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Shared decision support system on dental restoration

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ABSTRACT

Shared decision making (SDM) is an approach in which doctor–patient communication regarding available evidence and patient preferences is facilitated to enable the patient to participate in treatment decisions. SDM affords not only the inclusion of the ethical diversities involved in patient-centered care, but also the quality improvements in decision-making process. Though SDM has been studied extensively, there have been few practical implementations in real clinical environments. In this paper, we propose a shared decision-making system with its focus on dental restorative treatment planning. In our system, restorative treatment alternatives for SDM were generated by employing an ontology that had captured the clinical knowledge required for treatments. We considered patient preferences for treatment as an important support for mutual agreements between the patient and the doctor on healthcare decisions. We constructed a consistent and robust hierarchy of preferences using the analytic hierarchy process (AHP) method, to help determine treatment priorities. On the basis of our proposed system, we developed a Web-based application for the visualization of evidence-based treatment recommendations with preference-based weights. We tested our system using a scenario to illustrate how doctors and patients can make shared decisions. The application is of high value in supporting SDM between doctors and patients, and expedites effective treatments and enhanced patient satisfaction.

1. Introduction

A clinical decision support system (CDSS) is an application designed to assist health professionals in decision-making tasks as in regard to diagnosis and treatment planning (Shortliffe, Perreault, Wiederhold, & Fagan, 2001). Focusing on dentistry, there are only a few relevant studies exploring the potentials of CDSS. For instance, Brickley et al. (Brickley & Shepherd, 1996) developed a neural network application to provide decision support for lower third molar treatment-planning. Other CDSS examples for dentistry are caries management (Benn, 2002) and intelligent dental treatment planning (Finkeissen et al., 2003). However, none of these CDSSs were designed to consider patient preferences for enhancing the quality of patient-centred, or personalized, services and thereby improving patient satisfaction.

Restorative treatment decision making by dentists and patients often exhibit wide variations (Bader & Shugars, 1995). This appears to be due to differences between patient preferences and clinical judgments. Typically, dentists and patients exhibit differences in their preferences for dental restorative materials. For example, dentists tend to choose one with high longevity, while young patients are sensitive to aesthetics (Espelid et al., 2006). According to (Vidnes-Kopperud, Tveit, Gaarden, Sandvik, & Espelid, 2009), dentists use tooth-coloured restorative materials more often than dental amalgams for restorations in stress-bearing areas in young patients. In general, it is recommended that dentists consider patient preferences for dental restorative treatment alternatives prior to making a treatment decision, if the physical characteristics of the materials are not critical. Patients also tend to participate actively in the restorative treatment planning process when options abound and when they have material preferences (Oates, Fitzgerald, & Alexander, 1995). Furthermore, increased levels of patient participation tend to promote their satisfaction with treatment outcomes.

Shared decision making (SDM) is an alternative to the paternalistic care model (Charles, Gafni, & Whelan, 1997). It enables both patients and clinicians to reach mutual agreements on appropriate health care and treatment decisions (Frosch & Kaplan, 1999). In SDM, the patient is provided with all available evidences and information about a given medical problem, and the suitability of each alternative treatment plan is measured in relation to the patient preferences. SDM is a relatively new concept with a few implementations in health care settings. Implementation obstacles of SDM

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include the task complexity, lack of time (Gravel, Légaré, & Graham, 2006), and missing information (Elwyn, Edwards, Gwyn, & Grol, 1999). In dentistry, Johnson et al. (Johnson, Schwartz, Goldberg, & Koerber, 2006) devised the Endodontic Decision Board (EndoDB) as a decision aid, a popular SDM approach. Though EndoDB facilitates the communication between patients and clinicians through the articulation of alternatives between dental treatment processes, it does not effectively identify or discuss preferences from patients' perspectives and is not suitable for complex, busy clinical settings. The analytic hierarchy process (AHP) is one of the most well-known and widely used multi-criteria decision making (MCDM) methods. It is specifically designed for dealing with complex decisions that require the integration of quantitative data and qualitative considerations. AHP has been successfully applied to decision making processes across a wide variety of fields including health care (Liberatore & Nydick, 2008), resource allocation, and quality management. It provides both a patient and a doctor with a simple and robust mathematical method for measuring or visualizing preferences in the form of a psychological hierarchy tree with pairwise comparisons (Dolan, 2000), and patients find AHP as a suitable tool for sharing their preferences with their doctors (Singpurwalla, Forman, & Zalkind, 1999).

