APPLICATIONS AND USES OF DENTAL ONTOLOGIES

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ABSTRACT

The development of a number of large-scale semantically-rich ontologies for biomedicine attests to the interest of life science researchers and clinicians in Semantic Web technologies. To date, however, the dental profession has lagged behind other areas of biomedicine in developing a commonly accepted, standardized ontology to support the representation of dental knowledge and information. This paper attempts to identify some of the potential uses of dental ontologies as part of an effort to motivate the development of ontologies for the dental domain. The identified uses of dental ontologies include support for advanced data analysis and knowledge discovery capabilities, the implementation of novel education and training technologies, the development of information exchange and interoperability solutions, the better integration of scientific and clinical evidence into clinical decision-making, and the development of better clinical decision support systems. Some of the social issues raised by these uses include the ethics of using patient data without consent, the role played by ontologies in enforcing compliance with regulatory criteria and legislative constraints, and the extent to which the advent of the Semantic Web introduces new training requirements for dental students. Some of the technological issues relate to the need to extract information from a variety of resources (for example, natural language texts), the need to automatically annotate information resources with ontology elements, and the need to establish mappings between a variety of existing dental terminologies.

KEYWORDS

ontology, dental informatics, semantic web, dentistry, web science, e-health

1. INTRODUCTION

The advent of the Semantic Web (Berners-Lee, Hendler et al. 2001) has provided the means by which (at least some forms of) human knowledge can be made available on the World Wide Web (WWW). Typically, the knowledge associated with some target domain of discourse (e.g. dentistry) is represented in the form of an ontology using a special purpose knowledge representation language, such as the Web Ontology Language (OWL), and it is then made available for use by publishing the ontology on the WWW.

Within biomedicine, a large number of ontology development efforts have been established to support practitioners and researchers working in a variety of areas. Perhaps the most notable of these efforts is the Gene Ontology project[1] (Ashburner, Ball et al. 2000), which aims to standardize the representation of gene and gene product attributes across multiple species and data sources. However, many other biomedical ontologies[2] are available, and these support a rich range of actual (and potential) bioinformatics applications.

In spite of the general support for ontologies within the biomedical community, there are relatively few ontologies available for use by the dental community at the present time. What ontology engineering efforts have been undertaken have largely been directed to the provision of small, special-purpose and application specific ontologies (e.g. Bogdan 2011); large-scale dental ontologies with broad coverage of the dental domain are currently absent. This is somewhat surprising given the generally positive reception of dental ontologies in the scientific and medical literature (Sittig, Kirshner et al. 2003; Smith, Goldberg et al. 2010;

[1] See http://www.geneontology.org/
[2] See, for example, the ontologies available at the OBO Foundry website (http://obofoundry.org/).

Schleyer, Mattsson et al. 2011). Sittig et al (2003) thus argue that the development of a dental ontology constitutes a key challenge for dental informatics. They argue that "Such an ontology forms the basis of the field of dental informatics" and that "Without such a standardized controlled terminology, all other clinical data and knowledge bases will not be of much use."

The current paper forms part of an effort to develop an ontology for the dental domain that is being undertaken by the University of Southampton in collaboration with dental practitioners. The main aim of the paper is to identify some of the uses and applications of dental ontologies. This is intended to motivate ontology development efforts by highlighting the potential benefits of ontologies to the clinical and scientific dental communities. A second aim of the paper is to identify some of the sociotechnical issues associated with the uses of dental ontologies. Here, the main objective is to arrive at a better understanding of the research challenges facing those who work in the nascent fields of both Web Science (Shadbolt and Berners-Lee 2008) and dental informatics (Schleyer and Spallek 2001).

2. USES AND APPLICATIONS OF DENTAL ONTOLOGIES

2.1 Data Analysis and Knowledge Discovery

One of the main uses of ontologies is to support the publication, dissemination and exploitation of large datasets. Ontologies can therefore serve as a semantic backbone for linked data initiatives that seek to make data available on the Web in a form that is amenable to machine-based processing (Bizer, Heath et al. 2009; Heath and Bizer 2011). As an example of this kind of initiative, the UK Government is currently seeking to make large bodies of public sector information available via its data.gov.uk website[3]. The range of datasets currently targeted by this effort include UK geography, transportation and crime; however, future efforts may also include information from the health domain.

