <owl:Restriction>
          <owl:onProperty rdf:resource="#heart;hasRightVentricle"/>
          <owl:someValuesFrom rdf:resource="#RightVentricleAsPump"/>
        </owl:Restriction>
      </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

CQ7 and CQ8 in turn are concerned with the explicit representation of the meaning of the ECG elementary forms. That is, which sort of bioelectric phenomena are mapped by these ECG patterns (i.e., P wave and QRS complex). This is expressed by the formulae A4 and A5 below.

(A4) $\forall x (\text{pWave}(x) \rightarrow \exists! y (\text{saElectricalImpulse}(y) \wedge \text{maps}(x, y)))$

(A5) $\forall x (\text{qrsComplex}(x) \rightarrow \exists! y (\text{hisPurkinjeElectricalImpulse}(y) \wedge \text{maps}(x, y)))$

As it is enunciated by A4, the P wave maps the SA electrical impulse. The QRS complex in turn gives a trace of the His-Purkinje electrical impulse (cf. A5). In other words, the P wave and the QRS complex ECG elementary forms represent the bioelectric phenomena just mentioned in the ECG waveform. Moreover, it is worthwhile to say that the SA impulse triggers the atrial contraction and the His-Purkinje impulse (while passing throughout the Purkinje fibers) triggers the ventricular contraction. By considering the context of the end-application as well as the limitation of SWRL in expressivity, the formula A5 has been adapted to the following SWRL rule.

(R1) `ecgTbox:NormalQRSComplex(?qrs) ^
ecgTbox:isSelected(?qrs, true) ^
bioElectric:PurkinjeElectricalImpulse(HisPurkinjeImpulse-0)
→ ecgTbox:maps(?qrs, HisPurkinjeImpulse-0)`

When R1 is fired, it is inferred the relation *maps* correlating a QRS complex instance selected in the web application to a generic instance of His-Purkinje impulse.

2.2 Educational Animations

We have been inspired by García et al. [4] in using flash animations for education. In that article, the authors present several experiments that evidence benefits achieved in using animations to aid learning of Descriptive Geometry. Similarly, we believe that flash animations should offer support for exploratory learning in heart electrophysiology. By interacting with such web media, students could actively explore the ECG and the heart electrical system in a goal-oriented constructive process. They then could actually visualize the electrical currents generated by the heart pacemaker cells. At a first glance, we have chosen flash to present both the ECG chart and the heart electrical system simulation. The simulation responds to events generated according to results computed by the ontology reasoning engine.

3. THE ONTOLOGY-BASED APPLICATION

The ontology-based web application proposed here (see Figure 2) has been implemented in Java by using the GWT framework¹. GWT affords a client-server architecture in which asynchronous remote procedure calls (RPC) take place. As illustrated in Figure 3, on the server side, the main components are the ontology T-box² and A-boxes³ (the ECG record samples), the Pellet reasoning engine, the Jena ontology model, and the ECG Chart Generator. Whereas on the client side, they are the ECG chart and heart flash objects together with a widget of record samples; all they are included in the GWT Entry Point in the index page. Notice that both the ontologies and the flash objects are building blocks uncoupled from the application backbone.

For handling the OWL ontology, we have used the Java APIs Jena [14] and Pellet [17]. Jena is used here mainly for providing to Pellet an access to the OWL ontology loaded in memory. Thus, the reasoning itself is fully supported by Pellet. The choice for the latter was due to its interesting characteristics reported in the literature. Pellet is efficient, customizable and can generate reasoning log information. Moreover, it also holds decidability even using SWRL rules (if they qualify as DL-safe [15]) as well as consistency validation between OWL restrictions and facts produced by SWRL rules.

The application allows three basic user interactions (see Figure 3):

- (I1)** selection (always by clicking) of an ECG record sample: this loads the record waveform into the ECG chart.
- (I2)** selection of a point on the ECG chart: this enables the reasoning engine to answer which ECG pattern is associated with this point. In case it is not located in any ECG elementary form (e.g. if it is in the ECG baseline, which corresponds to

the heart resting state), just a message is shown in the log box; otherwise (i.e., the clicked point is located in an ECG elementary form), two events are triggered: (i) the chart is reloaded for emphasizing the identified pattern; and (ii) the bioelectric phenomenon is simulated in the heart-like image.

- (I3)** selection of a specific point of the heart-like image; this enables (i) the simulation of the bioelectric phenomenon correspondent to this point; and (ii) also reloads the ECG chart, but emphasizing the ECG pattern correlated to the point in all the cycles⁴ appearing in the ECG waveform.

In what follows these features are described in the context of the two client-server RPCs they produce.

3.1 ECG Chart Service

When the user clicks a record sample **(1)** (cf. the record samples' widget on the left in Figure 2), an RPC is triggered by the client requesting a URL. This URL locates a temporary file required by the flash object to plot the ECG waveform on the chart. This file contains the chart data generated by the server from the chosen record sample, which is represented by the ECG web ontology in an OWL A-Box. As soon as the client receives a successful RPC callback from the server, the flash object is loaded and the ECG data is populated on the chart.