A knowledge-based system that supports CDSSs in SDM requires a considerable amount of domain knowledge (Musen, 2001). A reusable and application-independent domain ontology, or structural framework, would be able to minimize the efforts required for knowledge attainment (GRUBER, 1993). Though CDSSs are developed using ontologies, few are applied to dental restorative treatment planning systems. In our previous study (Park, Lee, Kim, & Kim, 2010), we developed an ontology to represent the concepts related to the decision-making processes involving the choice of restoration types. The ontology specified the tacit knowledge of doctors participating in SDM, thereby facilitating communication and knowledge sharing between the doctors and the patients.

The paper proposes a shared dental restorative treatment decision support system that manages the knowledge required for problem-solving and converts it into a machine-understandable form, an ontology. The system computes priorities for treatment alternatives based on patient preferences for AHP methodologies. It offers doctors and patients common understanding on which shared decisions are reached based on patient preferences and accumulated clinical knowledge. The remainder of the paper will describe the system designs and illustrate a practical usage scenario.

2. Proposed approach

Our system (Fig. 1) collects the patient's dental information, such as the disease and affected location, through an oral examination. This information is entered into the ontology, which was first created and populated with knowledge gained both from journals and textbooks, and from consultations with dental experts. Evidence-based restorative treatment candidates are automatically obtained by querying the ontology that contains information about the patient's problem. In addition, the system quantitatively evaluates the preferences of the patient, such as convenience, price, aesthetics, and longevity of dental treatments. A priority for each of the previously gathered evidence-based treatment options is calculated using pairwise comparisons. Employing the AHP methodology, the preferences and evidence-based treatment options are arranged in order of priority. The dentist is now in a position to communicate the resulting decision aids with the patient and can make a definitive treatment plan.

2.1. Ontology design

When designing an ontology for dental restorative treatment plan formulation, we consider three main factors: tooth anatomy including spatial relationships, classification of diseases and findings, and restorative treatment options. We build the ontology, called TPSS (Treatment Planning Support System) ontology, which includes concepts and properties from ICD-10 (for diseases and findings) and the Foundational Model of Anatomy (FMA) ontology (for tooth anatomy). TPSS ontology is represented in the Web Ontology Language (OWL2) format. Its major classes and properties are described in the following. Properties are denoted in lowercase letters and bold, and classes in uppercase letters and italics.

ICD-10 acted as the basis for treatment options, which were further refined to represent restorative treatment options by combining diseases/findings with tooth anatomy concepts from the FMA. Juxtaposing the disease (and/or findings) with its location such as a tooth or jaw (i.e., mandible or maxilla) has led to more accurate treatment options as opposed to when dentists made restorative treatment decisions solely based on their beliefs or knowledge.

The FMA ontology is a reference ontology considered to be the most suitable template for aligning existing ontologies in the medical domain (Rosse & Mejino, 2003). Only those tooth-related concept classes were imported and converted to the OWL2 format while the original part-whole structure was kept. FMA uses frame-based formalism, and as such, if we carelessly convert it to description logic-based formalism, unintended conclusions or missing concepts may have resulted (Golbreich, Zhang, & Bodenreider, 2006). Therefore, we constructed a partonomic hierarchy by manually implementing **part_of** and **has_part** properties. In addition, we converted the tooth names into tooth numbers for convenience.

In regard to treatment alternatives, however, no comprehensive ontology exists that represents treatment alternatives. Furthermore, to our best knowledge, the existence of a relatively complete classification system or ontology on restorative treatment alternatives is very unlikely. Therefore, we manually created treatment alternatives using the concepts from the Unified Medical Language System (UMLS) metathesaurus.

