Clinical Decision Support System for Tooth Retention or Extraction

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ABSTRACT

Treatment planning with regard to retention or extraction decision-making is often challenging, especially to dental students and inexperienced dentists. Such a decision requires consideration of many factors and clinical parameters to achieve an accurate definitive plan and therefore proper dental care. Contemporary dentistry has adopted the concept of evidence-based practice guidelines. Our project has followed this concept, thus literature evidence, clinician's expertise, patient's desires and preferences were factored-in to develop a contemporary approach for determining the overall tooth prognosis accurately. Although, several studies have been published to report the affect of specific clinical parameters on individual tooth prognosis, these studies were isolated and focused on particular aspects for developing tooth prognosis scale rather than evaluation of teeth in comprehensive manner covering all factors relevant to retention or extraction decision-making. Retention of non-salvageable teeth as well as extraction of salvageable teeth can be drastically devastating to patients since they are time consuming, cost more time and money and may lead to loss of trust and confidence in care givers. Thus, a multi-factorial approach for development of accurate prognosis is required. This approach requires sound knowledge of principles and concepts that span across multiple dental specialties of restorative/prosthodontics, periodontics and endodontics. It is extremely difficult for clinicians to recall an extensive list of factors that determine the overall tooth prognosis, especially for dental students and less experienced clinicians. On the other hand, expert clinicians with their knowledge and years of experience are accustomed to critical thinking utilizing comprehensive list of factors on day-to-day clinical practice. However, experts may not always be accessible for consultation at the point of care. To fulfill this ever-outstanding need, we propose the development of a clinical decision support system that satisfies the concept of evidence-based dentistry considering all factors relative to research evidence, clinician's expertise, patient's desires and preferences. Utilizing Exsys Corvid expert system development platform, we have developed an efficient, interactive and user-friendly tool that can easily be hosted on the web, implemented in clinical settings, and integrated with treatment planning procedures into the daily clinical practice. In addition to assistance in clinical setting, our system can also be considered as an educational tool that helps dental students and inexperienced dentists to process challenging clinical scenarios like expert clinicians since it includes comprehensive list of factors that acquires evaluation and response prior to reaching final recommendations. Based on information entered by the user, our system provides clinical recommendations, options and alerts labeled with patients and providers identification numbers, time and date for documentation purposes. Since our system was designed to review user's entry at the results screen, this feature helps clinicians to educate their patients, justify their clinical recommendations and therefore obtain patient's trust and acceptance of treatment. It also allows sharing the results, electronically via emails, with patients and other providers for ease and quick communications. Due to the fact that our system was developed based on evidence-based guidelines, we anticipate improvement in prognostication and treatment planning of questionable teeth and therefore better clinical decision-making as a step to ensure patient's satisfaction and enhanced dental care.

Keywords: Tooth prognosis, CDSSs, Tooth extraction, Tooth retention, Decision-making.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURE

Chapter 1: Introduction

1. 1. Introduction:

The complete loss of teeth in one or both arches may present dramatic negative effects on the patient's ability of mastication, esthetic appeal, self-confidence and social interaction.[1] It has been reported that edentulism affects more than 158 million people worldwide.[1] Despite of its chronic non-reversible nature, proper rehabilitation treatment would improve the patient's quality of life. The goal of modern dentistry is to intervene against uninformed clinical decisions when it comes to dental extraction as it may affect patients negatively.[2] It is of a critical importance to restore normal contour, function, comfort, esthetics, speech, and health regardless of the atrophy, disease, or injury of the stomatognathic system. For decades, several clinical guidelines were emerged to preserve natural dentition and urged to involve the philosophy of evidence based clinical decision-making in daily dental practice. To us as dental clinicians as well for patients, tooth extraction has been considered the last choice in the dental management chain of options, especially when all other treatment modalities are not promising. Despite of this conservative approach, un-necessarily or heroic teeth retention would increases treatment time, presents financial burden and may results in compromised treatment for patients. In addition, implant dentistry has made a tremendous shift in treatment paradigm as being an alternative restorative modality following tooth extraction.

Shortly after the introduction of Branemark dental implant system in 1971,[3] an estimated one million dental implants were placed on annual basis worldwide. Currently, there are an approximate 80 different manufacturers marketing hundreds of implant brands.[4]

Unfortunately, this obvious shift toward implant dentistry, as a modern modality for tooth replacement, has been driven by strong marketing strategies and financial temptations to dental institutions and clinicians as well, which dramatically drifted clinicians' attention away from logical thinking and accurate decision to whether retain or extract natural dentition. Although financial gain and profits are critical for any dental institutions and practices to stay in operation, this compromised logical thinking process is in fact raising great concerns. While implant dentistry has proven long-term success and survival rates supported literature evidence, [5] a clinical decision of retaining natural teeth and restore them back to their functional form (i.e. root canal treatment, post, core and crown) versus extraction and implant restoration should be based on a structured evidence based decision-making approach since the long term success of root canal treated teeth is proven comparable to dental implants in scientific dental literature. [6] In addition, the use of periodontally compromised dentition as abutments for single or multiple splinted restorations has been introduced 3 decades ago and proven predictable over long term follow-up, given that periodontal disease was treated successfully. [7] Therefore, the naive approach of blindly embracing tooth extraction followed by dental implants as the first line of treatment has to be terminated, since this treatment modality is considered an invasive procedure and financially demanding to the patient when compared to other conservative treatment options. [8] An additional factor that predicates the importance of taking an informative clinical decision before extraction of natural dentition is that periodontal ligaments around natural dentition are equipped with complex proprioceptive sensory apparatus. This apparatus provides neuromuscular feedback that helps to avoid excessive occlusal trauma and protects vital oral structures.

This sophisticated feedback protective mechanism explains why tooth supported restorations have less biological and mechanical complications when compared with dental implant counterparts. [9]

The urge to resolve the dilemma of whether to retain or extract natural dentition is well worth to be considered using evidence based approach. Perhaps this urge is driven by the fact that more teeth are unnecessarily extracted due to misdiagnosis than that is conservatively saved. [10, 11] Although the clinical decision might be straightforward in some instances, this dilemma remains an undeniable conflicts among novice and expert clinicians when it comes to selection of a proper route of dental treatment. Thus, it is critical to understand the factors that are involved to develop an accurate and evidence based treatment plan for patients. In addition, long term treatment success relies upon proper diagnosis, planning and treatment execution from the clinician's side as well as compliance to clinicians' instructions from the patient's side.

The decision whether to retain or extract a tooth involves careful evaluation of numerous factors and logical analysis of obtained clinical parameters of variable complexity. In order to determine the long-term tooth or treatment prognosis, this process requires sound knowledge and understanding of physical and biomechanical principles, supported by evidence-based background that includes the restorative, endodontic and periodontal aspects. Multiple factors have been identified to influence the long-term tooth and treatment prognosis. Although these factors were not collectively considered in present literature, they include the following factors: the remaining tooth structure, crown-to-root ratio, extrusion, location of finish line, complexity of root canal treatment, need for RCRT, mobility, furcation, financial ability and risk tolerance, tooth involvement in treatment, bruxism, opposing occlusion, caries risk and oral hygiene status.

A complex clinical decision can be simplified with the use of evidence-based decision support systems (DSS). These systems are a group of computer-based information systems that interact with the end-user and provide possible solutions and recommendations, based on literature evidence, professional experience and patient's desire, that support informed decision-making in numerous disciplines. An appropriately structured DDS is interactive and user-friendly software that help professionals to solve problems of varying complexity and arrive at proper decisions. Since these expert systems are computer-based, it can be utilized conveniently by healthcare professionals for making evidence based clinical decisions. Despite the fact that these systems are versatile, they have numerous applications in healthcare field that comprise assistance in developing diagnoses, prognoses, treatment plans and recommendations, health-related alerts and smart electronic questionnaire forms for the purpose of survey and clinical scientific research projects.

We propose evidence based decision support system that helps in training of dental students, general practitioner and specialists with regard to critical thinking in dental diagnosis and analysis of given clinical data to arrive at accurate prognosis that ensures long-term treatment success based on scientific principles. Such system will consider series of clinical and patient-related factors, analyze them in systematic fashion and calculate the factors-assigned scores to give proper feedback that include: health-related alerts, overall tooth prognosis and recommendations to whether retain or extract the tooth in question and treatment alternatives.

The process of determining the proper treatment plan for questionable teeth can be challenging. Uninformed decision making may results in non-reversible clinical errors. Although a decision to retain or extract teeth may seems straightforward, it requires a complex thinking process and extensive dental training that relies on support and guidance of expert clinicians. For instance, high percentage of dental schools in North American is facing many challenges in clinical teaching and educational quality control. The shortage in clinical instructors number, their limited experience and reduced clinical teaching and training sessions have rendered the learning environment at these schools inefficient, which in turn impeded the students' progress of developing an adequate clinical competency. [12] This called upon an urgent need to develop an expert decision system that combines the available evidence based data and expert clinicians' knowledge and input to facilitate consistent clinical decisions among dental practitioners. It is of extreme importance to develop such a system to disseminate valuable knowledge among practitioners using an interactive and user-friendly interface on demand with ease of accessibility. Errors that may occur in delivered dental treatment are actually caused by buildup of errors throughout the initial phases of clinical examination, diagnosis, prognosis and treatment planning. This system will ensure a systematic analysis of all clinically relevant data in order to reduce dental treatment errors and therefore improve patients' dental care. Furthermore, the system will help dental students and recent graduates to learn, in-depth, the art of proper treatment planning of simple to moderately difficult clinical cases before starting any clinical interventions on them. Upon treatment planning phase that may or may not involve extraction and replacement, a careful critical thinking approach considering the possible success and failure rates for each given treatment modality is undeniably crucial. This critical thinking, through a holistic approach, is mandatory to improve the clinical decision making process, which in turn helps in achieving excellent long-term treatment prognosis and outcomes.

The proposed decision support system will be structured to include series of clinically oriented multiple-choice questions that requires feedback from end-user. It will train the users to think like an expert would think through the decision-making process. The system will acquire the collected data, process it according to the pre-structured decision trees, given rules and assigned scores, and finally provides health-related alerts, overall tooth prognosis, an ideal treatment plan and alternatives. The system will further inquire the end-users to collect data with regard to the patient's esthetic and functional demands, risk versus benefit ratio, financial ability and risk tolerance in order to take these factors into account and make sure that the given ideal treatment plan would satisfy the patient's needs and desires or otherwise suggests viable treatment alternatives. Thus clinicians would consistently manage their patient's treatment needs and deliver high quality dental treatment utilizing an evidence-based approach.

1. 2. Background and Statement of the Problem:

Dental treatment planning has been defined in the Code of Dental Procedures and Nomenclature (CDT) given by the American Dental Association (ADA)'s [13] as "The sequential guide for patient's care as determined by dentist's diagnosis and is used by the dentist for the restoration to and/or maintenance of optimal oral health". According to this definition, the ideal treatment progress, to arrive at predictable long-term treatment, requires diligent execution of following steps: a thorough collection of all clinically relevant data, which includes medical and dental history and clinical examination, development of a detailed problem list, and establishment of an accurate diagnosis that correctly addresses the data collected by the clinician and/or obtained via consultation with other healthcare providers. In continuation of the ideal treatment progress, the development of viable treatment options taking into account the patients' desires, financial ability and commitment toward treatment is crucial. These options should be ranked per status quo, i.e. management of emergency categories should usually be addressed immediately while management of comprehensive category cases would probably take a course of time depending on the selected treatment option. The final stage of this progress is entitled as development of a definitive treatment plan, using clinical decision-making or a holistic approach, which satisfies all previous requirements.

Hook *et al* in 2002, have discussed the reasons and essences of including treatment planning sessions as fundamental requirement for clinical education curriculum among US dental schools. The authors felt that this aspect of treatment should be reinforced formally, with continuing evaluation, to examine the ability of students to develop appropriate treatment plan in theoretical and/or clinical settings and to ensure a standard quality education among them. Despite the urge to officiate this concept, minimal evidence is available on how these treatment-planning courses would be developed and evaluated, how would they be incorporated into the academic curriculum, and the methodology of integrating such courses into treatment planning session chair-side. It is foundational to teach dental students that upon treatment planning at single tooth level, they must develop a comprehensive treatment plan that addresses the tooth in question taking into account the adjacent dentition, opposing dentition, neuromuscular function and managing all the previous entities at the context of the individual level.[14] This comprehensive approach for managing the patient as a person with specific desires and preferences guarantees patient compliance, personal satisfaction and ensures predictable short and long-term treatment outcomes. [15] This approach lays a solid base for successful dentist-operated and patient-specific diagnosis as well as custom made treatment plan rather than having one treatment plan that fits all patients.[16] Moreover, it is critical to educate dental students regarding prevention-based diagnosis and treatment planning in which the target is not just treating the problem in a small frame, but rather contemplate this problem in a much wider frame taking into account the problem's manifestation, underlying causative factors, sequelae and mutual relations with other problems existed and then address the collective problem in a comprehensive stepwise manner. For instance, it makes no sense to retain teeth in question and perform root canal treatment along with cementation of metal copings for tooth-supported overdenture without reinforcing the patient's compliance with oral hygiene instructions and healthy diet, taking into consideration the mutual relations of the treated area with the adjacent and opposing dentition.

Determination of predictable treatment plan of whether to retain or extract single or multiple teeth requires careful evaluation of numerous factors on an individual tooth level and correlates this finding with others in the context of the entire dentition. At the individual tooth level, a tooth should be assessed based on remaining tooth structure or in other words ferrule effect, the remaining tooth structure, crown-to-root ratio, extrusion, location of finish line, complexity of root canal treatment, need for RCRT, mobility, furcation, financial ability and risk tolerance, tooth involvement in treatment, bruxisim, opposing occlusion, caries risk and oral hygiene status. If tooth retention deemed satisfactory after applying all aforementioned factors, this tooth must further be assessed in several clinical scenarios to test the validity of the targeted tooth in relation to the rest of natural dentition. These clinical scenarios include: tooth involvement in the proposed treatment plan, interaction with the adjacent teeth and opposing occlusion (i.e. occlusal function), patient's caries risk, oral hygiene status and presence of parafunctional habits (i.e. bruxism). This systematic approach can be defined as a critical thinking process to produce the most logical and complete restorative treatment plan.[17] For instance, the clinical decision of whether to retain or extract questionable root canal treated teeth can sometimes be challenging. Figure 1-1 shows a difference in the treatment plan based on the remaining tooth structure. A minimum of 1.5 mm ferrule has been widely accepted as a requirement to restore root canal treated teeth with good restoration prognosis.[18-21] The clinical picture on left presents an endodontically treated premolar with adequate ferrule effect, more than 2mm all-around, which received a prefabricated post and composite core. Restoring this tooth with single crown renders a favorable long-term prognosis. On the contrary, the clinical picture on right shows an endodontically treated central incisor with inadequate ferrule effect (<1.5mm). This clinical finding presents another route for treatment and such a tooth requires comprehensive treatment approach that may includes surgical crown lengthening or orthodontics forced eruption, post and core followed by single crown restoration, only if the proposed crown-to-root ratio is favorable. In case of unfavorable crown-to-root ratio, tooth extraction and replacement is the treatment of choice.

Figure 1-1: Treatment plan depends on the amount of remaining tooth structure. (A) Presents an endodontically treated premolar with adequate ferrule effect all-around that received prefabricated post and composite core; restoring this tooth with single crown renders a favorable long term prognosis. (B) Depicts an endodontically treated central incisor with inadequate ferrule effect that present another route for treatment; such a tooth requires comprehensive treatment approach that includes surgical crown lengthening or forced orthodontic

eruption, post and core followed by single crown restoration; long term prognosis in such case depends on resulting C/R ratio.
Pictures adapted from:
(A) http://www.thenextdds.com/uploadedImages/The_Next_DDS/Clinical_Images/Quintas7.jpg
(B) Yonker CM, Rubinstein S, Nidetz AJ. Restoring Endodontically Treated Teeth: Clinicians have a host of factors to weigh when determining the best method for restoring an endodontically treated tooth. Inside Dentistry September 2011, Volume 7, Issue 8.

The aforementioned clinical decision should also consider the number of remaining dentinal walls and their thickness. In this concern, it is generally accepted that the remaining dentinal walls should measure 1mm or more in thickness. The remaining ferrule height has a valuable effect only if the sound dentinal wall measures 1mm or more in thickness.[23-25] Despite the available evidence, a lack of literature-based information on the mechanical performance of dentinal wall thickness of less than 1mm is evident. Tjan and Whang [22] tested 4 groups of varying dentinal wall thicknesses: 1 mm, 1 mm with a 60° bevel, 2 mm and 3 mm of remaining buccal dentine. There were no significant differences noted between the groups under compressive load except that the two groups of 1 mm thick dentine were more likely to fail due to fracture rather than cement failure. Likewise, Sorenson and Engleman in 1990[19] have studied the effect of dentinal wall thickness at the preparation's margin area with various contra-bevel ferrule designs. It was thought by the authors that the thickness of the coronal extension above the crown margin that is the only factor that plays significant rule in the fracture resistance of crowned teeth.