One of the benefits of making data available in a structured, easily accessible and understandable format is that it opens up a rich range of analytic opportunities. Some of the applications that have been developed using UK public sector information (see http://data.gov.uk/apps) attest to the diversity of ways in which linked data might be analyzed, manipulated and exploited. Of particular interest in this respect is the opportunities that such data provides for the discovery of new knowledge. Thus, when multiple bodies of data are made available, and the elements from different datasets can be easily aligned and integrated, it becomes possible to analyze data in a way that reveals new relationships, contingencies and causal relationships. In some cases, this can lead to new insights and scientific discoveries in a particular domain. For example, through the analysis of the International Classification of Diseases (ICD) codes entered in Electronic Health Records (EHR) in the US, researchers were able to identify an association between myocardial infarction and the COX-2 inhibitors rofecoxib and celecoxib (Brownstein, Sordo et al. 2007). These kind of data-driven discoveries highlight the value of efforts which seek to make data available using the techniques and technologies of the Semantic Web. When data is published on the Web as linked data, it becomes available in a form that supports the sort of filtering, retrieval and manipulation capabilities required for knowledge discovery. In addition to this, when data is made available alongside other datasets in the context of the Semantic Web, it becomes much easier to integrate data from disparate datasets. For example, one could attempt to integrate patient dental records and conventional medical records, or one could aim to analyze dental treatment outcomes with respect to a variety of socio-economic and geo-political variables. These kinds of analyses not only support decision-making at the national level (for example, highlighting the shortcomings of current social policy or indicating required changes to the way oral healthcare is delivered), they also support a range of scientific research activities intended to advance our understanding of dental conditions and the relative success of different treatment interventions.

In all likelihood, one of the main points of interest of Web-based data publication efforts in the dental domain is likely to be patient dental records. Such records typically provide valuable information about the kinds of conditions reported by patients, the diagnoses made by dentists, the advice given to patients, and the various treatments administered. They also, at least sometimes, provide important information about predisposing health factors, such as tobacco use and use of xerogenic medications. Clearly, the availability of

[3] See http://data.gov.uk/

such data at a national and international level would be a tremendous boon to those concerned with epidemiological and health-related research, especially if such data could be successfully combined and integrated with other kinds of information (for example, information about the psychosocial, environmental, familial, socio-economic, genetic and physiological characteristics of patients).

The main issues for ontology-mediated publication of patient information in the dental domain at the present time relate to concerns over patient confidentiality, the ethics of using patient data without consent, and the problem of making existing data available in the format required by the Semantic Web. In respect of patient confidentiality, for example, people are understandably cautious about the possibility of personal information becoming available for wider, even if steps are taken to anonymize patient data. It is here that one of the core strengths of linked data – its ability to easily link to other disparate datasets – becomes a potential point of concern. This is because the more linkages we establish between a particular data element (e.g. a particular dental condition) and other data elements (e.g. prevailing medical conditions), the easier it becomes to infer additional information. This is both a boon and a burden. It is a boon inasmuch as it enables us to reveal important relationships and associations that drive the process of scientific discovery and understanding, but is a burden inasmuch as it sometimes reveals information that we would otherwise want to be kept hidden. In the current case, there is a concern that the more we link patient-related data elements, the greater the chance that we might inadvertently reveal the identity of a particular patient. The solution is, of course, to somehow restrict data linkages in a way that protects patient confidentiality. However, it is not clear how (or whether) this could be done *a priori* for any particular dataset, and there is also a risk that by restricting the kind of networks into which data elements can be embedded we sacrifice some of the epistemic insights that such data promises to make available.

2.2 Education and Training

Ontologies form important resources in terms of the epistemic infrastructure of a domain, and it would thus be surprising if they did not have some sort of role to play in terms of education and training. In fact, the way in which ontologies have been used to support education and training is often indirect. Seldom are ontologies used by themselves as resources in the way that, for example, conventional textbooks would be used. Instead, ontologies tend to be used as a resource that supports the operation of e-learning systems. Within dentistry, for example, ontologies have been used to support the semantic annotation of virtual 3D models that are subsequently used in teaching students about dental anatomy (Dias, Brega et al. 2011). Ontologies have also been used in augmented reality applications that assist students in learning about the preparation of teeth for all-ceramic restorations (Bogdan 2011).

In addition to the use of dental ontologies to support the training and education of the next generation of dental researchers and clinicians, there is also an issue here concerning the extent to which the advent of the Semantic Web requires changes to the kinds of things that dental students get taught. If Semantic Web technologies are going to be an important element of future dental information technology, then there may be a requirement to teach students about such technologies as part of their dental training. As Mendonça (2004) comments: "From an educational perspective, educators have expressed concerns that health care professionals are not well prepared to meet society's expectations with regard to evidence-based practice and the use of information technology in the delivery of health care" (pg. 595).