The three bodies of knowledge—tooth anatomy, disease, and treatment—are semantically linked by the OBO Relation Ontology (RO) (Smith et al., 2005) and some application-specific properties. Three relationships such as **part_of**, **located_in** and **has_participant** are taken from the RO. The spatial relation **part_of** is to represent part-whole relationships. The **located_in** property is defined to be sufficiently broad to enable its use as a medium for spatial relationships. For example, each tooth has different functions, and this necessitates different treatment options for each function. The metal color of amalgam dictates that amalgam restorations cannot be used in esthetic zones, and hence, its location is restricted to posterior teeth. Therefore, we connected a treatment class (amalgam filling) to a tooth anatomy class (posterior tooth) using the **located_in** property as shown in Fig. 2. The **located_in** property not only represents a spatial relationship between biological objects, but also a rather broad connection between occurrents and biological objects, thereby effectively contributing to the development of a concise ontology (Schulz, Marko, & Hahn, 2007). A property in the RO that can link treatment (occurrents) and diseases (dependent continuants) is **has_participant**. Therefore, this property can be used to link diseases and findings with a certain treatment process. However, in order to make the property name more appropriate for our domain, we designed a new application-specific property **has_Indication** on the basis of the **has_participant** property.

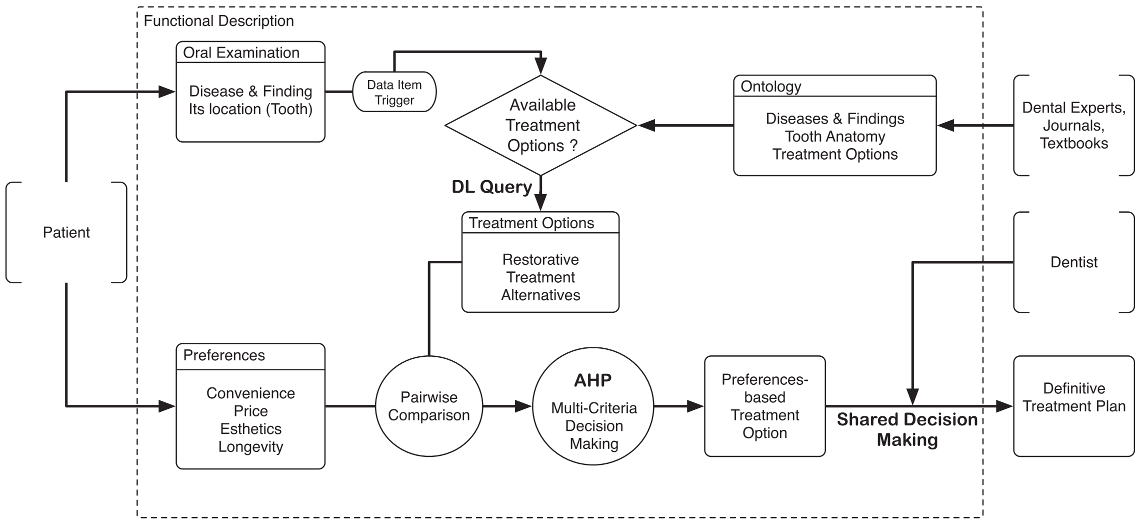

Fig. 1. Description of shared decision making system on dental restoration.