The number of remaining dentinal walls when restoring endodontically treated is also crucial. A tooth with 3-4 remaining dentinal walls, ≥2mm dentinal height and thickness is considered the most optimum followed by 2 remaining opposing walls of matching height and thickness. In contrary, a tooth with 'L' shaped wall distribution (i.e. mesial and lingual or distal and buccal walls) or no ferrule is considered at extreme risk of fracture during functional or parafunctional jaw activities. In figure 1-2, the image on the left presents a tooth with four remaining dentin walls of more than 1 mm in thickness. Such clinical presentation is considered favorable with predictable long-term prognosis. Likewise, a tooth with two remaining dentin walls in opposing configuration is considered acceptable tooth-condition for restoration. In both these scenarios, a post in adjunct to core-buildup is necessary for coronal restoration. Meanwhile, the image on the right presents a tooth with 2 remaining dentinal walls in 'L' shaped configuration and thickness of less than 1mm or a tooth with just one remaining dentin wall or no walls have poor short and long-term restorative prognosis.[26] In this clinical instances, tooth extraction should be considered in case crown-lengthening or extrusion are not viable options.

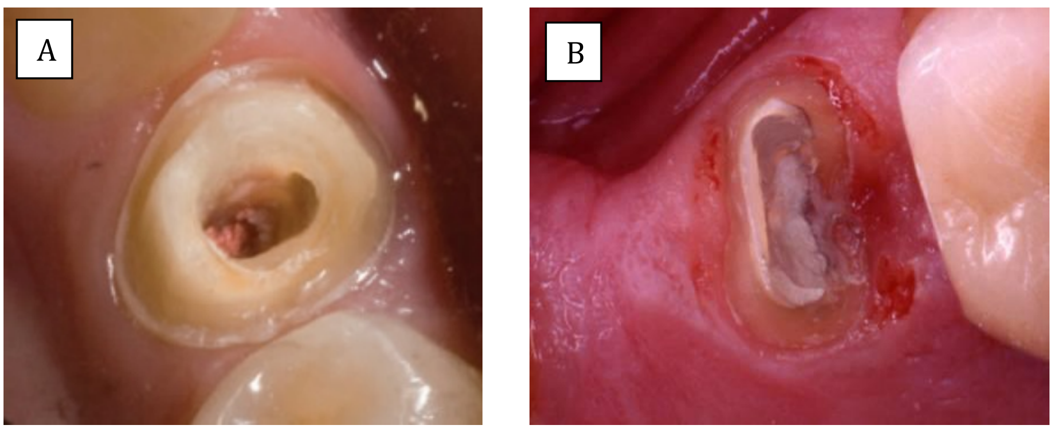
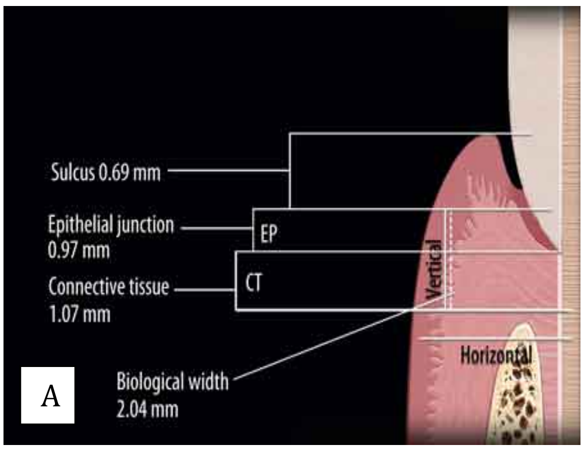


Figure 1-2: (A) Treatment plan variations based on dentin wall thickness. All, three or two walls in opposing configuration of at least 1 mm thickness is considered good for restoration prognosis. (B) Insufficient dentin wall thickness, two remaining walls in 'L' configuration or one remaining dentin wall are not considered good for long-term prognosis and must be carefully evaluated as part of the planning process.
Pictures adapted from:
(A) Jotkowitz A, Samet N. Rethinking ferrule – a new approach to an old dilemma. British Dental Journal 2010; 209: 25–33.
(B) Courtesy of Dr. Louis DiPede, Rutgers School of Dental Medicine, New Jersey.

Biologic width is another factor to be considered in order to determine the restorability of extensively decayed teeth. It consists of attached epithelium and connective tissues apparatus that are very important in periodontal health upon restorative procedures and prosthetic rehabilitation. Invading this zone can cause chronic inflammation, pain, unpredictable bone loss and gingival recession. Therefore the biologic width acts as natural seal around natural dentition and protects the alveolar bone from infection and disease [27]. It is well accepted in periodontal literature that biologic width has average dimension of 2.04mm. This dimension accounts for epithelial junction and connective tissue attachment.[28] Ghahroudi et al, in a clinical study, compared the dimension of biologic width around anterior and posterior teeth and found to be relatively similar (1.4651±0.39 mm vs. 1.6312±0.49 mm). However, biologic width dimension in teeth with thick periodontium was significantly thicker in comparison to teeth with thin periodontium (1.703±0.5 vs. 1.408±0.35). It has been proven that biologic width is different between individuals and teeth of the same individual; therefore it should be calculated routinely prior to restorative treatments. [29]

Radiographic interpretation can identify interproximal violations of biologic width. Violations could occur in common locations as the mesiofacial and distofacial line angles of teeth; therefore radiographs are not diagnostic in these locations because of tooth superimposition and possible distortion. Direct clinical probing in this case is the diagnostic procedure of choice. For instance, if a patient experiences tissue discomfort when the restoration margin is being assessed with a periodontal probe, it gives a good indication that the margin extends into the attachment apparatus and biologic width violation has occurred. The biologic width should be identified for each individual patient, when necessary, by probing under anesthesia to the level of bone in procedure referred to as "sounding to bone" and subtracting the sulcus depth from the sounding to bone measurement (Figure 1-3). This procedure should be performed in cases of healthy gingival tissues only and repeated on more than one tooth to ensure an accurate assessment. In case of diseased periodontal tissues, proper periodontal therapy through scaling/root planning, oral hygiene instructions and frequent follow-up visits should be established prior to planning any restorative or corrective procedures. Such a technique factors in all possible variations in sulcus depths among the examined patient(s). The information obtained is then used to diagnose biologic width violations, the extent of correction needed, and the parameters for placement of future restorations.[30]



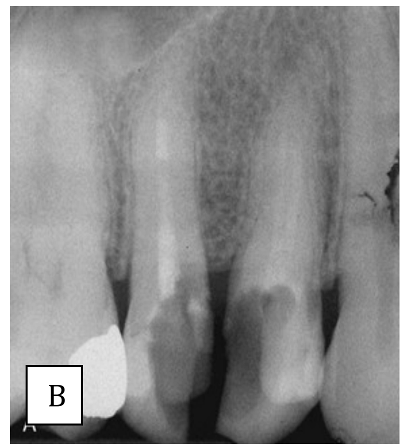


Figure 1-3: (A) Dimensions of biologic width (BW) around natural teeth (B) Periapical radiograph shows back-to-back carious lesions on maxillary premolar. Restoration of these teeth without consideration of biologic width dimension may result in violation and subsequent gingival inflammation and bone loss.
Pictures adapted from:
(A) http://www.thenextdds.com/uploadedImages/The_Next_DDS/Articles/Figure.jpg.
(B) http://pocketdentistry.com/wp-content/uploads/285/B9780323075886000013_f01-036-9780323075886I.jpg.

The current literature classified caries risk levels into: low, medium, high and extreme high categories based on subject's risk for developing caries.[31] The proposed treatment plan must be tailored for each of the four risk levels because management protocols differ greatly between these categories. Clinical photographs in figure 1-4 (A) shows intact dentition with low caries risk while image (B) shows a patient with extreme high caries risk (i.e. rampant caries) and poor oral hygiene. Clinical management for both cases differs significantly as the patient on left will be maintained under a minimal preventive regime, whereas the patient on right will have very strict multi-step preventive regime and frequent clinical and radiographic exams to maintain his teeth over time. Excavation of caries lesions must be done before proceeding with any treatment planning. This helps understand true extent of tooth damage and amount of restoration necessary. In case of hopeless teeth, extraction is the treatment of choice. Benn[32] discussed the importance of accurate assessment of caries risk level, patient's age, date of last examination, and the importance and possible difficulty of producing treatment plans that address different caries risk levels.

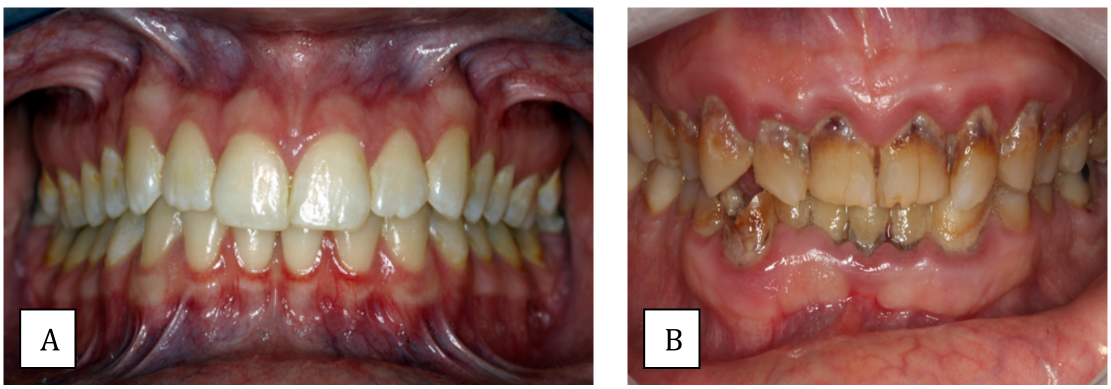


Figure 1-4: (A) Complete adult dentition with good oral hygiene and low caries risk (B) Patient with rampant caries and poor oral hygiene.
Pictures adapted from:
(A)http://www.softchalk.com/lessonchallenge10/lesson/hefinal/Dentalterminology/intro2dental/intro2dental_print.html
(B)http://www.dentalcare.com/images/en-US/research/media_library/clinical/large/caries/rampant-caries-and-calculus.JPG

All aforementioned case scenarios involved fraction of all possible factors that should be considered upon clinical decision to whether retain or extract natural dentition. These factors may present themselves in varying combinations. Therefore, evidence based and clinically oriented decision tree should be structured to arrive at accurate retention or extraction decision-making. This comprehensive decision tree should accounts for all the factors that are involved in restorative, endodontic and periodontic decision-making process. It can be burdensome for dental students and novice dentists to recall and apply a complex list of factors at the time of treatment planning or clinical intervention. This problem drives an urgent need for development of clinical expert software that supports clinical decision-making based on evidence-based literature, expert clinicians' experience and patient's desires. The possible clinical factors relevant to retention or extraction decision-making can be obtained from a domain expert and evidence-based guidelines. These possible problem-domains can be translated into software-friendly format by an informatician to construct a comprehensive knowledge-based database. This database would be programmed and stored in the clinical decision support system (CDSS) of choice. The inference engine of the CDSS rationalizes the entered patient's data, using series of relevant rules, processes all relevant rules and searches the knowledge database to put together options for treatment, alerts and recommendations. Several studies have shown the benefits of applying CDSS in all braches of dental profession.[33, 34]

Nevertheless, these studies have not targeted clinical-decision making relative to retention or extraction of natural teeth in question. In the current project, we propose a comprehensive and user-friendly CDSS to assist clinicians upon treatment planning of questionable teeth using Exsys Corvid Expert System.[35] The end users will receive a list of overall tooth prognosis, alerts, recommendations, treatment options and alternatives based on current evidence, dental expert opinion and patient's desires. This system will also assist clinical users in evaluation of all given treatment options, provide graphical illustrations and logical reasoning that help in justifying the selected treatment option over others.

Hendricson *et al*,[36] in a cross-sectional national study, investigated the adoption and implementation of electronic learning among dental schools in North America. They specified the lack of practical educational software as the main barrier against adoption and implementation of electronic curriculum in daily learning. The knowledge-based clinical decision support system will provide a computer-based educational tool that can be easily integrated into the academic curriculum at dental schools. This system will nourish students' knowledge and experience in the aspects of diagnosis, prognosis and treatment planning in the area of intended use. Due to the complex nature of the retention or extraction clinical decision-making and the possible catastrophic outcomes that may occur as a result of poor treatment planning, the proposed system will provide a comprehensive yet logical way to assist in accurate decision-making for this particular discipline of dentistry. This project could be extended to generate several rule-based systems that cover other aspects of dentistry as future direction for research and learning development.

1. 3. Significance of the Study:

Although several studies have shown that the use of clinical decision support systems have reduced medical errors and improved health care for decades, other studies have contradicted this finding and reported that not all CDSSs have been efficient to achieve these goals. Hunt and colleagues [37], in a systematic review, have reported that only 66% of computer-based decision support systems have significantly enhanced healthcare. A systematic review by Kawamoto *et al,* [38] identified the factors that may account for successful use of computer-based decision support systems in clinical setting. The following attributes were found common among the CDSSs that were successfully used in clinical practice: (1) the system is well integrated with clinical workflow, (2) the system is user-friendly and ready to provide information at the point-of-care, (3) the system is providing practical and executable treatment recommendations, and (4) the system is computer-based.

Our proposed CDSS is computer/web-based and user-friendly that can be launched in dental offices or clinics for ease of accessibility and to instantly provide treatment recommendations upon request. Clinical end users do not have to leave their clinical areas to seek expert consultation and treatment recommendations pertaining to teeth retention or extraction decision-making. In modern dentistry, this beneficial tool can be easily consolidated as an integral part of the providers' workflow. It can be efficiently used upon comprehensive clinical examination and treatment planning to assist with visual aids and logical and facilitate proper communication between the dentist and the patient. This interactive treatment planning permits an intellectual discussion with the patient prior to performing any irreversible dental intervention. In fact, it helps to gain patient's acceptance, confidence and consent to clear any potential responsibilities from medico-legal point of view. It can also provide up-to-date information that is critical to provide reasonable treatment options and their expected outcomes. In clinical situations where the provider's plan interferes with patient's desires, the provider is able to adjust the proposed treatment plan accordingly as long as the patient was informed about the prognosis and possible outcomes of the changes made to meet his desires. This does not only ensures safety from medico-legal point of view, but also guarantees patient's satisfaction and compliance toward the proposed treatment option and maintenance after completion of treatment.

From the practical point of view, this system can easily be implemented in classroom settings as an integral part of interactive academic curriculum. The empirical design of this system allows it to be started from any internet-connected computer station that are equipped with compatible web browsers like MS Internet Explorer, Firefox or Google Chrome. With the current advances in technologies, these systems could easily be run on tablets or even smartphones. Versatility of these browsers permits this system to be used virtually anywhere, particularly in smart classrooms where electronic modes of learning are becoming dominant. This system can be utilized, in conjunction with the old teaching modalities, to help dental students comprehend the varying facets of clinical decision-making process. Remote access to the system is also available outside classroom setting, which allows students to access it from home, work or distant locations. It also allows them to learn at their own pace. Any error in clinical decision-making may result in catastrophic consequences, especially when it comes to irreversible decisions such as teeth extraction. The proper use of our proposed CDSS is aimed to minimize treatment errors and improve health care outcomes. Thus dental students, recent graduates and low experienced dentists will have instant access to this system, which would help them to evaluate clinical cases in a systematic approach, receive accurate diagnosis and prognosis for each tooth in question, and develop a viable treatment plan and alternatives.

The treatment plan, alternatives and recommendations that are generated at the user end, are entirely based on professional expert opinions coupled with clinical evidence-based guidelines. These end-user outcomes have already been utilized by experts and demonstrated effective results based on clinical experience and published data or anecdotes. The proposed system is interactive where output relies on end-used answers to series of multiple-choice and relevant questions. Since the system is practical and user-friendly, it should be easy to use and present outcomes that are clear and understandable. The main purpose of using such a system in clinical setting, is not to undermine or replace clinician's artistic capabilities for proper diagnosis and treatment planning but rather perform as a supplement in an advisory magnitude. At the end, it is the clinician's choice to adopt, abandon or edit the recommendations given by the system, taking into account the variability among clinical scenarios. This system is classified in passive-mode capacity for delivering treatment recommendations. That means it can be considered as an adjunct in clinical-decision-making only if it does not interfere with the clinician's main treatment goals. This artificial intelligence system that is fed with the knowledge and experience of professional clinicians and informaticians, is considered beneficial for day-to-day dental education to include but are not limited to dental students and novice dentists. It would help the targeted groups to think like an expert and therefore its sole function is to be used for on-demand consultation. The system consultation won't be restricted to treatment planning of difficult cases, but also to help geographically isolated dentists, who do not have easy access to knowledgeable experts, to develop informative, organized and case-specific discussions. To achieve this distance-learning goal, the system should be supported in web-based mode and be available for open-access worldwide.

The proposed a clinical decision support system is designed to evaluate and weigh factors to arrive at the optimum clinical decision. It goes through series of logical evaluation and processing, according to the factors' sequence in the decision tree, prior to suggesting any treatment options or recommendations. The main aim for such project is to supply the dental students and low experienced clinicians with a computer-based clinical expert tool that provide an instant consultation on-demand, when needed. The end users might have mastered the skill of performing clinical procedures, but do not often have the insight of an expert clinician that think about the clinical problems holistically. The art of diagnosis and treatment planning involve dissection of all patient's relevant information and formulation of appropriate treatment recommendations that satisfy patient's needs and desires with promising long-term treatment prognosis. This holistic thinking approach comes with exceptional clinical experience only. This CDSS is targeted to act as an adjunct treatment-planning tool, thus reduces the chances of errors in decision-making when it comes to puzzling clinical scenarios of whether to retain or extract natural teeth in question.

The treatment recommendations proposed by this system can be saved in the patient's dental record for audit and medico-legal needs as well. The final treatment plan and consent forms that are signed by the patient, are parts of legal documentation that reflect professional clinical conduct and patient's comprehension and acceptance toward the chosen treatment option. The purpose of legal documentation is to ameliorate healthcare standards and permits unambiguous healthcare process.