2.3 Compliance with Legislative Constraints and Regulatory Criteria

In some countries, the provision of dental services is regulated by national agencies and compliance with the regulatory framework is often a condition for the financial remuneration of such services. In the UK, for example, dentists working within the National Health Service (NHS) are subject to regulatory constraints governing the conditions under which financial remuneration may be made for specific dental services (National Health Service 2005). One use of ontologies here is to support dental practitioners in understanding and complying with such regulations. One could imagine, for example, the conditions of the regulatory instrument being captured in an ontology and a reasoner being used to check proposed treatments for unintended violations of the regulatory constraints.

Of course, from the perspective of the regulatory body, there is often a need to detect abuses of the regulatory system. In the case of the UK, for instance, there have been a number of cases where NHS dentists

have been convicted of falsifying patient records in an effort to secure public funds. In addition, the manner in which dental services are funded within the NHS could make patients vulnerable to unnecessary reparative work by unscrupulous dentists. The use of ontologies to record patient information arguably makes it easier for regulatory authorities to detect incidences of non-compliance and malpractice. Once patient records become linked to specific individuals through other datasets at a national level, then the misrepresentation of patient information becomes harder to implement. Similarly, dentists who opt to undertake unnecessary treatments risk becoming statistical outliers when their treatment records subjected to comparative analyses along demographic and geographic criteria. All this argues in favor of greater transparency when it comes to the kinds of treatments that dentists administer.

2.4 Evidence-Based Dentistry

Evidence-Based Dentistry (EBD) is a specific form of Evidence-Based Medicine (EBM) (Sackett, Rosenberg et al. 1996) that emphasizes the integration of scientific and clinical evidence with the expertise of individual dental practitioners in order to improve patient care. However, while the goals of EBD are clear enough, the actual means by which scientific and clinical findings can be successfully integrated into routine clinical practice remains problematic. Clearly, like other forms of EBM, EBD requires streamlined access to the latest empirical data regarding specific medical conditions as well as prevailing views on what constitutes best practice in specific situations. As such, one application of ontologies in support of EBD could be to improve access to relevant information resources in particular clinical decision-making contexts. This can be accomplished by using elements from the ontology to 'semantically annotate' specific resources (e.g. research articles) on the Web. This process of semantic annotation makes the semantic referents of the annotated resources accessible to applications whose task it is to make practitioners aware of those resources. In practice, of course, this process confronts a number of challenges concerning both the annotation of resources and the mechanisms by which practitioners are made aware of the resources. In the first case, there is the question of whether the semantic annotation process is to be done automatically. If so, there is a requirement for robust resource classification systems that often rely on sophisticated machine learning techniques. In the second case, it is important to fully understand the human factors issues associated with information processing and decision-making in the dental domain (see Schleyer, Mattsson et al. 2011).

2.5 Information Exchange and Integration

One use of ontologies is to support information exchange and integration between user communities that countenance distinct data models and vocabularies. This particular use of ontologies has been a significant focus of research attention within the Semantic Web community for some time, and a rich literature has emerged regarding candidate techniques, technologies and representational formalisms (Kalfoglou and Schorlemmer 2003). There are, in fact, a number of ways in which ontologies might be used to support information exchange and integration in the dental domain. One use is to support the linkage of dental information with other kinds of information. For example, recent work has sought to develop ontologies in support of both salivaomics research (Ai, Smith et al. 2010) and the classification of orofacial pains (Nixdorf, Drangsholt et al. 2011). Both of these domains seem at least potentially relevant to dentistry in either a clinical or research context, and it is therefore important that appropriate linkages between the various ontologies are established.

A second use for ontologies in information exchange and integration contexts is to serve as a 'semantic bridge' between a variety of potentially competing taxonomies, terminologies and controlled vocabularies that have recently emerged in the dental domain. A particular problem is presented by the multiplicity of diagnostic coding systems that have been developed to describe dental diagnoses. One such system is SNODENT, which is maintained by the American Dental Association (ADA) (Goldberg, Ceusters et al. 2005). Another is the 'EZ' coding system described by Kalenderian et al (2011). The emergence of different coding systems constitutes a potential source of conflict and competition between different agencies, whereas genuine progress in advancing the state-of-the-art of oral healthcare arguably demands cooperation and collaboration at both the national and international levels. Ontologies may be seen as one means of reducing the inherent tension here. They enable existing coding systems to be used, while simultaneously providing the basis for meaning-preserving modes of information transfer. This does not mean that there are no

significant sociotechnical challenges confronting the realization of these interoperability solutions. In addition to the requirement for effective collaboration technologies, most semantic integration efforts require some degree of flexibility by one or more agencies in order to establish an effective mapping. This is particularly likely to be the case when it comes to dental diagnostic coding systems, since some coding systems have shown deficiencies in both content and coverage (Goldberg, Ceusters et al. 2005) and may therefore require modification.