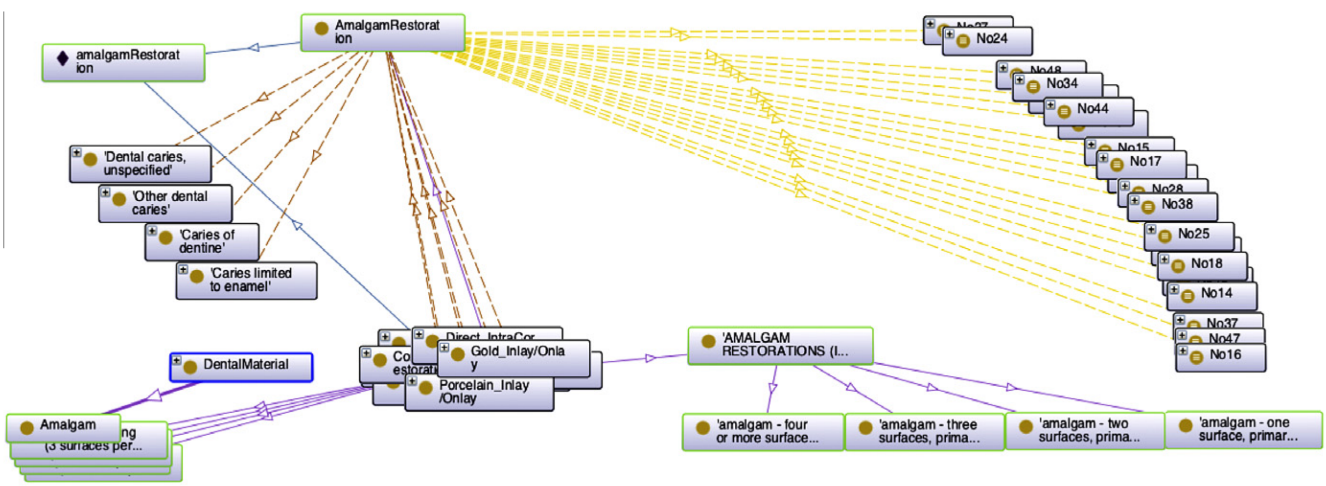

Fig. 2. Classes connected to Amalgam Restoration class.

2.2. Analytic Hierarchy Process (AHP)

Before a patient decides on a restorative treatment, various preferences are typically taken into consideration. Each potential treatment option for the patient typically entails compromises and trade-offs. And the more superfluous the preferences are, the more arduous it is for a patient to arrive at a definitive decision. Furthermore, a decision maker may have a set of preferences that are quite different from those of other decision makers. Hence, the decision process involves an intricate interplay of goals, preferences, and the decision maker himself/herself. MCDM is a technique that can address this problem. There are at present numerous MCDM methods in use. The AHP is an MCDM method, and has been extensively studied and refined. The AHP is advantageous even for constructing qualitative measurements such as preferences in the form of numerical weights or priorities.

The procedure for using the AHP in our study is as follows: (1) Model the problem as a hierarchy. The hierarchy comprises the decision goal, alternatives, and criteria. The decision goal is used to determine the best suitable restorative treatment. Goal-reaching alternatives are established after the analysis of the patient's dental findings in the system. The criteria for evaluating alternatives are in our study the preferences of the patient. Out of a number of potential preferences, four preferences were selected: convenience, esthetics, financial constraints, and quality of the restoration (Kotler & Clarke, 1986; Woodside, Nielsen, Walters, & Muller, 1988). These preferences are addressed in our application as preference decision elements: number of visits, aesthetics, price, and longevity of the restoration, respectively.

(2) Decompose and conduct pairwise comparisons to determine local priorities. Two types of comparisons are possible – comparison of the importance of the criteria in achieving the goal, and comparison of the capacities of the alternatives to meet the criteria. The doctor is responsible for the latter comparison because the patient is not equipped to fully understand the characteristics of the restorative alternatives. A comparison matrix is used to determine the relative capacities of the restorative treatment options that satisfy the patient preferences. For example, an amalgam filling treatment has low local priorities for the aesthetics and longevity factors, and high local priorities for the price and convenience factors. The patient will be asked to rate the importance of their preferences for pairwise comparisons, resulting in a total number of comparisons of $4(4-1)/2$.

When all the pairwise comparisons are completed, the normalized right principal eigenvector of the matrix should be calculated. This eigenvector is calculated by raising the matrix to successive