1. 4. Objectives of the Study:

This study is destined to achieve 5 goals that are described in details below:

1. Formulate a CDSS to fulfill outstanding clinical needs: up-to-date, there still urgent needs to address the clinical dilemma of whether to retain or extract natural dentition upon treatment planning of challenging clinical scenarios. Solving this dilemma could facilitate informed clinical decisions when it comes to this aspect of clinical dentistry. Although there have been many attempts to utilize expert systems in dental profession, the available systems have not yet addressed this important facet of daily clinical dentistry practice. Because there is a comprehensive list of factors to consider upon treatment planning and serious consequences that may result due to decision errors, the decision-making in this facet can be very challenging and stands as a dilemma even for professional clinicians. Uninformed clinical decision could affect the patient health and quality of life on multiple levels. Therefore, it is of prime importance to develop a clinical expert computer-based system to fulfill the outstanding needs in this particular aspect of clinical dentistry.

2. Continuing education and training tool for dental students and neophyte clinicians: this system can be set as benchmark for electronic education and training of undergraduate dental students and novice practitioners in various dental professions, to help for prognostication for questionable teeth and therefore deliver a predictable treatment plan with long-term success potentials. The end users will be taught to think like an expert upon clinical decision-making process. The system will take into account all patient's relevant information that were input by end users, operate series of rules evaluation and generate customized alerts and treatment recommendations as final system's outcomes. This comprehensive approach will help the targeted population to rationalize their treatment recommendations and satisfy their patient's needs and desires accordingly.

3. Provide a knowledge-based platform that combines clinically oriented evidence-based information and expert knowledge: the main goal of this study is to empower the CDSS (i.e. Exsys Corvid Expert System) with evidence and expert knowledge combined with patient's desires and needs to generate a robust rule and knowledge-based clinical expert platform. The knowledge-based rules that will be fed to such system are complex amalgamation of expert clinicians' knowledge, clinically oriented evidence-based guidelines combined, and patient's needs and desires. A series of back and forth chaining algorithms will be applied to process the patient's relevant data in addition to future needs and desires to generate assumptions based on previously given rules within the knowledge database. These assumptions will be processed by the inference engine and will be delivered in a format of alerts, prognosis, and prosecutable treatment recommendations along with viable alternatives. In total, this form of logical reasoning and processing will result in remarkable reduction of decision-making errors in challenging clinical scenarios of tooth retention or extraction decisions thus facilitate adequate management of potentially difficult clinical cases.

4. Fulfill crucial needs for effective and practical CDSS: our proposed structure of the CDSS (Exsys Corvid Expert System) will follow the basic principles that are undeniably fundamental for guaranteed future success. [38] These principles include: (1) integration with the clinical workflow, (2) delivery at the desired point-of-care, (3) production of practical and executable treatment recommendations, and (4) computer-based system. Fulfilling these basic principles will ensures the practicality of this system in clinical setting and facilitates users' adoption.

5. Expansibility and flexibility: to ensure this system to longer in action, it should accept knowledge addition and subtraction to its database. This upgrading ability is not restricted necessarily to updating outdated knowledge, but also adding new knowledge of diverse dental perspectives to ensure its versatility and persistent use in various clinical settings. Formulating a long-lasting robust CDSS (Exsys Corvid Expert System) can be assured by its capability for instant addition and subtraction of variables, rules and logic blocks within the system at any point of time. The necessity of integrating the new information into the existing database will expand and strengthen the ability of the system to untangle complex clinical scenarios or come to action when specific condition is presented.

6. Evaluation of clinical cases for medicolegal purposes: the system will aid in evaluating clinicians' performance and accuracy in developing accurate diagnosis, prognosis and treatment recommendations for variable case complexities. Because of the fact that this system is fed with state of the art knowledge that are based on expert opinion, experience and evidence-based guidelines, it can be used by the state board of dentistry as a benchmark to justify whether or not appropriate management was performed by the treating dentist.

7. Enable clinicians to evaluate dental conditions in a uniform way: consistency in clinical decision-making might be necessary for reliable treatment planning process within and between clinicians. For instance, Lanning *et al* [39] have found significant variability in diagnosis and treatment planning for common periodontal diseases among undergraduate, graduate students and clinical instructors. These existing variations in clinical assessment and treatment planning would raise serious issues that affect the adequacy of the proposed treatment plan and its alternatives, which in turn result in erroneous treatment and failed clinical management. Unification of clinical thinking process among dentists at the education and training levels will aid in practicing dentistry at its best standards.

1. 5. Hypotheses:

In order to unravel the clinical challenges and fulfill the outstanding needs that are presented earlier, we intend to develop a comprehensive clinical decision support system for the purpose of education and training to help achieving proper diagnosis, prognosis and treatment planning of questionable teeth. The hypotheses that are involved in the structure, design and development of the proposed system are as follows:

1. It is feasible to develop a CDSS to be used in clinical setting, on-demand, for diagnosis and treatment planning of challenging case scenarios that involve retention or extraction of teeth in question, as a facet in restorative dentistry.
2. It is feasible to develop a CDSS for continuing education and training purposes to help the undergraduate dental students and novice dentists to develop a better

understanding and adequate knowledge in order to properly manage these questionable cases.

3. It is feasible to obtain lists of rules to feed the proposed CDSS's knowledge-database to include input from expert clinicians, evidence-based guidelines, and patient's desires or preferences.
4. It is feasible, as a future extension of the current project, to reduce decision-making errors when it comes to challenging clinical scenarios of tooth retention or extraction, as a singular aspect of complex restorative treatment planning process.
5. It is feasible to empower the proposed CDSS (Exsys Corvid Expert System) with an expansible and flexible database, for tooth retention or extraction decision-making, that allows addition or subtraction of rules and update of the existing database with the latest knowledge or information that are extrapolated from recent scientific evidence and developments in this particular field.

This CDSS will be constructed to deliver patient or treatment related alerts, tooth prognosis, treatment plan recommendations and alternatives to either retain or extract the teeth in question. The alerts are intended to notify the end-users to either obtain critical information from other specialists and healthcare providers or tooth-related concerns that end-users should consider upon treatment planning. This system will take into account all the factors that affect the individual tooth in context of the adjacent teeth in the arch, the treated area in context of the opposing dentition, and the entire dentition in context of the patient's risk to develop future carious lesions, compliance to oral hygiene instructions, risk tolerance to the proposed treatment plan, financial ability to cover treatment charges and patient's anticipated functional and esthetic needs and desires among many other critical factors.

Chapter 2: Literature Review

2. 1. Incidence, Prevalence and Etiology of Tooth Loss:

A comprehensive review included 15 longitudinal studies published from seven different countries regarding tooth extractions over an observation period 2–28 years, revealed that the annual incidence of individuals losing one or more teeth varied from 1% to 14%. These studies quantified the mean number of teeth lost to be 3-24% per year. The range of baseline tooth loss varied from 0.1% to 28.5%[40] in individuals with possible risk for developing caries but healthy periodontium to an extreme value of 38% per year for individuals reported with periodontal disease.[41] Several studies have investigated the factors associated with tooth loss. They showed that oral disease-related factors were the most crucial, however the demographic, behavior, attitude, and education backgrounds were considered as important co-factors for tooth loss in some studies. In addition, the review has revealed that some studies developed a comprehensive list of contributing factors that ascertain this disease's multifactorial nature.[40] A cross-sectional survey study on a representative adult Norwegian population, reported that the proportion of respondents who have lost one or more teeth during the last 12 months was 6.5%. Within this percentage, a significant portion reported mean tooth loss of 1.5 (range 1–9) teeth.[40] Moreover, a study on Swedish population involved 60-, 70- and 80-year-old subjects, showed that the mean number of teeth lost during a 5-year period was 0.4, 0.8 and 1.4, respectively.[42] Whilst the mean number of teeth lost during a 10-year period among 65-, 75- and 85-year-old subjects were 0.9, 1.5 and 3.1, respectively. Men, in this study, had lost significantly more teeth than women (means of 1.5 and 1, respectively).[43]

Several studies have reported considerable differences in the prevalence of edentulism between several studied countries. For instance, a review of studies performed in the period of 1980s reported that tooth loss has ranged between 30% to 60% among 65-year-old subjects in six different countries.[44, 45] Another comprehensive review of 55 published studies, over the period of 1960 to 2001 among 14 different countries, demonstrated that variations in the prevalence of edentulism were ranged from 3% to 80% for population aged 60 years or more. However, when the focus was limited to the eight European countries, that were involved in that review, the percentages were ranging between 11% and 80%.[46] Furthermore, the countries that have similar economic and social conditions, such as the Nordic countries, presented significant differences in the percentages of tooth loss among their populations.[47] A nationwide survey study was performed in the early 1990s, reported that the prevalence of edentulism among 75-year-old subjects in Swedish, Danish and Finnish cities were found to be 27%, 45% and 58%, respectively.[48] A collective worldwide reports have postulated the prevalence of tooth loss to be ranged between 0% to 72% for elderly population (65- to 74-year age group), in which Europe presented a range 15–72%.[49] A remarkable finding of that survey indicated that the rate of edentulism was neither associated with the country's economic or social status nor with the number of dentists per capita. (Figure 2-1)

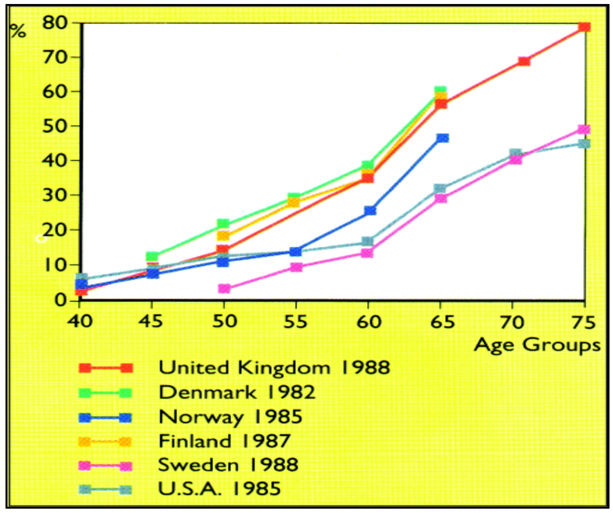


Figure 2-1: Incidence of tooth loss in the US and 5 european countries. This linear graph represents the results of a review study that included several survey studies conducted over the period of 1982-1988. Direct correlation was found between the percentages of tooth loss among elderly population. The incidence varied among the countries that were included in this review study (Adapted from: Öwall B, Käyser AF, Carlsson GE. (1996) Prosthodontics Principles and Management Strategies. London: Mosby-Wolfe).

Although the overall prevalence of tooth loss has been slightly decreasing in the US and Canada in the past few years, high percentage still exists among populations of lower socioeconomic education status.[50] A recently published data from Phase 1 of the Third National Health and Nutrition Examination Survey (NHANES III) reported the most current estimates of the prevalence and distribution of tooth retention and tooth loss in the United States.[50] This report includes adult populations of 18 years and more (n=8,366). The studied population was distributed based on age, gender, and race-ethnicity groups. In the period of 1988 to 1991, 89.5% of the studied population was fully dentate; within this percentage 30.5% had maintained all teeth except third molars. The result of this study showed that the mean number of teeth maintained was 21.1 for all adults, however the mean for fully dentate persons was 23.5. In addition, the most commonly maintained teeth were the mandibular six anterior teeth, while 10.5% of the population was completely edentulous. Partial loss of teeth was much more common in the maxillary arch when compared to the mandibular arch. The earliest teeth to be missing were the first and second molars in both arches. Age, as covariate among the studied population, was significantly associated with all measures of tooth retention and tooth loss, while gender was not associated with those measures when age variable was adjusted. With regard to race, Mexican-Americans presented the lowest whilst African-American presented the highest rates of tooth loss. [50]

Socioeconomic status is a factor thought to be associated with the prevalence to tooth loss. The prevalence of complete tooth loss in the US was significantly higher for adults with a family income of <200% FPL in comparison to adult with higher income groups. Furthermore, this prevalence rates declined in the periods of 1988-1994 and 1999-2004 for the adult population with income rates of more than 100% FPL groups, however population of lower income rates (<100% FPL) had either the same or increased prevalence of tooth loss.[51] (Figure 2-2)

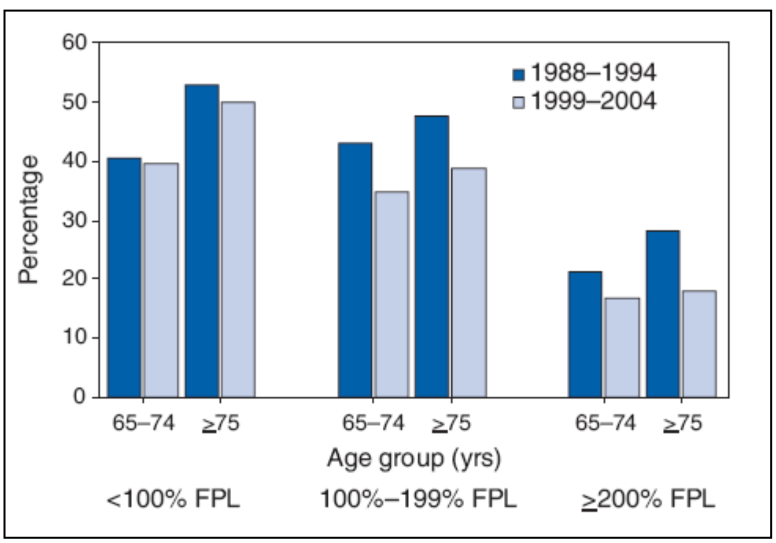


Figure 2-2: Prevalence of complete teeth loss in the US between 1988-1994 and 1999-2004. Variation among age, time period and federal poverty level (adapted from: Prevalence of Complete Tooth Loss Among Older Adults By Age Group and Federal Poverty Level (FPL) National Health and Nutrition Examination Survey, 1988-1994 and 1999-2004).

Several studies have reported the factors associated with tooth extraction or loss. These factors include: dental caries, extensive periodontal disease, prosthetic and orthodontic reasons, accidental trauma, pain due to endodontic or periodontal infection or disease, symptomatic wisdom teeth and to satisfy patient request.[52-54] Among these factors, significant number of studies have indicated that dental caries is the most common reason of extraction or tooth loss followed by periodontal disease.[43,55] Other factors such as demographic, behavioral and attitudinal factors have been reported as additional factors contributing to tooth loss.[40] A classical study has also attributed complete edentulism to the social-behavioral status of individuals as much as other oral disease-related factors. On the contrary, social–behavioral factors were less attributed to partial edentulism in dentate persons; the other oral disease-related factors were the most prominent in these individuals.[56]

2. 2. Consequences of Tooth Loss:

2. 2. 1. Partial Edentulism:

Failure to early replace any missing anterior or posterior tooth is believed to distort the balance of the stomatognathic system and cause a series of negative host-related consequences. These consequences include: extrusion of opposing teeth, tilting of adjacent teeth and breakdown of the health supporting periodontium, which are critical to maintain the same tooth and therefore retain the integrity of the entire dentition.[57,58] Supra-eruption or extrusion of an unopposed tooth into the missing tooth space may disturb healthy occlusion and complicate the efforts to replace the opposing missing tooth. Additionally, drifting of teeth into adjacent missing tooth space may cause periodontal disease and increase the risk for developing caries relative to the same tooth. It also may complicate the effort for replacing the missing tooth as it may necessitate orthodontic uprighting or overpreparation of the drifted to gain a parallel path of insertion, which may result in irreversible pulpal damage and/or poor prosthesis retention, given that fixed partial denture (FPD) was planned for tooth replacement.[57-59]

In a clinical follow-up study of 120 patients, Craddock and Youngson [60] have reported the incidence of the negative sequential consequences that may occur following tooth loss. The study reported that supra-eruption might occur in 83% of unopposed teeth, and that the degree of supra-eruption relative to the occlusal plane is substantially significant. They proposed that such findings are of clinical significance, not entirely for treatment planning and prevention of damaging vertical tooth movement, but also for the purpose of adequate restoration of the opposing edentulous space. These findings were reliable and were justified by well-structured study methodologies. Among the teeth that undergone vertical movement, 51.6% of them if not opposed will probably cause interferences in in centric and eccentric jaw movements. This incidence rate is clinically important upon treatment planning of the supra-erupted tooth and its opposing unrestored space. The study also proposed a weak relationship between the extent of vertical tooth movement (supra-eruption) and the existence of negative occlusal interferences.[60]

Additionally, Craddock *et al* [61] in a case-control study of 100 patients, found a statistical significance in the extent of drifting of teeth (in mesial and distal directions) to occupy the extraction sites between study subject and control groups. They noticed that teeth adjacent to the extraction site of present variable degree of horizontal movements, with the teeth located mesial to the edentulous site had a tendency to drift distally. The degree of noticed drift was higher in the maxillary teeth and in individuals presented with a cusp-to-cusp occlusion relationship (range of 19.4°–21.6°). However, the possibility of rotation relative to the teeth located mesial to edentulous site was significantly higher in the mandibular arch (mean 15.59°). On the other hand, drifting of the teeth located distal to the edentulous site could be excessive and was detected significantly in individuals with reduced overbite and in the mandibular arch (mean 19.55°). Moreover, rotation of teeth located distal to the extraction site was prominent in the maxillary arch and was also associated with reduced overbite (mean 10.91°). The movement of the distal tooth was also associated with the rotation of the tooth mesial to the edentulous site (Figure 2-3).[61]

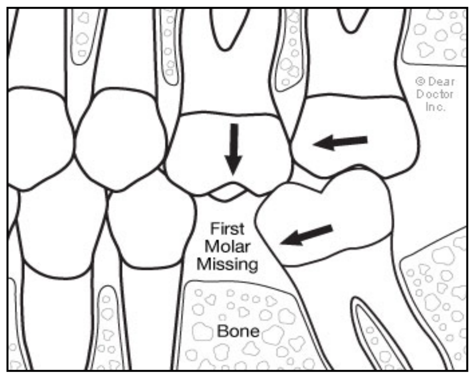


Figure 2-3: The loss of individual tooth may result in loss of arch balance and subsequent over-eruption of opposing tooth, rotation and drifting of adjacent teeth and occlusal interferences (adapted from: http://www.deardoctor.com/inside-the-magazine/issue-1/replacing-back-teeth/).