On the other hand, when the user click comes from the heart flash object **(2)**, an extended version of the RPC just mentioned is triggered with an additional parameter. It informs the clicked part of the heart electrical conduction system. The server then generates the correlated ECG chart, but with an additional feature: the ECG waveform pattern associated with the clicked part of the heart electrical system is emphasized in all *cycles*.

3.2 Inference Service

This service is requested by the client as answer to a click performed on the ECG waveform **(3)**. The service comprises an RPC passing as parameters the current selected record sample as well as the *x* coordinate of the chart clicked point. In the server-side logic, the following actions are triggered:

- (i) searching in the ECG ontology A-Box that holds the record sample what is the ECG pattern where the click has been performed;
- (ii) reasoning about the fetched ECG pattern and infer new facts according to the properties of the pattern (e.g. whether it is an elementary form, or just heart a resting state);
- (iii) requesting the ECG chart service for reloading the chart with the recognized pattern emphasized (just in case it is an *elementary form*);
- (iv) enabling a simulation of the pattern-correlated heart electrical phenomena;

As an example, consider the case illustrated in Figure 2. The click took place in the second cycle of the waveform. As soon as the server has fetched the clicked pattern in the ECG ontology and recognized it as a QRS complex in the *Cycle 2*, one fact indicating that the *QRSComplex 2* was clicked is asserted into the ontology A-Box. The reasoning concerning the selected elementary form is then performed. Since it is a normal QRS complex, R1 is fired (cf.

¹ Google Web Toolkit website: <<http://code.google.com/webtoolkit/>>

² A T-Box (or Terminological Box) in a DL-based ontology is the collection of concepts and relations in that ontology.

³ An A-Box (or Assertional Box) in a DL-based ontology is the collection of the so-called facts (or instances of concepts and relations) in that ontology.

⁴ Heart beats appear in the ECG waveform as periodic cycles. Each normal cycle has known patterns called elementary forms.

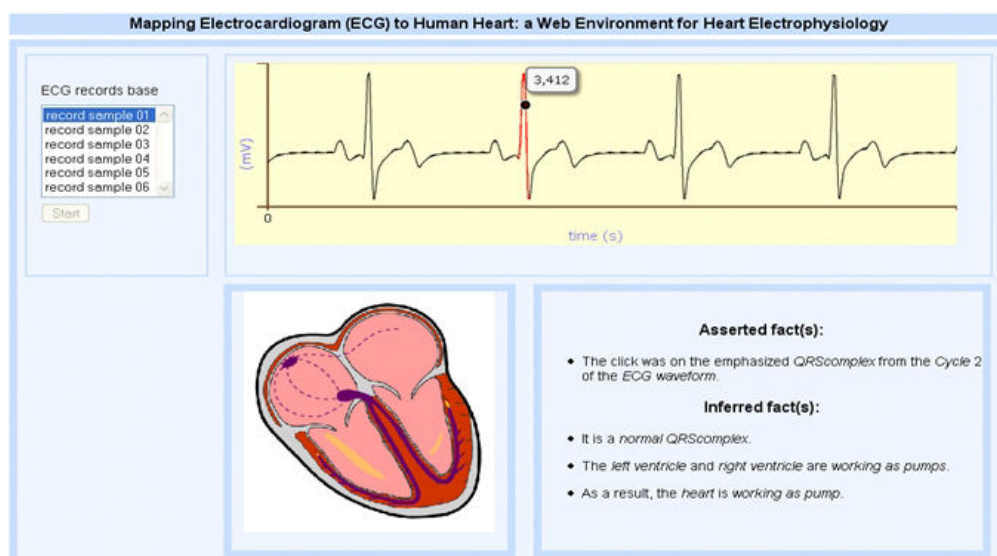


Figure 2. The ontology-based web application.

Section 2.1). As a result, the heart behavior associated to the elementary form is inferred and described in the log box. The ECG chart is then reloaded showing only the QRS complex in the second cycle emphasized. Finally, the correlated heart electrical phenomenon is simulated through the flash animation (cf. Figure 2). Those correlations between ECG patterns and heart electrical phenomena are therefore made explicit to the human observer.

4. PERFORMANCE EVALUATION

In this section, we report experiments conducted in order to evaluate the performance of the proposed application. They were performed using the application server Apache Tomcat 6.0.16 on a Microsoft Windows machine featuring AMD Turion 1.8 GHz and 1GB of main memory. The web application is implemented in Java 1.6.0_02 by using GWT 1.4, Jena-2.5.5 and Pellet-1.5.2.

The timing measurements for **I2** are the foremost in relevance. The reason is that they give an outlook of the application performance bottleneck: the OWL DL + SWRL-based automated reasoning. The first results are encouraging. As shown in Table 1, the reasoning takes just 1.6 ms, on average; while *information retrieval* is also not so time-consuming (2689 ms, on average).