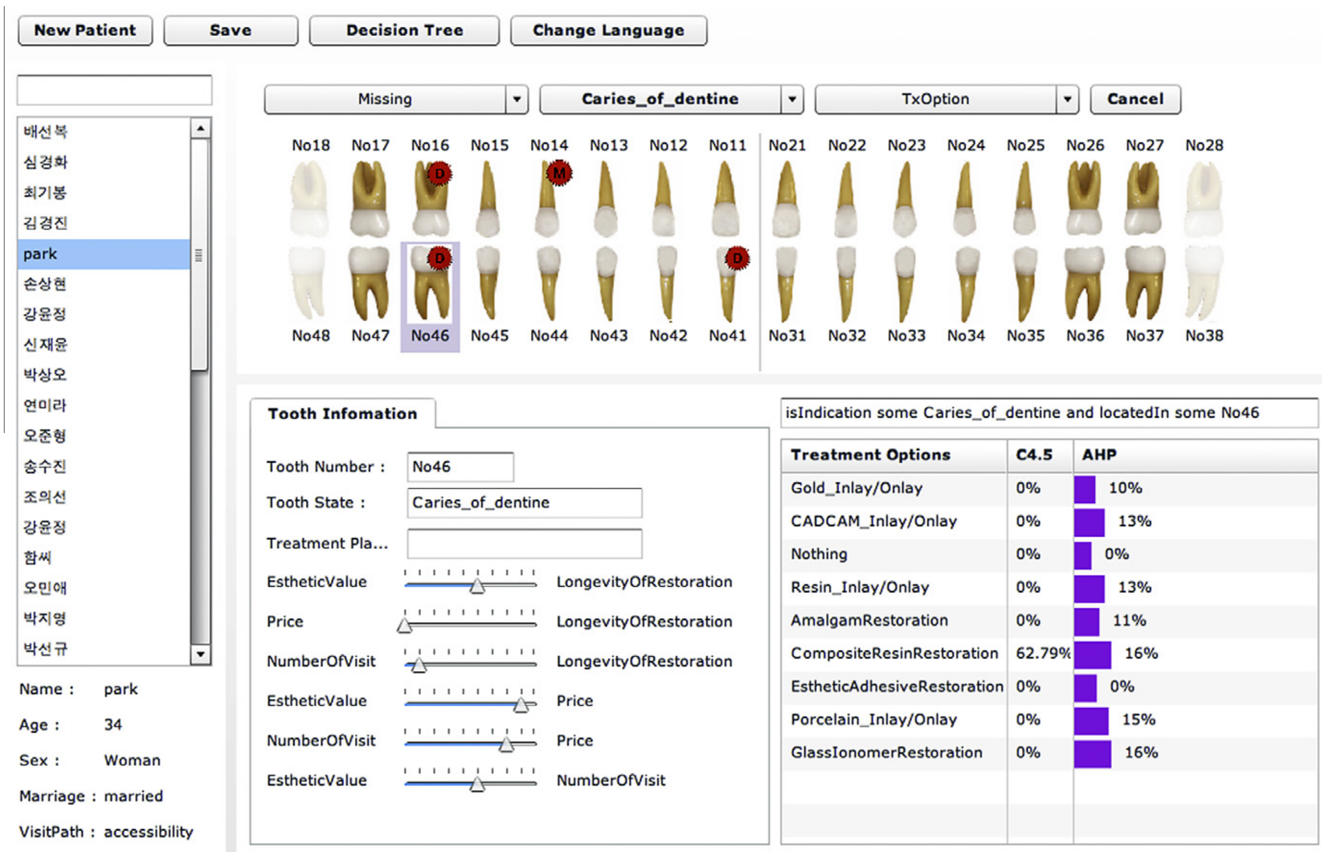

Fig. 3. Application screenshot.

powers and then normalizing it. In addition, the comparison matrix is used to calculate a measure of the consistency of the judgments, called the consistency ratio. The standard definition of acceptable consistency is a consistency ratio $\leqslant 0.10$. If the consistency ratio is greater than 0.10, the pairwise comparison should be re-measured. Such matrix algebra is included in our application.

(3) The final step is to combine the normalized eigenvectors to determine how well the restorative alternatives meet the decision goal. Data regarding the alternatives and preferences are manipulated using a weighted addition that is analogous to the formula for calculating a weighted average. In our application, a bar graph is used to display the weights and it changes when patient preferences are modified. The doctor and the patient can now make a shared decision with the help of the value for the restorative alternative.

2.3. Implementation

Our implemented Web-based application[1] for restorative treatment planning support system is shown in Fig. 3. The application was implemented in the open source framework, Adobe Flex. OWL API (Horridge & Bechhofer, 2009) was used to construct the Create, Read, Update, and Delete (CRUD) functions of the ontology. FaCT++ and HermiT reasoners were used to determine the ontology consistency, establish the subsumption relationships between the classes. A java module was developed to support the AHP methodology in our study.

[1] Our web application is available at http://bike.snu.ac.kr:8080/TPSS_Web2/TPSS.html.