Tooth extraction may present potential destructive effects on the adjacent teeth as it may reduce their long-term survival rates especially when the extraction site left untreated. Aquilino *et al*[62], found significant differences in the survival rates of adjacent teeth among 3 treatment categories over 10 years period. It was suggested that the spaces treated with fixed partial denture (FPD) presented the highest survival rate of abutment teeth (92%) followed by untreated spaces (81%) and spaces treated with a removable partial denture (56%).

Tooth extraction presents a negative effect on jawbone volume. It is well established that tooth extraction is followed by viable degree of reduction in the buccolingual (BL) and apicocoronal (AC) dimensions of the alveolar bone at the edentulous site.[63,64] Seibert[65] classified the ridge defects in two dimensions among partially edentulous sites into:

- Class I: Loss of ridge width (BL) with normal ridge height (AC).
- Class II: Loss of ridge height (AC) with normal ridge width (BL).
- Class III: Combination of BL and AC loss of tissues resulting in deficient ridge width and height.

The purpose of this classification was to show the potential challenges that clinicians' may face during the surgical and restorative phases of rehabilitation. Efforts to restore the ridge deficiency may prove costly and result in compromised function and esthetics.

The current literature gives an insight that the biological mechanism and causative factors of bone loss following extraction are not yet clear. Roux[66] proposed that the volumetric bone loss following extraction in senile population could be explained by the concept of disuse atrophy. His viewpoint is that following extraction, the forces transferred to the bone is significantly reduced, which result in volumetric bone loss along and loss of the regenerative bone potentials. However the contemporary knowledge of bone physiology has been updated periodically since 1881. Wolff's[67] law proposed that bone tissues adapts its mass and structure to the mechanical demands. For instance, when a certain load applied on the mandible, resultant stress and strain are generated within the bone mass, compressive and tensile stresses projected perpendicular, and shear stress parallels the bone mass external surfaces. The shear stress usually disappears leaving perpendicular stresses (compressive and tensile) active on the external bone surfaces. These remaining external stresses are called principal stresses while the corresponding internal stresses are called principal strains. If principal strain stimulus that is needed to maintain bone mass is partially or completely lost, then the biologic response to this is to remove bone, which is usually performed at the external bone surface resulting in reduction of bone mass volume.[67]

Regarding the extent or quantity of alveolar bone loss, Covani *et al* [69] in a clinical study of 50 patients concluded that the most significant reduction of ridge height and width occurs within 6 months following single tooth extraction. The reduction of width occurs significantly in the middle of edentulous space in anterior posterior direction (19.4 ± 9.4% at mesial point, 39.1 ± 10.4% at midpoint and 20.3 ± 10.7% at distal level). Similarly, the reduction in ridge height is significant at the same midpoint (59.1 ± 11.2% at mesial point, 64.8 ± 10.5% at the midpoint and 56 ± 12.5% at distal point). Therefore, the highest amount of bone remodeling (reduction) occurs at the central point of the edentulous ridge in both dimensions, which may complicate all efforts to restore the missing tooth space.

2. 2. 2. Complete Edentulism:

Following the extraction of teeth, the fully edentulous ridge goes through series of bone remodeling phases that include internal and surface alterations.[70] These alterations, or in other words residual ridge resorption (RRR), occurs significantly in the first 6 months up to 2 years following tooth extraction, however in some individuals these changes sustain throughout life, which in certain cases result in significant reduction of jaw bone volume and dimensions. The effect of these changes may extend to compromise the prosthetic management of such cases. For instance, the support, stability and retention attributes of removable prostheses whether RPDs or complete dentures rely on the volume and dimensions of the residual edentulous ridge. Achieving these attributes will satisfy the patient's comfort, functional and esthetic demands. In 1963, Atwood[71] proposed a theory that related the percentage of residual ridge resorption (RRR) to time since tooth extraction, bone metabolism, amount of load applied on bone and biomechanics-related factors. He proposed six orders of ridge form following complete tooth loss into six orders (Figure 2-4). Orders V and VI presents the highest challenges for prosthetic management.

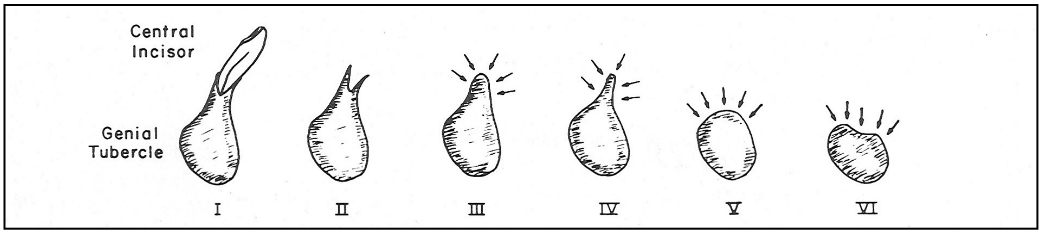


Figure 2-4: Six orders of mandibular completely edentulous ridge form: Order I, pre-extraction; Order II, postextraction; Order III, high well-rounded; Order IV, knife-edge; Order V, low well-rounded; Order VI, depressed. (adapted from Atwood D. J Prosthet Dent 13: 817, 1963)

The average of edentulous bone loss over time (mm/year) was noted to be substantially variable within dental literature. Tallgren[72], in a clinical study of 20 complete denture-wearing patients over period of 5 years, reported a bone loss rate of 0.2mm/year. On the other hand, Carlsson[73] in a similar study reported a bone loss rate of 1.8mm/year with minimum of 2mm and maximum of 14.5mm total bone loss after 5 years of function in complete denture wearers (Figure 2-5). This tremendous variation in bone loss between individuals is caused by multiple factors as mentioned earlier. Bone loss of 14.5mm would render extremely non-retentive prostheses, which impairs patient's function and therefore dissatisfaction with provided treatment. For this reason, tooth extraction should be considered as life changing and be approached with caution.

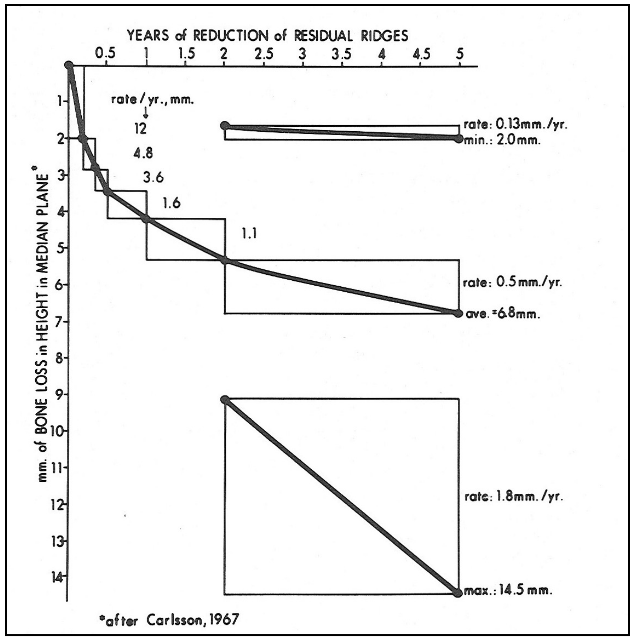


Figure 2-5: Mean mandibular bone loss curve during 5-year postextraction period (adapted from Carlsson GE, Persson G: Morphologic changes of the mandible after extraction and wearing dentures. Odontol Revy 18: 27-54, 1967)

Furthermore, the keratinized mucosa that covers edentulous ridge has compelling viscoelastic properties. This unique attribute gives these tissues the ability to act as secondary supporting structure under complete dentures in edentulous patients. Even though alveolar mucosa possesses viscoelastic properties, it does not mean that it is shielded against excessive or traumatic occlusal stresses. These abnormal stress, either during impression or mastication, cause distortion and displacement of alveolar mucosal tissues.[74] In addition, these distortive changes could generate compression within the tissues and therefore result in denture-induced irritations on the surface of the alveolar mucosa. These internal forces may sometimes cause alveolar bone loss.[75]

Trauma-induced ulcers are considered the most common intraoral lesions in complete denture wearers.[76] In comparison to the maxillary counterpart, the mandible possesses relatively less stress-bearing area and therefore denture-related lesions are more common in the mandibular arch. Moreover, a classical study has reported that the most common denture-related lesion sites are the retromylohyoid area (17%) followed by the lingual sulcus (14%), and the vestibular sulcus (13%).[77]

2. 2. 3. Effect on Quality of Life, Function and Esthetics:

Extraction (loss) of single or multiple teeth has long been recognized as a serious life event [78,79,] which definitely contribute to significant disability harnessing the practice of day-to-day living activities.[80] These daily activities include but not limited to food mastication, food selection, and phonetics.[81] The possibility of negative changes in the facial appearance, caused by single or multiple teeth loss and surrounding anatomical structures, may affect individual's psychological well-being leading to isolation and avoidance of social interactions.

Fiske *et al*[82], in a comprehensive long-term study, have evaluated the possible range of reactions and feelings regarding loss of teeth experienced by edentulous people and reported that it has undeniably a significant effect on quality of life in studied individuals. Changes in individuals' behavior were also noted, which include isolation and avoidance of forming close personal relationships. A recent study has quantitatively assessed the emotional changes of tooth loss among UK population, found that ~50% of the studied individuals presented difficulty toward acceptance of tooth loss with one third showing persistent psychological reactions toward it.[83] Scott et al,[84] have evaluated the emotional effects of losing teeth among 3 different populations of patients (London, UK; Dundee, Scotland; Hong Kong, China) who have attended dental schools for primary dental care and concluded that difficulty of tooth loss acceptance was relatively common among the studied populations (44%), with approximately one-half felt that their confidence had been compromised. Significant percentage of the studied populations (66%) had experienced restriction of food choices and declined food enjoyment. Large percentage of the studied populations was relatively distressed about their appeal without prosthesis. One third, approximately 34%, avoided looking at their appeal without dentures. Further, 41% avoided exposure to their partners, while 73% avoided exposure to close-friends without their prostheses in. Among the studied population, 43% have complained that were not conditioned properly prior to loosing their teeth.

Due the fact that tooth loss, whether partial or complete, has presented a relatively high global prevalence and tremendous negative consequences that may affect the oral structures alone and/or the entire person collectively, the decision of tooth retention or extraction should be carefully thought out. In fact, all the viable restorative options should be exhausted to retain the tooth in question and avoid all the aforementioned local and general negative effects. This conservative approach should also be well thought out, as heroic retention of the teeth in question may result in longer treatment time, high financial burden and poor long-term prognosis. Therefore, a comprehensive list of factors should be considered prior to taking such a challenging decision.

2. 3. Factors Determining Retention or Extraction Clinical Decision-Making:

2. 3. 1. Remaining Tooth Structure:

Restoring natural teeth forms and contours to meet the patient's function and esthetic demands is achievable giving that all relevant factors are considered and addressed to ensure long-term success of performed restorative procedures. The remaining, disease-free, tooth structure is most critical factor to be considered for restoration of severely damaged and root canal treated teeth. To meet the functional, esthetic and biologic requirements, these teeth should have a minimum of 5mm of tooth structure above the bone crest. Within this dimension, 3mm below the preparation finish line is needed to constitute for biologic width that maintains health of periodontium around natural dentition, and 2mm of vertical tooth structure coronal to the finish line to maintain the tooth integrity. These minimum dimensions are basic constituents of factors that determine tooth prognosis, in which clinical decision-making are based to retain or extract teeth in question.[85] In clinical presentations where the amount of remaining coronal tooth structure (<5mm) is deficient, corrective procedures utilizing either surgical crown lengthening or orthodontic extrusion are needed to obtain the minimum tooth structure above the bone crest to satisfy all the aforementioned requirements. Both corrective procedures are predictable to expose more tooth structure for restorative purposes; however proper planning is critical hence they may result in poor crown-to-root ratio or esthetic complications that negatively affect treatment outcomes. [86]

The vertical dentinal wall or in other words the ferrule effect was defined in the Glossary of Prosthodontic Terms as ‘‘a metal band or ring used to fit around the root or crown of a tooth’’. [87] The apical part of complete coverage crown acts as a ferrule when surrounding the tooth structure located between the apical end of the core and preparation finish line. The importance of this vertical dentinal wall is to provide structural reinforcement that could resist heavy masticatory stresses, wedging stresses of tapered posts and lateral post cementation stresses.[19] Among the literature that support the importance of ferrule effect, Libman and Nicholls[88] reported that a minimum dimension of 1.5 mm of vertical dentinal wall is crucial for RCT teeth restored with cast posts and cores and full coverage crowns. However, for RCT teeth that are restored with prefabricated posts, composite cores, and full coverage crowns, Ng et al[89] found that a minimum of 2.0 mm of vertical dentinal wall is important to increase their structural durability and strength. Moreover, similar studies have also reported that the presence of adequate vertical dental wall (ferrule) is more crucial to maintain the strength and structural durability of RCT teeth than post length[90] or post type (custom or prefabricated) [91].

Ng *et al*[92], in a laboratory study, studied the effect of remaining walls number on fracture strength of RCT anterior teeth where they had grouped their samples according to the circumferential extension of dentinal walls around the post-core complex into: group 1 with 360° remaining dentinal wall, groups 2 through 4 with 180° of dentinal walls located on the palatal (group 2), labial (group 3), and proximal (group 3) aspects of teeth, and group 5 without any remaining walls above the preparation margin. They noted higher fracture resistance for group 1 samples (607 N) followed by groups 2 through 4 while group 5 showed the least fracture resistance among all groups (172 N). It was also reported that group 5 samples showed post dislodgement as the main type of failure. It was extrapolated that the presence of 360° remaining dentinal wall was the best case scenario to ensure optimum fracture strength and structural integrity for RCT anterior teeth.

Similarly, Tan *et al*[93], investigated the effect of vertical wall uniformity on the fracture resistance of RCT anterior teeth and found that the groups with 2mm uniform vertical wall (ferrule) were more fracture resistant in comparison to non-uniform walls (0.5-2mm) and both groups showed more fracture resistance in comparison to the group without vertical wall (ferrule) above the finish line (Figure 2-6). Failure of obtaining the above requirement even after utilization of presented corrective procedures would indicate extraction and future tooth replacement with either implant, FPD or RPD per given case and planned treatment.

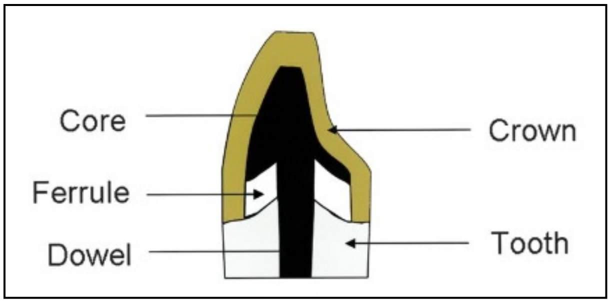


Figure 2-6: Components of restored endodontically treated anterior tooth (adapted from: Tan PL, Aquilino SA, Gratton DG, Stanford CM, Tan SC, Johnson WT, Dawson D. J Prosthet Dent. 2005 Apr;93(4):331-6)

2. 3. 2. Crown-to-Root Ratio (C/R Ratio):

The alveolar bone support, among series of other determinants, is critical to determine the overall restorative prognosis of teeth in question utilizing the concept of crown-to-root ratio.[57, 86, 94] Several studies have investigated the value of this ratio to determine the prognosis of periodontally compromised teeth, hence periodontitis is the main factor that control this ratio.[95-97] In fact, the present literature is supporting the use of this ratio to determine the restorative prognosis of teeth that experienced bone loss due to periodontal disease and intended to be used as an abutment to support fixed or removable prostheses.[98]

Among the theoretical and clinical guidelines concerning this ratio, an ideal crown-to-root ratio of 2:3 or 1:2 was proposed for abutment to support FPD, however clinically this is seldom presentation. [99] This ratio was proposed based on studies of subjects with healthy periodontium and ideal bone support, which is rare among patients presented for restorative replacement of missing teeth.[100, 101] Dykema *et al* [99], in a published scientific textbook, proposed a crown-to-root ratio of 1:1.5 for the tooth to be used as an abutment to support FPD. Further, they also suggested that clinical presentation of reduced periodontal support and crown-to-root ratio (i.e. 1:1) may sometimes considered acceptable given that the periodontium was stabilized and occlusal stresses were controlled. Despite the need for utilizing teeth as abutments to support planned fixed prostheses, teeth with more than 1/3 loss of bone support should in fact be of questionable value as abutments.[102] Shillingburg *et al*[103], in another published textbook, proposed a C/R ratio of 1:1.5 as ideal ratio for abutments supporting FPD. They also suggested 1:1 ratio as the minimum in average clinical situations; however, when the opposing occlusion presented tooth or implant supported prosthesis, a crown-to-root ratio of more than 1:1 should be considered to resist excessive vertical and horizontal occlusal forces. On the contrary, the ratio of 1:2 as standard for abutment selection was considered unusually conservative and such ratio could restrict the viability of many treatment options (Figure 2-7). [104]

Treatment plans and clinical procedures may directly affect the crown-to-root ratio. For instance, preparation of a tooth as abutment to support removable overdenture has the highest effect on this ratio. An occlusal reduction of overdenture abutment tooth to within 2mm above the gingival tissues could change this ratio from 1:1 to 1:3.[105] Reduction of the coronal tooth structure to near the gingival vicinity helps to shorten the corresponding lever arm length, naturalizes the negative lateral stresses transmitted to supporting structures, and therefore diminishes the abutment tooth mobility.[106] In this regard, Renner *et al*[107] in a 4-year longitudinal study of overdenture patients, reported that 50% of the studied roots did not show any signs of mobility, 25% of the roots that presented mobility on intervention exhibited no mobility following treatment, and 25% of the roots that presented mobility on intervention exhibited decreased in mobility following treatment. They noted that crown-to-root ratios were increased when increasing the vertical dimension of occlusion (VDO) is needed, however literature have not yet shown the effect of this relationship on tooth mobility following VDO increase for restorative or orthodontic purposes.