Table 1. Timing measurements (in ms) for (2)

Event	Mean	Median	Stand. Deviation
Click processing	0	0	0
RPC call	7.9	8.3	7.5
Loading OWL files	200	58.8	179.5
Fetching ECG pattern	0	0	0
Reasoning	1.6	5.1	0
Information retrieval	2689	2860.4	2422
RPC callback	14	4.9	15.5
Callback processing	46.9	32.1	39.5
Total time	2959.4	2844.3	2742

For the case of 76 classes, 85 properties and 222 individuals, the information retrieval time stays up to 5111 ms. Nonetheless, there are multiple ways of retrieving the same piece of information in Pellet/Jena, and we have not yet given attention to optimization. The DL expressivity of the implemented OHE is ALCHIN(D) (see

[1, Chapter 5] for DLs' expressivity details). Depending on the expressivity, different completion strategies are used by Pellet. RuleStrategy has been used in this case (it is the default one in the presence of rules). With respect to the media, the ECG chart and heart animation SWF files have 64 kb and 35 kb respectively. These sizes are quite small for the server-to-client transmission.

5. DISCUSSION & RELATED WORK

Biomedical domain ontologies have been mostly applied up to date for [2]: (i) semantically driven integration of information from different sources that use different biomedical terminologies; (ii) modeling and reasoning about complex entities, which requires knowledge in basic science such as, e.g., anatomy, where many non-trivial modeling issues arises; and (iii) reasoning about individual data, i.e., biomedical domain ontologies can provide generic knowledge for reasoning about individual data in various systems. The proposal of this paper fits in (ii) and (iii). To our knowledge, there are many research efforts in (i), which are mostly concerned with the enhancement and alignment of biomedical terminologies such as SNOMED-CT⁵ and UMLS⁶. On the other hand, in the sense of (ii), Rubin et al. [16] applies an ontology of anatomy linked with geometric models to reason about penetrating injuries in military scenarios.

On one side, as discussed in the introduction of this paper, the OBO literature highlights the need for promoting domain ontologies in Biomedicine. On the other side, existing ECG standards, e.g., HL7 ECG Annotation Message v3⁷, are developed by using standard conceptual modeling languages (e.g. UML) that allow the production of models of poor expressivity and clarity (see [8, Chapter 8] for an analysis of UML). This becomes, in fact, a challenge to overcome since these standardization initiatives are mainly concerned to foster semantic interoperability, in general, and data integration, in particular, between heterogeneous health information systems. Analogously

⁵ Available at: <<http://www.ihtsdo.org/snomed-ct>>

⁶ Available at: <<http://www.nlm.nih.gov/research/umls>>

⁷ Available at: <<http://www.hl7.org/V3AnnECG>>

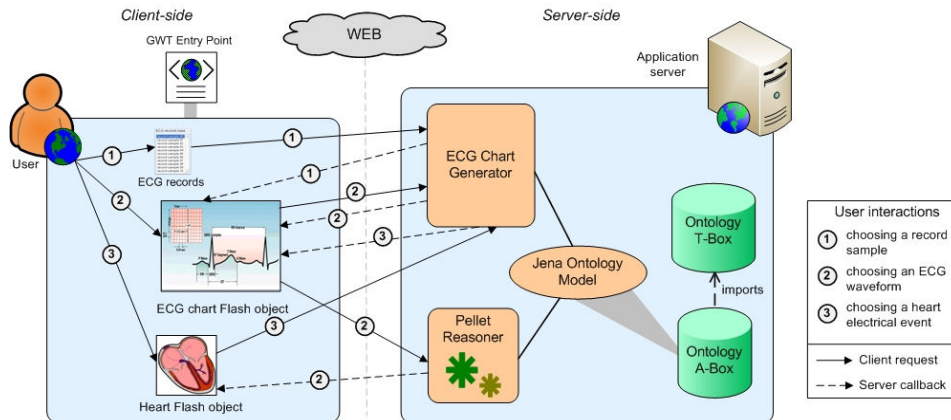


Figure 3. Architecture overview: components and possible user interactions.

to Burgun [2], we believe that a domain ontology such as OHE can be used to support the design of interoperable versions of ECG standards (the case (i) aforementioned). To cite one of the benefits achieved, (viz., cost-effective), n ontologies require $n - 1$ mappings to a domain ontology whereas $n(n - 1) / 2$ pairwise mappings [2].

6. CONCLUSION

The application proposed in the present paper is a prototype that can illustrate the potential of using OHE for representation, reasoning and visualization of heart electrophysiology on the web. As presented here, this application has exhibited promising results to further support teaching heart electrophysiology. It, however, ought to be augmented in many aspects (e.g., optimization issues, OHE extension, experts' evaluation, ethical issues and so on) in order to properly serve in real scenarios.

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