3. Clinical case scenario

Mrs. Park visits a dental clinic for treatment of a mild toothache on the right lower first permanent molar. The doctor takes a dental examination and diagnoses caries of the dentin. Description logics (DL) queries are used to retrieve restorative treatment alternatives suitable for the patient context. For Mrs. Park's case, a DL query that includes dentin caries in the right lower first molar can be formulated as follows:

has_Indication some *Dentin_Caries* and **located_in** some *Right_Lower_First_Molar*

The subclasses satisfying the above query are *Amalgam_Filling*, *Composite_Resin_Filling*, and *Gold_Inlay_Restoration* as shown at Fig. 4.

Subclass subsumption relations allow the final query result to reach the last leaf (descendent) classes: Gold_Inlay/Onlay, CADCAM_Inlay/Onlay, Resin_Inlay/Onlay, Amalgam Restoration, Composite Resin Restoration, Esthetic Adhesive Restoration, Porcelain_Inlay/Onlay, and Glass Ionomer Restoration. If the caries were found in the right upper canine, instead of the right lower first molar, Amalgam_Filling and Gold_Inlay_Restoration would have been excluded from the classes.

Incidentally, Mrs. Park prefers a cheaper restoration without prolonged treatment, and she is not concerned about the esthetics or longevity of the restoration. These preferences are measured using a pairwise comparison and converted to weights on the target restorative alternatives. The AHP results for the treatment options show that a direct intracoronal restoration (i.e., composite resin restoration) is the most satisfying treatment option for her. Note also that AHP values change in tandem with the changes of her preferences and the changes are instantly shown on the screen

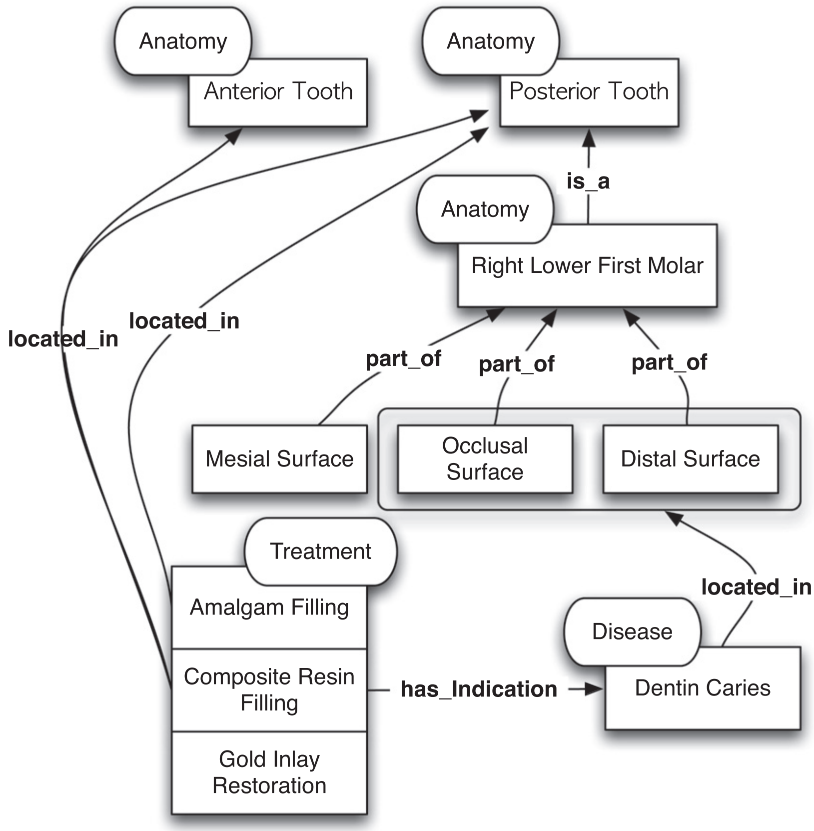

Fig. 4. Classes and their relationships in case scenario.

as shown at Fig. 3. Assume that there is another patient, Mr. Lee, whose disease and its location is the same as Mrs. Park's (i.e., caries of dentine, right lower first molar), but who exhibits interest in restoration longevity and are indifferent to other preferences. In his case, *Gold_Inlay/Onlay* seems to be the most suitable option for him, as shown at Fig. 5. Aided by interactive display of available options and related AHP results, decision-making becomes significantly more sophisticated and intuitive.