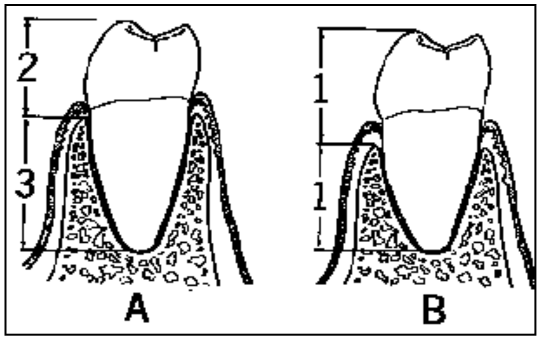


Figure 2-7: Clinical presentation of C/R ratio. (A) Ideal ratio of 2:3 or 1:2 is presents in healthy peridontium (B) Ratio of 1:1 is the minimum for clinical acceptability, it is often seen in teeth diseased or arrested periodontium (adapted from: http://kumhobest.ipdisk.co.kr:8000/list/HDD1/pros/crbr/24/CJFDR037.GIF).

2. 3. 3. Extrusion:

The current literature is lacking clear guidelines to relate the extent of tooth extrusion, relative to the presented occlusal plan, to its restorability or viability of utilizing it as abutment to support prostheses. However, the current adopted principles[108] suggest that corrective and/or restorative procedures are indicated to achieve an ideal occlusal plan and optimum occlusion between teeth since extrusion and mal-alignment may sometimes disrupt esthetics and causes occlusal interferences upon functional and parafunctional jaw movements.[61, 109, 110] In patients with single or multiple tooth loss, extrusion may complicate the restorative management of missing spaces in the opposite arch.[111] Corrective management of extrusion ranges from enameloplasty in minimally extruded, orthodontic intrusion in moderate cases, to extraction of severely mal-aligned or extruded teeth.[112]

Cases in moderate extrusion range may require several correction strategies. While in some moderate cases a partial or complete coverage crown may be considered an adequate management, other cases may require a combination of RCT, surgical crown lengthening and full coverage crown to achieve ideal occlusal plane (Figure 2-8). Clinicians should pay an attention upon planning such cases hence dramatic corrective procedures, i.e. tooth devitalization and surgical crown lengthening, may compromise the structural integrity and crown-to-root ratio of the tooth in question and cause irreversible periodontal damage to its adjacent teeth. [113] A segmental osteotomy procedure was also proposed in literature for management of severely extruded posterior teeth, especially in the maxilla, to achieve an ideal occlusal plane.[114] However, such procedure is considered invasive and may requires special expertise and higher cost while the long-term success of such procedure is not yet proven. The risks of performing such procedure may include series of irreversible intraoral changes that surpasses clinicians ability for correction when compared to simple treatment option of extraction and prosthetic management with either implant supported prosthesis or tooth supported FPD or RPD treatment options per the quality and quantity of available bone and condition of adjacent dentition.

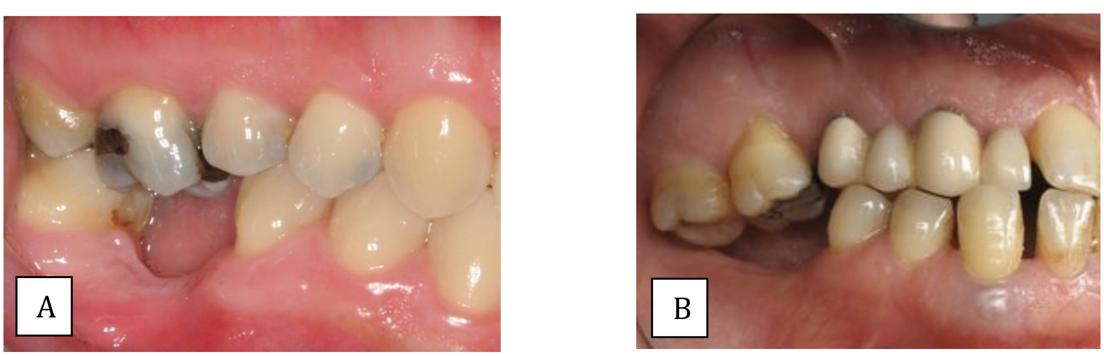


Figure 2-8: (A) Minimum extrusion of the maxillary first molar into edentulous opposing space, in order to restore the mandibular space, this extruded tooth should receive full coverage crown. (B) Severe extrusion of maxillary second molar into edentulous mandibular edentulous space, restoration of mandibular partially edentulous ridge requires extraction of this severely extruded tooth.
Pictures adapted from:

(A)http://www.aadmrt.com/uploads/2/5/4/0/25405419/1180496_orig.jpg
(B)http://www.burbankdentalimplants.com/wp-content/uploads/2009/12/Collapsed-bite-need-for-dental-implants.png

2. 3. 4. Vertical Root Fracture and Location of Finish Line:

According to the American Association of Endodontists a vertical root fracture can be defined as: "a longitudinally oriented fracture of the root that originates from the apex and propagates to the coronal part". [115] The current dental literature has placed vertical root fracture as the 3rd most common causative factor for extraction of RCT teeth. [116] VRF is undeniably crucial to determine the overall tooth prognosis before, during or following root canal treatment. Detection of VRF can be very challenging depending on its size and location and may often require advanced diagnostic imaging (i.e. CBCT) rather than clinical examination. It can sometimes be elusive, as its clinical and radiographic appearances closely resemble that of periodontal and endodontic-related lesions. Therefore, accurate detection and differentiation from other dental condition is crucial as its management vary significantly from periodontal and endodontic-related lesions.

Mild pain can be an initial identifying finding for VRFs in most of clinical case presentations[116] while spontaneous dull pain on biting or minimal tooth mobility may be detected in other clinical cases. In spite of the fact that single sinus tract is a common finding in some clinical scenarios, a diffused swelling with multiple tract openings is not uncommon. Isolated deep periodontal pocket with probing feature of fistula tract is also indicative. The depth of these pockets may sometimes be measured from the gingival margin till the apex of the involved tooth. Tooth sides away from the fracture line are characterized by normal periodontal sulci. Finding may also include development of periodontal abscesses along the line of fracture that is caused by chronic inflammation at that specific surface of the root structure. [117]

Radiographic characteristics of VRF can widely be varied per clinical cases. It may sometime appear as bizarre widening or radiolucency of the PDL space[116], separation of retrograde root canal filling material [118], infra bony or angular bone defect [119], split root portion [120] or fracture in the apical part of the root [121]. In fact, the apical radiolucency 'halo-effect' was recognized as the diagnostic feature of vertical root fracture in some cases. [122] Lesions of periodontal feature are also uncommon. In mandibular molars, especially the root canal treated molars, radiolucency at the bifurcation area is considered significant feature for radiographic diagnosis of VRF.

VRFs are not limited to RCT teeth, their causative factors in vital teeth may include but no limited to small cracks, tooth infraction, acute sport or motor vehicle related trauma or excessive occlusal trauma due to biting on hard objects. Further causative factor of root fracture in vital teeth is what has been recently reported as 'the cracked tooth syndrome'. [115] The current literature on the incidence of root fracture in vital teeth is abundant among Chinese population.[123] It indicated that male are more prone to root fracture when compared to females. Among the teeth that were studied, significant portion (sixty four) were posteriors with sound or minimally restored coronal tooth structure. In Chinese population, significant occlusal wear was noted among full coverage crowns. This finding was related to the dietary pattern, in which was considered as the main causative factor of root fracture in this population.

The majority of VRF cases require tooth extraction as the first line of management.[124] Due to its multifactorial nature; the causative factors were classified into iatrogenic or pathologic categories. These risk factors include excessive dentine wall reduction upon root canal preparation, excessive horizontal and axial compaction of root canal filling material upon canal obturation, desiccation of root canal treated teeth, excessive reduction during post space preparation, aggressive load application upon post insertion, and weakening of tooth integrity due to extensive carious lesion or overpreparation.[125] While root hemi-section can be used to retain posterior (multi-rooted) teeth, the potential fate for anterior teeth in case of VRF is extraction in almost 11%–20% of cases.[126]

Treatment planning should take place as soon as VRF is diagnosed and confirmed. Since proper management of such cases is complex and requires special expertise, predictable management relied on the location of the tooth in the arch, the degree and direction of fracture line, duration between fracture and subsequent treatment, and the location of fracture line on root surface. High percentage of these cases involves extension of fracture line deep into the sulcus, which allows invasion of bacteria and other local irritant [123] and therefore causing periodontal disease and progressive bone loss. [127] To treat this condition and regenerate the lost tissues, the local factor (VRF) should be eliminated hence predictability of managing these cases depends on elimination of bacterial infection.[118] The goal of management is to conceal the fracture line from ingestion of bacteria and other irritants, and therefore maintain healthy periodontium. The effectiveness of treatment intervention depends on the factors mentioned earlier. Furthermore, the site and degree of VRF can be classified into three categories: subra-crestal, crestal and sub-crestal in relation with adjacent alveolar bone crest. Treatment of fracture lines that are at or above the level of bone crest is predictable whether or not surgical correction procedures are performed. It has been well documented in current literature and anecdotal clinical findings that these cases presented high short and long-term treatment prognosis. [128] However, clinical management of sub-crestal fracture is challenging and may result in poor prognosis where extraction is considered the first line on treatment. In fact, several options have been suggested for treatment of such cases. Crown lengthening and orthodontics extrusion are the most common options for treatment, however they may result in a compromised crown-to-root ratio after treatment completion. In general, the proposed ratio should be analyzed carefully and considered upon treatment planning prior to intervention. Although many cases were documented in literature showing various techniques, modalities and adequate treatment results, no solid evidence has been reported on long-term success of treatment intervention in such cases.[128] Extraction may be considered as the first option in sub-crestal fractures to save effort, time and cost (Figure 2-9).

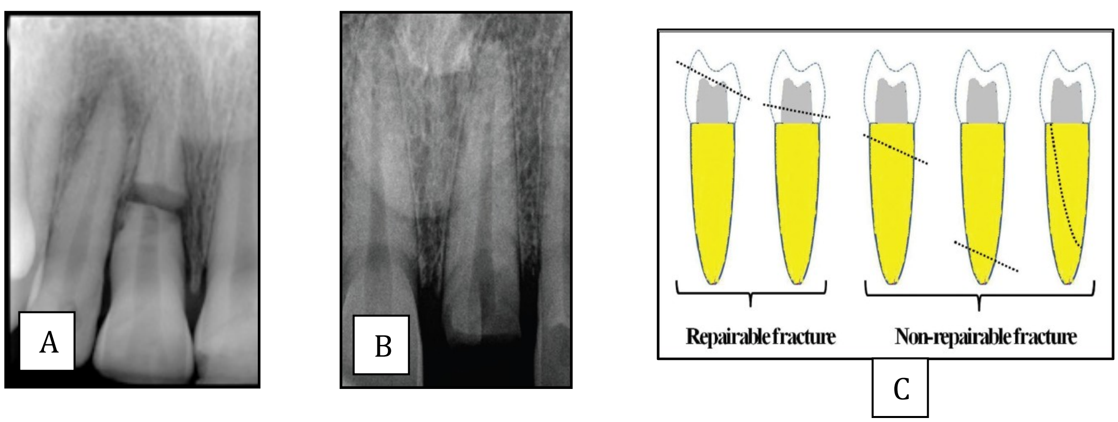


Figure 2-9: (A) Sub-crestal root fracture that can managed with extraction and implant restoration or 3 units FPD. (B) Supra-crestal horizontal fracture that can easily be managed with orthodontic extrusion or crown lengthening. (C) diagrammatic representation of the extent and location of fracture and corresponding treatment where non-repairable means extraction is the treatment of choice.
Pictures adapted from:
(A)http://snellville-dentist.com/wp-content/uploads/2012/05/horizontal-fracture.jpg
(B)Mittal R, Gupta S, Singla A, Gupta A. Managing sub-gingival fracture by multi-disciplinary approach: Endodontics-forced orthodontic extrusion and prosthetic rehabilitation. Saudi Endod J 2013;3:82-6.
(c) Aggarwal V, Singla M, Yadav S, Yadav H, Sharma V, Bhasin SS. The effect of ferrule presence and type of dowel on fracture resistance of endodontically treated teeth restored with metal-ceramic crowns. J Conserv Dent 2014;17:183-7.

The location of finish line in relation to adjacent bone crest should carefully be considered during treatment planning of teeth with VRF or large carious lesions. Although placing the margin slightly below the gingival margin may be acceptable, the depth of margin extension in the gingival sulcus is critical as deep placement causes disruption of biologic width and subsequent periodontal disease, pain and bone loss. Waerhaug[129], in a clinical study, suggested that subgingival placement of restorative margins attribute to plaque retention and complicate the accessibility to gingival sulcus to achieve proper supportive therapy. Since deep margins are inaccessible for scaling and periodontal maintenance, treatment of ongoing periodontal disease is not feasible. In addition, Orkin *et al*[130] reported that restorations with subgingival margin extension exhibited higher chances for bleeding on probing (i.e. active periodontal disease) and recession in comparison to restorations with supragingival margins.

An agreement in literature was noted regarding the destructive effects of deep subgingival margin placement, to include chronic inflammation, gingival recession, and crestal bone loss. Newcomb[131], in a clinical study, investigated the effect of subgingival margin placement in 66 anterior full coverage crowns with varying extension depths within the gingival sulcus in comparison to their unrestored counterparts. It was concluded that the deeper subgingival crown margin placement, the more chances for severe inflammation, recession and crestal bone loss occurred. Ingber *et al*[132] proposed a dimension of 3mm to be maintained between the restoration's margin and alveolar bone crest to maintain health of periodontium and achieve successful treatment. In fact, this dimension should be maintained to achieve long-term prognosis.

2. 3. 5. Root Canal Treatment Complexity and Needs for Retreatment:

The significance of root canal treatment, as one factor among many others affecting tooth prognosis, is associated with the complexity of the presented case and expertise of the treatment provider.[133] The factors that attributes to increasing endodontic case difficulty, include but not limited to: presence of intra-canal calcifications, difficulty of tooth isolation, presence of internal or external root resorption, abnormal root anatomy, extra or hidden canals, need for surgical RCT, presence of restorative posts, dentinal wall ledges, and root perforations. Several classification systems and clinical guidelines have been proposed to assist clinicians in determining the potential complexity of presented endodontic cases. Four important guidelines were readily identified in the current literature, to include the UCSF (University of California, San Francisco) Endodontic Case Selection System, case difficulty indices and guidelines proposed by the American Association of Endodontics, the Canadian Academy of Endodontics, and the Dutch Endodontic Society.[134]

The second factor affecting the endodontic prognosis is the presence of a periapical infection i.e. detection of periapical radiolucency on the periapical radiograph. The present clinical evidence indicated reduced long-term success rates for endodontic cases presented with periapical infection due to prolonged exposure to causative pathogenic factors. [135] Detection of these causative factors and nature of present infection (periapical radiolucency) are crucial for successful endodontic treatment. Therefore, long-term prognosis of a tooth that has been endodontically treated multiple times is poor. The presence of quality coronal seal is also important for long-term success and survival of root canal treated teeth.[136-138] This concept strengthen the intimate relationship between endodontic and restorative prognoses. It has been suggested that RCT is not finalized until coronal restorative seal has been delivered. [139-141] Other studies have suggested that the coronal restorative seal is at least as equally important, if not more, than the apical seal for achieving long-term success and survival rates of RCT teeth. [142] In clinical setting, it won't actually matters which one of them is more important than the other, quality coronal seal should be attempted immediately following RCT to maximize success rate of delivered treatment and avoid possible failures complications (Figure 2-10).