2.6 Clinical Decision Support

Clinical decision support systems (CDSSs) are computer programs that are used to support clinical decision making, often by exploiting bodies of domain-specific knowledge. CDSSs have been the focus of considerable research and development attention within the dental community over the past several decades (White 1996; Mendonça 2004), and a number of applications have been developed to support decision-making in specific areas. For example, in a comprehensive review of the literature, White (1996) identified over thirty decision support systems in the dental domain. He grouped these systems into seven areas, including dental emergencies and trauma, orofacial pain, oral medicine, oral radiology, orthodontics, pulpal diagnosis, and restorative dentistry. Other systems that have emerged since White's review include systems to support decisions related to oral surgery (Brickley and Shepherd 1996), caries management (Benn 2002) and treatment planning (Finkeissen, Böhret et al. 2002) (see Mendonça 2004, for a review).

In spite of their potential benefits to dental clinicians, CDSSs are not commonly used in dental practice. One reason for this may be that such systems often have very limited scope in terms of the kinds of decisions they support – they are often designed to support one particular kind of decision (e.g. treatments for lower third molar problems). CDSSs also impose an overhead in terms of the cost associated with knowledge maintenance – it often requires a lot of time and effort to keep the knowledge base of a CDSS up-to-date. Both of these problems may be seen as having their origins in the 'knowledge acquisition bottleneck' associated with many knowledge engineering efforts. The problem is that CDSSs rely on expert knowledge, and such knowledge is both difficult and expensive to acquire. Dental ontologies may provide a partial solution to this problem. Firstly, by making knowledge available in the context of the WWW, ontologies enable CDSSs to automatically update their knowledge bases with respect to the latest knowledge that is available. Furthermore, by acting as a consensual representation of knowledge in the dental domain, ontologies can effectively harness the efforts of researchers, clinicians and knowledge engineers on a global scale. Finally, the use of ontologies as a representational device for the publication of dental datasets (see Section 2.1), provides a means by which the requisite knowledge for CDSSs may be made available as a side-effect of the daily process of recording human clinical decision and dental treatment outcomes. Of course, not all the reasons for the poor uptake of CDSSs relate to the technical difficulties of acquiring and maintaining knowledge. Work in knowledge engineering has often failed to pay adequate attention to the way in which humans process information and make decisions in real world situations. As Schleyer et al (2011) comment, "Without a good understanding of how clinicians review, analyse, and process clinical information, the design of effective computer-based tools to support these activities is severely handicapped." The highlights the importance of adopting human-centered design approaches in the development of future CDSSs.

3. CONCLUSION

In spite of an ever-increasing number of biomedical ontologies, dentistry still lacks a high-quality ontology with good coverage of the dental domain. One reason for this may be that the potential uses and applications of dental ontologies have not been adequately described. This paper represents an attempt to address this issue. It describes a number of ways in which dental ontologies might be used and the kind of benefits they might provide to patients, the dental profession and society at large. If we are to press maximal social benefit from dental ontologies, however, we need to have a clear idea not only of the kinds of uses to which ontologies may be put but also the kind of sociotechnical issues that are raised by these uses. Most of the applications described in this paper are associated with significant social and technical issues, and these highlight important areas for future research and development. Importantly, many of the issues associated

with the exploitation of dental ontologies are unlikely to be resolved by researchers working within a single discipline. Instead, the resolution of many of the issues described herein requires the concerted effort of experts from multiple fields, including social scientists, computer scientists, psychologists and legal experts. This requirement for multidisciplinary collaboration suggests that the topic of dental ontologies is a excellent candidate for research attention in the nascent discipline of Web Science (Shadbolt and Berners-Lee 2008). Web Science is a discipline which focuses its attention on the sociotechnical aspects of the Web, and it also seeks to orient technology development in ways that benefit society. Such scientific and social goals are perfectly compatible with the future development and exploitation of ontologies in the dental domain.

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