4. Discussion

A medical decision can be qualified as either 'effective' or 'preference sensitive', to the extent that it is related to scientific evidence of benefits and risks to patients (O'Connor, Legare, & Stacey, 2003). An *effective* decision is reached when both the doctor and the patient believe that it will effectively deliver substantially more benefits than risks to the patient. A *preference-sensitive* decision holds an inherent uncertainty as to the benefit to risk ratio, in which case the 'best' treatment will depend on the patient's preference.

Most dental restorative treatments fall in the category of preference-sensitive services. Thus, recommending a patient preference-based restorative treatment with scientific evidence is highly desirable, which inevitably entails an SDM environment. Our system is designed to be used as a decision aid for preference-sensitive decision-making.

A domain-specific task ontology, such as the TPSS ontology, should be built on solid foundations proven from previous work, which would ensure levels of compatibility and reusability between the TPSS ontology and other extant ontologies and terminology systems. To that end, we imported ICD-10 and FMA. They were then refined and extended to suit our needs for the restorative treatment decision support system. The TPSS ontology is an ongoing effort in that the concepts can be refined and extended, but at the same time it is a completed work for the purpose of the restorative treatment support system that includes tooth anatomy, dental diseases/findings, and restorative treatment options.

Ontology-based dental treatment options provide individualization. Establishing connections between the teeth and surrounding hard/soft tissues in the oral cavity, with the concepts of diseases and findings, helps to create an appropriate, relevant, and individualized knowledge base. For example, a dentist may believe that, contrary to other doctors' preferences, an anterior tooth should be treated with a metal-free restoration. An ontology can link the concept of a metal-free restoration (e.g., Empress crown, Zirconium crown, or Inceram crown) to an anterior region that includes two incisors and one canine. Our TPSS ontology is generic enough for a clinical case to be linked to doctor-specific restorative treatment decisions that form a robust knowledge base for his/her needs.

Various clinical guidelines can be incorporated into the ontology we have developed. Several reports (Casteleiro & Diz, 2008; Isern & Moreno, 2008; Martínez-Costa, Menárguez-Tortosa, Fernández-Breis, & Maldonado, 2009) have demonstrated that ontology-based clinical guidelines influence the management and re-usability of the guidelines. The major benefit of incorporating ontology-based clinical guidelines is that new or missing concepts outside our TPSS ontology can be added effortlessly, in contrast to cases with static clinical guidelines. Although we are not going to construct a full-featured dental restorative treatment guideline in our system, the TPSS ontology can be readily expanded. In this manner, the evolving clinical guideline ontology can provide dental professionals with evidence-based restorative treatment alternatives.