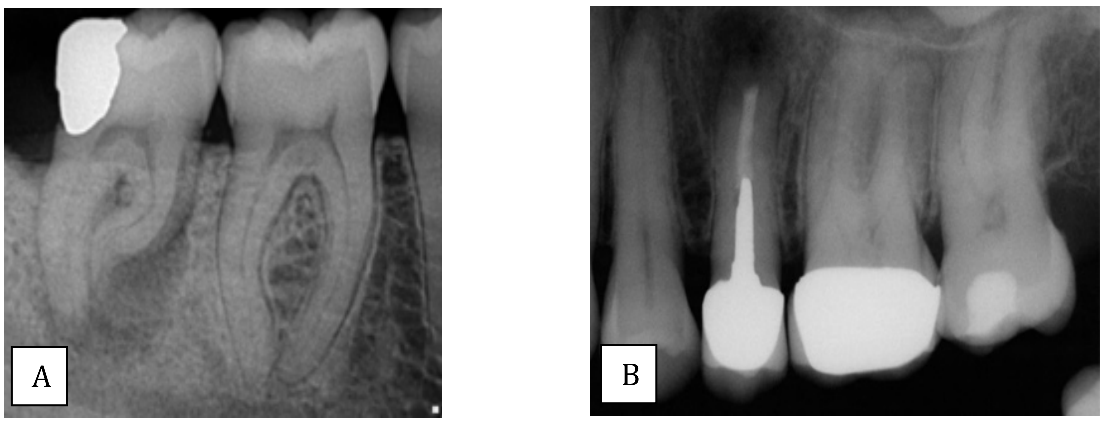


Figure 2-10: (A) Mandibular second molar with severe mesial root curvature that presents complexity to achieve proper root canal treatment. (B) Maxillary second premolar with failed root canal treatment, post/core and crown with possible root resorption. Retreatment for such case present poor long treatment outcome.
Pictures adapted from:
(A)http://www.ppdentistry.com/images/uploads/clinical-articles/feature/fig2.jpeg
(B)http://endopracticeus.com/wp-content/uploads/flynn_main.jpg.

2. 3. 6. Tooth Mobility:

Despite of its questionable value and reliability, tooth mobility is one of the most important periodontal parameters that are widely used to determine individual tooth prognosis.[143] Whilst several studies [144,145] proposed that mobility negatively affects the overall prognosis and survival rate of periodontally involved teeth, other studies disregarded the conceptual association between tooth mobility and treatment outcomes.[146] The conceptual variations between available studies could be explained by its multifactorial nature of and variation of methodologies that have been used to determine the extent and direction of tooth mobility. Muhlemann[147], proposed a technique to assess tooth mobility, in which two metallic (rigid) hand instruments are used to test the tooth in question and therefore record the extent and direction of its mobility within 100g-load application, if present. Classification system of tooth mobility according to degree and direction of movement was proposed by Miller[148]. He classified tooth mobility into three categories where Class I was given for teeth with mobility slightly greater than normal (<1 mm); Class II for teeth with mobility equal or slightly more than 1 mm in horizontal projection only; and Class III for teeth presenting more than 1 mm horizontal mobility and vertical displacement with or without rotation. Regarding the impact of mobility on tooth prognosis, it has been suggested that teeth showing Miller's Class III mobility are definitely indicated for extraction as such teeth present hopeless long-term prognosis and are more likely to cause discomfort upon masticatory function. [149] However, teeth that are exhibiting Miller's Class II mobility require careful evaluation and investigation of all relevant factors to determine the appropriate treatment protocol to address such condition. For instance, occlusal equilibration and splinting of teeth can be considered the treatment of choice in cases of secondary trauma from occlusion or periodontal therapy. Further, clinicians must keep in mind there are physiologic range of mobility that may present in elderly population or all others at variable time during the day.[150] In addition, it has long been recognized that anterior teeth usually show higher horizontal physiologic or pathologic mobility in comparison to the posterior (multi-rooted) teeth.[151] These literature based facts should always be kept in mind and involved in diagnosis, prognosis, treatment planning and maintenance of teeth that experienced tooth mobility whichever the causative factor may be, to achieve successful long-term treatment outcomes (Figure 2-11).

Figure 2-11: Two rigid instruments are used to determine the degree of tooth mobility by application of alternating pressure (100g) in buccal and lingual direction. An incisal/occlusal pressure with one rigid instrument is used to determine presence of vertical tooth mobility. Sulcular bubbles will be noted in case of vertical tooth mobility.
(Adapted from http://pocketdentistry.com/wp-content/uploads/285/9783131604835_f215.jpg).

2. 3. 7. Furcation Involvement:

It is well documented in contemporary dental literature that furcation lesions influence the clinical decision-making of whether to retain or extract a particular tooth. From anatomical standpoint, the furcation is located near the root trunk where root cones originate. Due to the complex anatomy present at the tooth furcation, spread of periodontal disease to this area makes proper periodontal treatment and/or maintenance substantially challenging. [152] This clinical condition is frequently linked with moderate alveolar bone loss, recession and loss of attachment. In fact, furcation lesions are often considered clinically challenging even for an experienced periodontist due to their potentially complex anatomy, difficult accessibility especially for second molars and distal lesions and other anatomical variations. Consequently, proper treatment of furcation lesions requires corrections of all potential local factors such as root concavities; root surface irregularities and approximation.

Hamp *et al* [153] in 1975 classified furcation lesions according to their extension into the inter-radicular area and amount of alveolar bone loss. They have given Class I for furcation lesions that presents less than 3 mm of extension into furcation area when probed; Class II with more than 3 mm of extension into furcation, but not through and through upon probing; Class III for lesions that present through and through extension into furcation upon probing, but no recession and exposure to oral cavity and Class IV with through and through lesion exposed to oral cavity. Class I furcation lesions are the most reliable for periodontal treatment and maintenance. The chances of disease progression in Class I lesion following proper management is almost negligible. [154,155] However, predictable management of Class II furcation lesions is often challenging. The location of lesion, extent, accessibility for treatment and type of tooth are among the factors affecting Class II furcation lesions. Even though the current literature supports the long-term predictability of treating such conditions utilizing advanced regenerative procedures and maintenance, [156, 157] stability at these areas depends on the type of treatment that constitutes a significant concern. [158] For these reasons, careful diagnosis, planning and progression through treatment must be followed. The available periodontal literature proposed poor prognosis for teeth presented with Class III or IV furcation lesions. It has been reported that periodontal regeneration is not a viable treatment in almost all clinical scenarios. [159, 160] Other conservative treatment options, e.g. Tunneling, has been suggested for Class III furcation lesions, nevertheless long-term survival rate following treatment is not reliable as many complications may occur (root caries), which result in hopeless tooth prognosis.[161] Thus, tooth extraction is considered the first line in management of teeth with Class III and

Class IV furcation lesions. [162] Clinicians must differentiate between furcation lesions of endodontic and/or periodontal origins, as the former necessitates RCT to achieve treatment success (Figure 2-12).

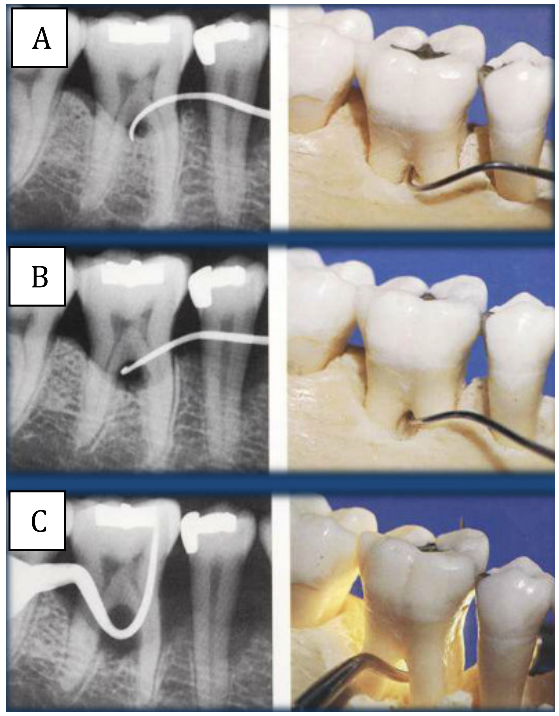


Figure 2-12: Clinical and radiographical manifestation of furcation defects. (A) Hamp Class I defect measures less than 3mm on probing. (B) Hamp Class II measures more tham 3mm on probing without through and through probe penetration. (C) Hamp Class III involve through and through probe penetration when probing furcation area. (Adapted from http://www.intelligentdental.com/wp-content/uploads/2012/04/2012-04-05_223533.jpg).

2. 3. 8. Treatment Expectations and Risk Tolerance:

Successful treatment planning requires consideration of all patient-related clinical factors. Among these factors are patient's desires, expectations and risk tolerance relative to treatment outcomes. These factors should be clearly identified, documented and involved in clinical decision-making process. For instance, teeth that are diagnosed with poor prognosis after comprehensive evaluation and are indicated for extraction, however the patient expresses desire and interest to retain them, patient decision for retaining these teeth should be respected, although the patient should be informed and consented about all possible outcomes and risks associated with this decision. Independent to all other factors controlling the decision-making of retention or extraction of questionable teeth, patient's desires, expectation and risk tolerance are major determinants for this decision and should be satisfied for teeth with questionable (fair, poor) prognosis, excluding teeth with hopeless prognosis that should be extracted regardless of presented desires and expectations. On the contrary, if the patient shows no interest in retaining questionable teeth, low treatment demands and risk tolerance, then extraction may be the right option.

2. 3. 9. Financial Ability:

Patient's financial status is a key-factor that controls decision-making relative retention or extraction of questionable teeth to a great extent. Tooth replacement options, whether conventional or implant-assisted, are often more expensive that retaining a tooth. In fact, significant portion of the patients seeking implant treatment are not aware of the additional cost and time involved in such procedures. Rustemeyer and Bremerich[163], in a survey of 315 patients, reported that the majority of the patients (61%) had unreasonable idea of the cost involved in restorative dental treatment options, especially for patients seeking implant-assisted restorative treatment. In addition, a recent study also indicated that poor financial status is the most contributing factor the population refrains from required dental care. [164] In case financial limitations exist, retaining a tooth of questionable condition may present a viable option given that the patient agrees to this decision; whilst a patient with financial ability whom presented with the same condition tooth, extraction and restorative replacement may present an ideal treatment option. In both cases, careful treatment planning while taking into account patient's financial status is crucial.

2. 3. 10. Tooth Involvement in Planned Treatment:

Generally, experienced dentists based their treatment plans and recommendations on experience they have gained in dental schools, attendance of scientific meetings and continuous education courses, anecdotes and clinical experiences following graduation.[165, 166] Clinicians' abilities to apply objectives is limited by the lack of formal outcome evaluations even for simple and mostly utilized treatment modalities. [167] To avoid all aforementioned local and general consequences of extraction and tooth loss, clinicians are obligated to restore missing tooth spaces as soon as possible, utilizing either implant assisted crowns/fixed restorations or the adjacent teeth to support FPD, RPD or complete overdentures..[86]

During the five decades ago, restorative dentists have attempted to rationalize their treatment plans and recommendations based on Devan's Concept that is targeted to maintain the remaining teeth and not necessarily restore missing tooth areas especially if the planned treatment would place the remaining teeth at risk of loss.[168] In fact, the literature is lacking information on long term prognosis of the remaining teeth when edentulous spaces is not restored. For instance, the majority of the current literature on restoration of edentulous spaces with FPD or RPD predominantly reports the success and survival rates of prostheses only. [169,170] Even tough these information is valuable, it does not provide information on short and long term prognosis of the remaining teeth that were used as abutments to support prostheses as apposed to free standing remaining dentition. While loss of abutment teeth may present negative treatment outcomes, it may have been positive and meaningful to patients whom treatment objective is retaining natural teeth as long as possible. Whilst using survival rate as crucial prognosticating factors is fundamental, a recently study investigated the survival rates of teeth adjacent to 569 treated and untreated partially edentulous spaces.[171] The study concluded that the survival rates (within 8 years) of teeth bounding edentulous spaces were not effected by their utilization as abutments, however subtle differences were noted per the type of restoration used. Although no statistical significant differences were noted in survival rates among untreated edentulous spaces and spaces restored with RPDs, a statistical significant increase in survival rates were noted when spaces restored with FPDs. Another study evaluated the adjacent teeth survival for a period of 10 years, revealed that the survival rates of neighboring teeth were negatively associated with spaces restored with RPDs in comparison to spaces restored with FPDs or untreated spaces. [62]

Several studies have evaluated the load applied on abutment teeth per their involvement in prosthetic designs. It has been reported that abutment teeth that support FPDs receive higher load in comparison to fee standing teeth supporting single crowns. [86, 172] However, the abutment teeth that are used to support RPDs were reported to receive the highest amount of load in comparison to other prosthetic designs. [173, 174] In comparison to abutment teeth in bounded edentulous spaces, the distal abutment tooth in a distal-extension partial denture design receive significantly higher axial and non-axial loads. [175-177] These loads may cause trauma induced mobility, exacerbate existing periodontal disease or cause fracture especially in RCT teeth with large post-space preparation.

Furthermore, Ettinger *et al*, in a clinical longitudinal study, investigated the survival rate of 666 teeth involved in prosthetic treatment as abutments to support removable complete overdenture in 273 subjects over a period of 22 years. They found that periodontal disease (29.3%) was the most common etiology for abutment loss followed by peri-apical lesions (18.8%) and caries (16.5%). In addition, the authors postulated that many of the lost teeth could have been retained if patients had practiced better oral hygiene. Considering the number of abutments involved in the study, follow-up period and subsequent low failure rate, the predictability of utilizing questionable teeth as abutments to support removable complete overdenture is outstanding, taking into account that patients maintained regular follow with the treating dentists and practiced oral hygiene measures and care at home.[178]

2. 3. 11. Opposing Occlusion:

Prognosis, in general, can be defined as prediction of probable course and outcome of a disease or a condition. However, in dentistry, this definition has been modified to include the probable results of a given treatment. Utilization of the current clinical techniques and technologies made the technicality of dental procedures relatively less complex. The real challenge remains in accurate diagnosis and prognosis of presented clinical scenarios since it determine what procedures or options to be used for clinical treatment. The clinical procedures are manual skills that could be learned with practice over a period of time, while accurate determination of diagnosis and prognosis require critical thinking and application of all relevant knowledge and clinical experiences. Because that prognosis is of a multifactorial nature, identifying the accurate prognosis of presented clinical scenarios is challenging and may differs from one clinician to another. In fact, these controlling factors may affect individual teeth and overall treatment prognosis to a great extent. While individual tooth prognosis will determine how adequately the tooth be involved in the planned treatment, the overall treatment prognosis will determine which of the treatment options presented better short and long-term survival and success rates and therefore to be selected for a particular case scenario. It is undeniably important to consider opposing occlusion upon treatment planning as it affects short and long-terms prognosis of questionable teeth in the opposite arch. Occlusal loads, that are applied on questionable teeth, are expected to be the highest in cases with opposing natural dentition and fixed restorations on either teeth or implants followed by opposing occlusion of removable partial dentures, overdentures and conventional complete dentures. [57, 86, 94]

2. 3. 12. Caries Risk:

The concept of caries management by risk assessment was based on series of clinical and in-vitro studies that proven dental caries is a chronic disease that initiated by presence of plaque film attached on the tooth structure, in which responsible bacterial organisms attach and lead process tooth destruction pathway. Saliva possesses powerful buffering capacity and in conjunction with other preventive measures such mechanical plaque control, fluoride application and antibacterial agents could help preventing caries initiation and progression. This new concept is in fact contradicting the old medical philosophy that 'one bacteria causes one disease', therefore the current treatment approach is not focusing on that single bacterial organism, but rather determine all underlying causative factors (e.g. dietary habits, oral hygiene measures etc.) and takes corrective action. This caries prevention protocol can be summarized into: (1) identification of all caries risk factors leading to future development of lesions, (2) control the bacterial causative factor, (3) reinforce caries preventive measures, and (4) conservative control and restoration of existing lesions.[179]

The current dental literature is unclear regarding accurate determination of caries risk indicators and individual's caries risk level. Disease indicators are defined as clinical signs that entail the previous history and activity of dental caries. They also include signs of current disease presence as active and ongoing carious lesions. Although it is of prime importance to identify caries risk indicators, they actually do not inform us regarding to disease etiology and appropriate methodology to treat such a disease. They are just signs to be detected upon direct clinical examination (e.g. carious cavitated lesions and white patches) that confirm the current caries disease presence. The indicators are not factors involved in the pathway of caries in any shape, way or form. The sole purpose of them is to predict that the same or new lesions will develop and continue unless therapy and preventive measures are performed.[180, 181]

While caries risk varies between patients, a patient in low caries risk category doesn't show any disease indicators (i.e. no history of caries or restorations of any type) whereas patient in moderate caries risk category shows at least one restoration done more than 3 years of recalls with no current active lesions. Although patients in these categories don't present active carious lesions, it does not mean they are disease-proof and preventive measures and frequent recall visits should be undertaken to avoid future development or progression of caries. [179, 182] It is very crucial for practitioners to carefully evaluate the following risk indicators: (1) white patches or spots on smooth tooth surfaces, (2) dental restorations performed within the past 3 years, (3) superficial proximal lesions (within enamel) seen on bitewing radiographs, (4) active carious lesion(s) identified by cavitation limited to enamel or extended to dentine that are detected clinically and confirmed by periapical and/or bitewing radiographs. The presence of one or more of these four risk indicators put the patient in high caries risk category, unless preventive measures and restorative therapy are well-planned, executed and disease progression has been controlled. A high caries risk patient, as mentioned earlier, may present with cavitated lesions that act as local reservoir for cariogenic pathogens. Excavation of such lesions and restoring the tooth alone are not sufficient to control these pathogen and their activities in the mouth, therefore an adjunct preventive measures are indicated. The fourth level of caries risk categories, extreme caries risk, is similar to high-risk category, but involves reduction of salivary flow or in other words 'dry mouth'. [179, 182, 183] It has been reported that the long-term prognosis of questionable teeth for patients in high and extreme high caries risk categories is poor, especially for ignorant patients who do not follow oral hygiene instruction, preventive measures or frequently missed recall visits. For this clinical instance, tooth extraction is the treatment of choice and tooth replacement relies on patients' attitude afterwards. [179, 183]