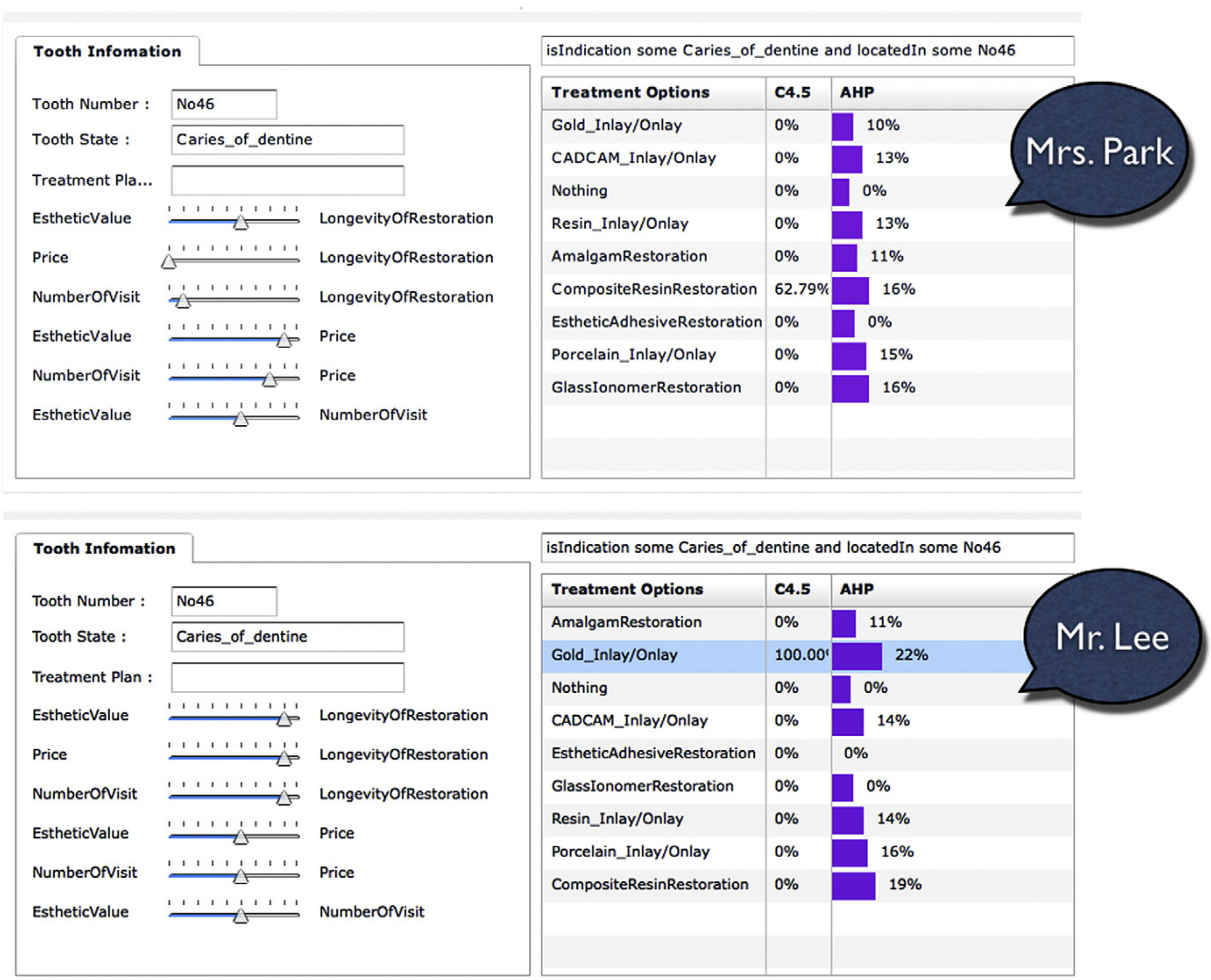

Fig. 5. Same disease and location with varying preferences.

Both individualization and expandability strengthen our ontology base and make it suitable for supporting restorative treatment decisions. Our system presents treatment options generated from the ontology along with individualized AHP goals. We believe that a dynamic ontology knowledge base is a core foundation on which methods for capturing different kinds of patient information can be developed, and restorative treatment knowledge can evolve seamlessly.

There are two issues being investigated: (1) the number of alternative treatment options generated for each clinical case, and (2) patient preference measurements in the AHP. Regarding the first issue, we currently use only two parameters—location and disease—to determine patient-centered restorative alternatives. While these two parameters seemed sufficient, the numbers of alternatives created and presented to users in some cases were simply too many, revealing a need for refinement in the generation of alternatives. One possible solution is to include disease severity and treatment prognosis, which can help limit the alternatives to a more 'manageable' number for the user.

The second issue is linked to the fact that the preferences of a patient are not static or consistent across all his/her medical encounters. This is a legitimate problem in applying the AHP method to medical domains. A patient may typically seek economic value but will rarely simply select a cheap treatment if the disease is severe or emergent. Thus, pre-determined preferences are not always a good solution for finding a satisfying treatment option. To resolve this, we allow our interactive user interface to cater immediately to altered patient preferences.

5. Conclusions

In this study, we have presented our ontology-based SDM system for dental restorative treatment planning. Using an ontology, domain expert knowledge such as a CPG is organized, structured, and implemented to construct a CDSS. Using the AHP methodology in our system, we built a consistent and robust hierarchy of preferences and performed preference measurements. A preference hierarchy with ontology-generated, evidence-based alternatives is an effective means by which to reach a shared decision between the doctor and the patient. A Web-based interactive CDSS application is implemented to support shared decision making. The system is useful in various clinical cases in restorative treatment by providing effective treatments and enhanced patient satisfaction.

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