2. 3. 13. Oral Hygiene Status and Compliance:

It has been well documented that the presence of pathogenic bacteria in a prone host are the most important causative factor in the pathway to develop periodontal disease. The abundant presence of dental plaque, that act as a bacterial shelter, and active periodontal pathogens are key factors not only for periodontal disease progression, but also failure of maintenance following periodontal therapy. A cross-sectional clinical study was performed to evaluate periodontal health of a given SriLankan population and its association with tooth loss. [184] The results of this study indicated that participants who missed periodontal therapy due personal negligence or poor financial status had lost all their teeth due to periodontal disease by 45 years of age. Furthermore, another clinical follow-up study[185] indicated that the chance of caries occurrence and progression, continuation of periodontal disease following therapy and tooth loss were almost negligible in patients with excellent compliance to oral hygiene instructions and regular recall visits. It has been indicated that compliant patients, who were treated and kept excellent oral hygiene, may have improved tooth prognosis in comparison to negligent patients.[186]

The current literature proposed so many techniques to evaluate oral hygiene performance over time.[187, 188] These techniques are either visual or recorded in percentages (%), however all of them record plaque containing tooth surfaces, efficacy of plaque control and therefore the ability of patient to achieve good oral hygiene. It does not matter which technique was utilized to evaluate the patient's ability for plaque control, when a patient cannot meet adequate standards of oral hygiene, the long-term success of periodontal treatment and tooth prognosis are questionable. Even though the pathogenesis of periodontal disease is multi-factorial and risk of recurrence remains high especially in patients with previous disease history, tooth preservation can be predictable with long-term success rate in patients with excellent oral hygiene in comparison to poor hygiene patients. Nevertheless, the option of tooth extraction and replacement with implant-assisted crowns or prosthesis may not be the first option to consider for every patient, therefore careful assessment of the patient's current and anticipated oral hygiene status, adequate diagnosis and treatment planning to address patient's needs and desires are crucial in all clinical scenarios.[162]

2. 3. 14. Bruxism:

In general, the occlusal contact between teeth upon normal jaw activities, mastication and swallowing, generate an average load within physiologic level and therefore the incidence of tooth wear is minimum. However, the presence of parafunctional jaw activities or habits (e.g. bruxism) increases the amounts of load on teeth extensively resulting in wear or fracture. A clinical observational study investigated the time of contact between teeth in patients with versus without bruxism,[189] revealed that the overall occlusal contact time in patients with bruxism was 7 times longer than control patients. Although this study focused on the time of teeth in contact, it also suggested that when the time of teeth contact increased, the occlusal load increased exponentially. It would make sense that when occlusal load exceeds physiologic limits, it might present negative effects on periodontal attachment apparatus; however such theory was not documented in the current literature. A clinical study was conducted by Shefter *et al*, [190] to investigate the relationship between occlusal load and periodontal condition of teeth, revealed that occlusion presented minimum to no effect on initiation and continuation of periodontal disease in healthy patients and periodontium. Therefore, the presence of parafunctional jaw activities (i.e. increased occlusal stresses) may have presented negative effects on unhealthy patients and periodontium. There have been no documented studies in literature to investigate the relationship at unhealthy conditions because some periodontal parameters (e.g. mobility and furcation) are difficult to be managed and since periodontal disease is complex multifactorial disease, accurate identification of occlusion-related factors are impossible. Another study by Ramfjord and Ash[191] suggested that elimination of occlusal trauma should be considered as the first step in the treatment sequence of similar cases and that such step is a key for successful periodontal treatment and rehabilitation of the stomatognathic system. Clinicians should keep in mind that in case of tooth mobility, splinting and/or utilization of occlusal splints are needed to alleviate occlusal forces acting on the tooth in question and distribute the load on the neighboring teeth equally. The need for occlusal management can be of an extreme value especially in cases with advanced periodontal disease. Thus, the presence of parafunctional jaw activities could shift the prognosis of questionable teeth to poor especially when patients show no interest to cooperate in occlusal splint therapy. [191]

2. 4. Clinical Decision Support Systems: Definition and Dental Applications:

2. 4. 1. Definition and Concept of Computer-based Clinical Decision Support Systems:

Clinical decision support systems (CDSSs) can be defined as "computer programs that are designed to provide expert support to healthcare professionals making clinical decisions". [192] The sole function of these systems is to provide clinicians with patient-relevant recommendations, which resulted from series of rules evaluation in holistic fashion, at the required location and time to enhance healthcare decision-making and therefore avoid medical errors. [193] These systems provide condition and case relevant information and recommendations. However, these systems were not designed to perform clinical decision making, but rather present case-specific recommendations and alternatives to healthcare providers who could share decision-making with their patients to arrive at informed decisions regarding diagnosis, prognosis, treatment plan, recommendations and alternative options. [194] Agency for Healthcare Research and Quality's (CDS Five Rights Model) stated, "CDS-supported improvements in healthcare outcomes can be achieved if CDS tools are implemented to communicate":

1. **The right information:** evidence-based information, adequate to guide for appropriate action, relevant to the given condition.
2. **To the right person:** taking into account all healthcare providers, to include practitioners, patients and their caregivers.
3. **In the right CDS intervention format:** the outcomes should be presented in conceivable format, to include clinical questions, alerts, recommendations, alternative options.
4. **Through the right channel:** These systems should be readily accessible to healthcare providers. Examples for these channels include electronic health records (EHRs) and general accessed channels such as the Internet or mobile devices. [195]

5. **In the right location and time**

A clinical study was conducted to investigate the relation between improvement of medication use and outcomes of clinical decision support systems, the study has addressed each of the above five CDS rights in further details as failure to do so have been associated with failure in CDS adoption and implementation. [196]

2. 4. 2. Applications of CDSSs in Dentistry:

The existence of dental informatics science is relatively new and still in its early stages of development in comparison to its medical counterpart, nevertheless significant development has been noted in the past few decades. Extensive review of literature has been done in 2003 to track progression and development stages of dental informatics. [197] Dental-oriented clinical decision support systems have covered multiple areas and specialties in dentistry utilizing different knowledge representation approaches. Such systems have been programmed to help clinicians upon diagnosis, prognosis, and treatment planning phases and act as physical aids to collaborate between clinicians and their patients to reach to informed clinical decisions. In the year of 1992, a review study of clinical decision support systems was conducted to determine characteristics that are needed for development, implementation and evaluation of these systems in clinical settings.[198] The authors examined the available dental expert systems that were developed over the period of 1980s among different areas of dentistry, to include: oral diagnosis[199], oral radiographic diagnosis[200], orthodontic treatment advice[201], diagnosis of pulpal disease[202], and treatment planning of dental trauma[203]. They concluded that such systems were able to provide comprehensive evaluation and explanatory outcomes for the examined clinical problems, user friendly and interactive platform that were programmed to be integrated with the existing clinical workflow and readily conceivable among international clinicians and experts in the field, high specificity and sensitivity with regard to presented outcomes and sufficient robustness that made them acceptable among clinicians and experts in their specific fields.

Another review study by Siegel *et al* [204] was intended to investigate the effectiveness of computer use for the purpose of oral diagnosis. They reported that many computer-based systems were existed around the period of 1970s, however the best example of a true system, robust enough for oral diagnosis use, was in 1973 for automated diagnosis and treatment planning in the field of craniofacial pain.[205, 206] This particular system utilized algorithmic reasoning methodology that was based on weighted linear pattern recognition technique. The system was able to perform limited automated-training utilizing information obtained from simulated or reported clinical cases to assign values to specific parameters used by the inference algorithm. Such sophistication made this system unique in comparison to many other systems in that era of time. Several other systems were also reviewed, to include: clinical decision support system for diagnosis of pulpally involved teeth using Bayesian classification reasoning, [202] expert systems for analysis and differential diagnosis of oral panoramic radiographs using Bayesian classification algorithms,[207, 208] the most comprehensive oral radiographic diagnostic (ORAD) system developed by White in 1987 that remains in use to date[200], a Computerized Radiographic Differential Diagnostic system (COMRADD)[209] for diagnosis of oral osseous radiographic abnormalities and radiographic teeth alterations using weighted and non-weighted pattern recognition algorithms, CDSS to aid in the diagnosis and treatment of dental emergencies and soft tissue lesions using algorithmic decision trees,[210] CDSS for differential diagnosis of oral soft tissue lesions called Differential Diagnostic Assistant for Soft Tissue (DDST),[211] a system capable of identifying hard-and-soft-tissue anatomic landmarks used in cephalometric analysis,[212] an automated system for periodontal diagnosis and research that can monitor changes in the area and radiographic density of alveolar bone,[213] system to analyze dental radiographs to produce quantitative description of angular periodontal bone defects,[214] and an automated system[215] for the precise measurement of marginal alveolar bone height based on bite-wing radiographs. These systems presented significant contributions in the field of dental informatics and their chronological developments gives insights the advances made in their fields as well as their future potentials. Table 2-1 presents the available clinical decision support systems, their chronological development, and classification by knowledge representation approach used.

Year	***CDSS Description***	***Knowledge Representation Approach***
1973	Automated diagnosis of craniofacial pain[206]	Algorithmic reasoning based on weighted linear pattern recognition technique
1974	Automated diagnosis and treatment planning for craniofacial pain[205]	Algorithmic reasoning based on weighted linear pattern recognition technique
1983	Computerized endodontic diagnosis[202]	Bayesian classification reasoning
1983	A dental trauma diagnostic program[203]	Algorithmic logical classification
1986	CAREOP: A new system for computer-assisted radiographic evaluation of oral pathology[207]	Bayesian classification reasoning
1986	Computer-aided diagnosis of odontogenic lesions[208]	Bayesian classification reasoning
1986	Computer-assisted dental diagnosis[210]	Algorithmic decision tress
1987	A computer-controlled expert system for orthodontic advice[201]	Rule-based fuzzy logic

1987	An expert system for oral diagnosis[199]	Rule-based pattern matching
1987	Computerized monitoring of alveolar bone by area and densitometric methods[213]	Not reported
1988	Precision of computerized measurement of marginal alveolar bone height from bite-wing radiographs[215]	Not reported
1989	Computer-aided differential diagnosis of oral radiographic lesions[200]	Bayesian classification reasoning
1990	COMRADD: Computerized radiographic differential diagnosis[209]	Algorithmic pattern recognition
1990	Computer-assisted diagnosis of soft-tissue lesions[211]	Not reported
1991	Automated identification of landmarks in cephalometric radiographs[212]	Image processing
1991	Computer-aided interpretation and quantification of angular periodontal bone defects on dental radiographs[214]	Image processing

Table 2-1: List of CDS applications in dentistry [198,204], which were ordered chronologically and classified by knowledge representation approach.

White[216] published a classical and truly comprehensive review of literature on the versatility, classification and effectiveness of the current decision support systems in the field of dentistry. He recognized over 40 CDSSs, in which he grouped them into seven dental specialties (Table 2-2).

Classification of CDSSs in Dentistry
1. Dental emergencies and trauma
2. Oro-facial pain
3. Oral medicine
4. Oral radiology
5. Orthodontics
6. Pulpal diagnosis
7. Restorative dentistry

Table 2-2. Shows seven dental specialties outlined by White[216] and used to classify the identified CDSSs.

White[216] classified these systems according to the knowledge representation approach used, to include: algorithmic, statistical, rule-based, and image processing systems. He also postulated an urge to closely combine these systems into clinically-practical environment, establish supportive platform for diagnosis and treatment planning, structure a robust database for comprehensive clinical decision evaluation and predictable outcomes, and provide real-time quality assurance of these expert systems. Brickley *et al* [217], in an experimental study conducted in 1996, investigated and tested twelve neural network systems of variable designs and format that were programmed to assist in mandibular 3rd molar treatment planning and decision-making. The results of the study showed that while these systems gave the impression of being sophisticated and computer-rigorous, they were truly user-friendly, presented great potentials to be integrated into the clinical workflow, and could be considered as indispensible tools in clinical decision-making in the field of dentistry. In fact these systems could be self-trained and upgraded utilizing clinically relevant data and can used where rule-based decision-making is unfeasible.[218] The effective use of neural network systems was also studied for recognition of individuals or patients that are at risk of developing oral pre-cancerous or cancerous lesions. [219] It was suggested by Bruins *et al*[220] that it crucial to design effective expert systems that could help in evaluation and evolution of the current evidence-based clinical guidelines for pre-intervention oral cancer examination, diagnosis and therapeutic management of patients with cancer in oral and maxillofacial regions.

The literature also reported another clinical decision support system that was designed for the purposes of endodontic diagnosis and treatment planning. [221] The system design was based on data-driven Bayesian technique that illustrated the mutual relationships between multiple endodontic parameters for evaluation of final treatment results. Receiver operating characteristic curve results showed that the model was highly predictable and accurate (i.e. area under the curve = 0.90). The system's outcomes for most of the presented clinical cases were in agreement with experts' opinions. Despite the fact that this system provided unreliable response to small fraction of the presented cases, its ability to predict endodontic treatment outcomes was found promising. The literature also identified remarkable expert system applications in dental field to include: computer based system for application of evidence-based dentistry in caries management [222, 223] and internet-based expert systems for dental treatment planning. [33]

2. 4. 3. Features and Classes of Clinical Decision Support Systems (CDSSs):

Formerly, a comprehensive review of literature was established on chronologic developments of clinical decision support systems in the dental field along with associated representation approaches that was utilized for their designs and developments. In this section, the author will discuss in-depth the features of the current systems based on their applications and proposed designs. Clinical decision support systems can operate as freestanding tool or integrated with other computerized systems such as electronic health systems, electronic drug-prescription systems, or computer-based radiographic systems. These systems' applications were distinctly classified into three types according to their data content and action format into: (i) systems that produce case-related diagnosis, prognosis, alerts and treatment plans and recommendations for proposed intervention; (ii) systems that can retrieve relevant information from internet sources or databases specific to patient's needs to help in accurate diagnosis, prognosis and treatment planning upon decision-making; or (iii) other systems that are capable of presenting pertinent information that are helpful upon clinical decision-making in the forms of dashboards, order sets, documentation templates, graphical displays or detailed reports.[224] All of these platforms and outcomes are undeniably important and serve specific purposes for intended clinical usage. For instance, case-relevant diagnosis, prognosis and evidence-based treatment planning and recommendations could be of valuable assistance to healthcare providers (e.g. dentists) upon assessment and treatment planning a particular clinical case in hand. In addition, systems-generated alerts could be crucial to prevent medical errors such as dangerous drug-related allergies. A possible scenario to explain this importance is that when a clinician orders medication to which patient has an electronically documented allergy, the system fire alerts to avoid such medication and recommend possible alternatives. Such systems are can also be equipped to prevent potentially dangerous drug-drug interactions among prescribed medications.

System-based reminders could be beneficial to healthcare providers in case of tasks that involved patients who were classified into high-risk category for developing dental caries, or more frequent screening for oral cancer in a cigarette smoking patients, or for periodontal diseases in patients with diabetes, or reminders for use of prophylactic antibiotics in patients with sub-acute bacterial endocarditis. Likewise, applications providing context-aware knowledge retrieval known as, info-buttons, can entirely satisfy healthcare providers' information needs with ease of access at the point of care.[225-227]

The data that are stored in such systems may either be transferred through a push mechanism in which all pertinent information is presented in a pre-programmed format, or where relevant information is automatically presented at appropriate times, or via a pull mechanism in which the system's users request information when required at the point of care. [228] The systems' applications that operate in pull-mode work in simultaneous fashion and interact with the systems' users who are in need for case-specific outcomes. An accurate example is a system that generates case-specific diagnosis, prognosis and treatment plan or recommendations according to the data presented or entered by the end users (i.e. healthcare providers). A second example would be a health record system that is able to scrutinize for possible drug interactions or allergy to a specific medication that was prescribed by a care provider to a particular patient. On the other hand, the systems' applications that operate in push-mode work simultaneously in which system reasoning or processing is independent of healthcare providers. The best example of push-mode systems is a system that automatically produces reminders at the desired point-of-care in order to effectively manage patients with medical or dental chronic conditions.

The computer-based systems' applications can also be classified according to the methodology of knowledge representation within the systems. Representation in this instance is relative to formatting the clinical knowledge and guidelines into computer conceivable format. Mendonça[229] published a scientific paper in which he reviewed and classified clinical decision support systems' applications according to their proposed representation model into four generic categories: algorithmic, neural networks, probabilistic, and logical (rule-based). However, Berner[230] in another scientific approach had described a different classification scheme for these applications in which he focused on whether they are knowledge-based applications or not. His classification identified the current rule-based systems as knowledge-based applications, whereas neural networks-based systems were considered as non-knowledge-based applications where such systems were capable of self-learning and pattern recognition procedures. Hence utilizing one form of knowledge representation is not sufficient to solve sophisticated problems and conditions, the majority of the systems are integrating several forms of knowledge representation techniques.[231] Such systems were entitled as "hybrid systems" that are unique in combining the advantages of several systems while overcoming most of the disadvantages associated with single knowledge representation schema.

Algorithmic systems, as described by Mendonça[229], are models that structure and present clinically relevant decisions in the form of decision trees and flowcharts. In fact knowledge in these systems is constituted in all practical, logically ordered clinical decision or options for a particular condition that guide the end-users to obtain the required outcomes or intended destination.[232] A clear representative of this class of clinical decision support systems that use decision-tree platform was noted in a study by Gerald *et al*, [233] which reports a clinical decision-tree that was constructed to help public health workers for determination of which contacts of tuberculosis patients were presumably to result in a positive tuberculin skin test. The results of validating their model showed a sensitivity of 94%, specificity of 28%, and a false negative rate of 7%. One of the principal examples to use decision trees on dental-oriented CDSS was the Diagnostic Aid Resource Tool (DART) that was designed to help clinicians in the diagnosis and treatment planning and management of variable conditions or diseases in the head and neck regions.[234, 235] These algorithmic-based expert systems do not require development of extensive diagnostic or knowledge database, however they could be used effectively in their intended purposes due to their robust nature. It is also arguable that these systems are closed circuit, as they don't accept direct feed of updates or upgrades. They won't be applicable in cases of uncertainty. Therefore, the only way to solve this issue is to re-program the system back to its functionality potential. Modeling decisions and treatment options in dentistry are particularly difficult since they involve risks that are continuous over time, and timing is critical in dental care. Among those risks are development dental carious lesions and periodontal diseases that have potential to occur anytime, more than once and in multiple sites. A clinical decision of whether to retain or extract natural teeth can sometimes be challenging due it catastrophic consequences. Due to the complex nature of these clinical decisions, the use of simply formatted decision trees may seems primitive and unreasonable. On the other hand, an attempt to match such complex decision-making, a system may design may result in very complex platform with clinical advices or recommendations that are either inconceivable or difficult to apply in real clinical settings. [229, 236]

Furthermore, the artificial neural networks (ANNs) are valid alternative to algorithmic empirical systems. These systems are non-knowledge based adaptive CDSSs that utilizes machine self-learning, a unique type of artificial intelligence, to acquire knowledge from previous experiences or conditions and identify a specific design or pattern in the data presented to them. In a consolidated view, these systems simulate some of human's brain function thinking process of gaining knowledge from various experiences and conditions. [217] This area has been under continuous investigations since the 1940s.[237] The design of these network involves three layers or levels that include: the input, the output and the hidden intermediate layers. The input layer is the layer responsible for receiving and storing the data, while the output layer is designed to interact with end-users and present results. The middle layer, the hidden layer, is responsible for processing the data given by the users through the input layer and establishing a predictable relationship between it and the programmed network design to determine the outcomes. In fact these networks have long been used to design various intelligent systems in both clinical and non-clinical fields. In contrast with knowledge-based CDSSs that rely on knowledge given by programmers relative to evidence-based practice, the artificial neural networks process the given patient's data and establish a relationship between the given problems or symptoms and their closely matching diagnosis.

As mentioned earlier, the applications that are based on artificial neural networks could learn from past experiences and conditions that have fundamental outcomes as a training platform for the application in hand. In this instance, the designed system will process the given information, estimates the plausible output, contrasts the estimated outcomes with the given results, explores the patterns that correspond the given input to the correct output, and finally calibrates the relationship between the given input and generated output to produce the correct results. This frequentative and mathematically calculated process is well-recognized as training the artificial neural networks.[238] To apply such modality for dental diagnosis, once the system is programmed and the relationship between the patient's given data (e.g. sign and symptoms) is established to a specific diagnosis, this system can be utilized to diagnose a new patient with incomplete data and to ascertain whether or not a particular patient has that particular disease.

Due to their adaptive learning nature, the artificial neural networks have the ability to process partial data by reasoning what the data should be and continuously refining the accuracy of the outcomes. These networks do not require extensive datasets to estimate the results, however they require extensive training to establish predictable and sufficiently reliable outcomes. In fact the more extensive the training dataset is, the more robust system and outcomes are likely to be. In addition, in contrast with deductive knowledge-based systems, neural networks exclude the need for "if and then" that are based evidence-based guidelines and practices. Despite of their powerful and robust designs, some challenges remains standing against the applicability of artificial networks-based systems. Training the ANNs-based applications is exhaustive and can be time consuming. Reliability, accountability, and maintenance of these systems can also be of challenging taking into account machine learning process for weighting and gathering information that is often not readily reasonable nor conceivable to the common neural networks' platforms.[230, 239] Regardless of the challenges presented earlier, there are many applications in the fields of medicine and dentistry that are still utilizing ANNs-based applications. These applications are uniquely suitable to process the given data, compare it to datasets obtained through learning, narrow down findings and, provide predictable diagnosis for variable clinical conditions such as diagnosis of bacterial endocarditis, joint pain, STDs, and skin diseases.[240] In addition, these systems were utilized in dental field long ago to determine individuals at risk of developing oral cancer and pre-cancerous lesions[219] and for mandibular 3rd molar treatment planning decisions.[217]

On the other hand, the systems that utilize probabilistic approach are using published prevalence and incidence rates of diseases or common problems in particular population to identify the possibility of certain disease occurrence taking into account that all relevant signs and symptoms of those diseases are present. These systems rely on numerical estimates of disease probabilities, common findings, and conditional probabilities, and therefore these systems generally apply Bayes' rule to overcome unpredictability that is common in some areas of clinical decision-making. Bayesian-based systems can be defined as knowledge-based graphical representations of a set of random variables and their conditional probabilities, the probability of an event given the occurrence of another event. Relative to clinical decision support systems, a Bayesian network accounts for the probabilistic relationship between particular diseases and their signs and symptoms. This network gives a mathematical background for expert systems to be able to compute the probability that a given patient has a particular disease given the prevalence of that disease in a population with similar characteristics and findings as the patient's.

The Bayesian approach in itself is often complex and clinical decision support systems that are based on this approach can be restricted due to the reality that the numerical probabilities can sometimes be unknown or driven from a particular population differing in characteristics from those of patient case at hand. In addition, this approach is not empirical for comprehensive systems that given multiple problems (e.g. signs and symptoms) as this approach may perform complex calculation and processing on multiple simultaneous symptoms that can often be confusing or overwhelming to the end-users. Nonetheless, their beneficial utilization has been revealed through many applications taking into account their capability to represent knowledge in a simply engaging method. These systems are unique in allowing causal reasoning and probabilistic inference that can help CDSSs in proper decision-making and achieving predictable treatment success in complicated and multidisciplinary clinical scenarios. There are many examples of Bayesian network based probabilistic clinical decision support systems, however important examples include: Iliad[241], a general CDSS, Mammonet[242], a mammography CDSS, LUCADA[243] based CDSS for lung cancer care[244], and SimulConsult[245] for initial differential diagnosis and suggestions in the area of neuro-genetics. In addition, further examples of Bayesian systems in the field of dentistry include Oral Radiographic Differential Diagnosis (ORAD) [200], a system that is able to assess the clinical and radiographic findings for cases that present with intra-bony lesions in order to help clinicians to diagnose them accurately along with treatment suggestions, a system that helps in pulpal diagnosis [202], a system for assessment of given treatment plans for caries management [246], an open case scenario-based decision support system for diagnosis of oral pathology lesions [247], and Dental Clinical Advisory System (DCAS) [248, 249], which is a program that utilizes probabilistic causal approach and Markov model for management of prosthodontics-related problems for the purpose of providing viable treatment plans for patients with ongoing risk for developing caries and periodontal diseases and changing transition probabilities over time. Such systems are aimed to improve healthcare services and avoid errors that could be devastating on patients' health and quality of life.

Furthermore, rule-based logical deduction systems that are also known as production-rule systems, gain relative knowledge and experiences of field experts in format of if-then rules to make knowledge-based informed decisions. Once a system of this kind is fed up with rules that are structured, arranged and weighted according to designer's plan to address problems or assist in clinical diagnosis and planning, current information about patient health status and findings can be assessed in comparison to existing rule-database by forward or backward chaining rules together until a diagnosis or treatment related decision relative to that patient is made. In fact, there are many successful CDSSs that are utilizing knowledge rule-based systems have been designed to suit many healthcare specialty areas in order to assist care providers upon diagnosis and treatment planning of patients in hand. [250-260]

On the other hand, production-rules systems are effective in representing knowledge in much simpler and attractive way within the clinical decision support system. In fact, much of routine healthcare services provided by clinicians in daily practice follow specific well-known rules such as antihistamine prescription as the treatment of choice and first to consider for treatment of patients with allergy to pollens. Further useful characteristics of such systems include their ability to adding and updating rules that rectify the decision-making logic and capability to store extensive amount of data in the system as new knowledge or advances are developed. Such feature ensure scalability and updating needs of clinical decision support systems, since new knowledge based-rules can be processed parallel to the old rules avoiding the need to rewrite the inference engine algorithms to generate accurate and predictable decisions and recommendations. Nonetheless, it may be difficult for experts to format their in-depth knowledge into algorithmic formatted-rules, and such systems require extensive experience in deduction-based knowledge in order to provide accurate rules and therefore accurate outcomes. This feature can make these systems quite complex for inexperienced rules maker, designer and areas of narrow domains. In addition, if-then rules may exaggerate specific diseases, especially when they are not modified to reflect accurate incidence or prevalence rates of particular diseases. Additionally, the if-then rule based systems have difficulty dealing with uncertainty. MYCIN[261] is a good example of early rule-based expert systems, which was based on nearly

600 rules to assist in identification of the type of bacteria that are responsible for an infection. The developers of this system have addressed the problem of uncertainty by engineering the concept of certainty factors, which are numerical estimates of confidence that are proposed by field experts with regards to facts in the system's knowledge base. These factors ranged from -1 that refers to false data to +1 that refers to its true counterpart with 0 value indicating no belief in either positive or negative directions of the statement's accuracy. Although MYCIN system showed strong probabilistic basis to address the issue of uncertainty, it also assisted to present the power of these systems by contrasting the extensive size of knowledge base, an approximate of 600 rules, to the narrow view of the problem domain. Several examples of rule-based expert systems in dentistry include: RHINOS, a consultation system for diagnosis of headache and orofacial pain[262], and RaPiD[263] for designing removable partial dentures (RPDs). RaPiD offers CAD-style graphical interface for design automation and a critiquing model, a variant of rule-based systems, that responds to proposed diagnosis or treatment planning with agreement or alternatives.

However, there are several other representational applications and systems that have been used in healthcare field for decades that do not belong to the four categories described above, which have been proven successful and credible to improve healthcare services. An example of these systems is case-based, in which an information from the past is stored in the knowledge base that can be repossessed with specific index activation in order to address a relevant problem in future. The success of such a system in solving pertinent problem is relating the problem in hand to previous experiences. This methodical technique present unique advantage in comparison to traditional knowledge-based systems, especially when the presented problems are open-ended with weakly identified concepts or deficient logic algorithms. In this instance, Clinical case scenarios can be used as explanations and assist to obtain adequate answers in short time. Although this index retrievability feature is a strong indicator of this system's performance, such systems present powerful potentials for clinical applications especially when large knowledge bases are indicated. Granularity of indices, general framework for index content, and design of case retrieval algorithm remain as strenuous tasks for designers of systems that utilize case-based problem solving approach.[230] Regardless of their associated difficulty, case-based approach have been considered as a valuable alternative for building user-friendly and expansible knowledge-based systems as have been successfully developed and implemented in clinical decision support systems used in various areas of medicine[264-266] and dentistry[267].

Minsky[268], in 1970s, pioneered an alternative approach for knowledge representation that was designed to include a unique frame-based structural representation in which clinical knowledge is programmed into distinctive blocks. These frames are complex data structures, which contain information about specific principles being reported accompanied by procedural information and instructions on how the utilized frames may change over time. This frame-based approach present distinct advantages due to the fact that frames can be structured and conceptualized as self-contained classes that are consistent with currently updated clinical guidelines. Such systems enable knowledge development and generate operational recommendations and perceivable explanations for healthcare providers. The versatility of such systems also facilitate their integration with elements of a network, logical or hierarchical decision process. Although these systems are effective in processing diagnostic and therapeutic decision-making, the frames could also be programmed to operate database queries and make changes in the user interface or stored program variables. A classical clinical study was conducted to investigate the applications of frame-based knowledge representation approach in hospital based setting, the investigators have reported a successful development and implementation of a simple, user-friendly and accessible at bedside clinical decision support system for ventilator weaning.[269] Regardless of its enormous advantages, this approach present a set of challenges. This approach was not implemented to deal with changing data over time, and therefore frame-based systems can not be used in complex clinical situations with "what if" scenarios. Russell and Norvig[270] reported the challenges of using such approach, in which each input could affect the method this system approaches and processes a problem in ways that make prediction of final outcomes potentially impossible. Despite the ability of humans to rationalize and process "what if" conditions, frame-based clinical decision support systems need extensive knowledge bases accompanied by complex structure of rules in order to simulate this kind of reasoning including a dynamic and continually changing problems and domains representation.[230]

With such clinical decision support systems becoming more complicated, information requirements could not be fulfilled with representing facts alone within the knowledge database. Such complicated systems will also require instant accessibility to principal features to support clinical field. To meet these outstanding needs, ontological engineering concept along with its associated knowledge have helped to develop ontologies platforms to solve such needs. In this context ontologies can be defined as "formal, explicit specification of a shared conceptualization".[271] this concept assist in accurately defining and standardizing essential principles in given, to which targeted groups are employing the ontology experience uniformly in terms of using the same concepts, terms, and relationships. Due to the fact that the knowledge contained within ontologies is indexed, it enables the development and implementation of clinical decision support systems in easy and conceivable manner. In addition, this approach facilitates the use of metadata for extension and maintenance of key knowledge in the knowledge database. Nevertheless, the principal challenge that stands against the use of this approach for developing expert systems is the absence of clearly defined standards for internal knowledge-representation format, communication platform, or choice of terminology. For example, several healthcare institutions that are adopting ontologies may accept the use of particular terms in a given context, however they may wind up conceptualizing these terms differently. Therefore, this variability could possibly alter the use and access to such knowledge-based systems. Moreover, tremendous efforts are needed to uniformly define such concepts, actions, and terms for these problem domains, which in fact could be a very complex process.

Despite that ontology-based clinical decision support systems are not currently familiar in healthcare environments, they actually set a good example of systems that utilize such approach for knowledge representation in clinical settings. Among the noteworthy examples of such systems is Unified Medical Language System (UMLS)[272-275], which combines extensive amount of terminology and principles from around sixty different coding and vocabulary systems in order to produce a unique conceptual background for term categorization. Another example are Generalized Architecture for Languages, Encyclopedias, and Nomenclatures (GALEN)[276], which was developed as medical terminology reference to be used among variable clinical systems and SNOMED CT[277,278] that involves extensive amount of clinical terminologies and semantic relationships. On the other hand, such systems exist in dental field to include SNODENT[279], which is the Systematized Nomenclature of Dentistry developed and implemented by the American Dental Association (ADA) over the period of 1990’s. Despite of its continuing development over the past two decades, this system did not present teaching or practical value in both academic and clinical settings. This application deficiency had led to development of a practical system named "EZcodes", which involves an extensive dental diagnostic terminology designed and brought to existence by COHRI[280], a group of expert academicians and practitioners in dentistry. This system is composed of 13 categories, 78 subcategories, and nearly one thousand diagnostic terms that are systematically arranged and mapped to match relative terminologies systems such as SNODENT. Due to the fact that this system can be conveniently operated in conjunction with dental electronic health record systems (D-EHR) that are mostly utilized in dental institutions, this characteristic led to its familiarity and widespread implementation and adoption as well. Development of such unique diagnostic terminology system reveals numerous potentials to improve clinical research in dentistry, academic teaching curriculum and methodology, diagnosis and treatment planning, quality of delivered dental care, and clinician-patient communication.[281]

In addition to several knowledge representation clinically oriented systems that were discussed throughout this chapter, additional attempts have been made to design a standardized system for the purpose of publishing of important clinical guidelines that are programmed into various clinical decision support systems. These clinical guidelines were developed by expert healthcare providers and publicized by professional or government organizations. Such healthcare-related guidelines entitle specific recommendations relative to best healthcare practices at specific clinical settings and conditions. Practical examples of proposed standards for computer-interpretable design that are used for clinical practice guidelines include Arden Syntax[282], and Guideline Interchange Format (GLIF)[283]. These standard formats improve clinical education, healthcare quality assurance, adoption of clinical guideline-based expert systems that are effective to use in variable clinical domains. Similarly, Current Dental Terminology (CDT)[284], that are prominently used in dental care settings, is a terminology wizard system that contains extensive amount of dental terms that was developed and upgraded by American Dental Association (ADA) for documenting and reporting dental care services and clinical procedures to responsible insurance companies. Nonetheless, our careful literature review indicated clear absence of standardized format among clinical practice guidelines and clinically oriented corrective or rehabilitative procedures throughout all studied dental disciplines.

The current adoption rates of dental electronic health records (DEHRs) and computer-based order entry systems used in many disciplines of medicine and dentistry reflect promising future for next generation expert system applications. Tremendous efforts were done to develop knowledge representation approaches, as shown throughout this section, have actually created opportunities for developing potential systems that have theoretical and practical applications in the field of health informatics. The success that was associated with implementing clinical decision support systems in various clinical fields has also assisted in transient shift in attitude, behavior and adoption of computer-based decision support systems by healthcare providers. The devotion of modern health insurance companies and advocates of current technologies that destined to achieve patient safety and high quality care has greatly assisted with buy-in from provider community. Nonetheless, this devotion can be declined if researchers and developers of clinical decision support systems do not design products that are aimed to address outstanding clinical needs, maintain the virtue of practitioner-patient relationship, and prevent possible disturbances in clinical workflows.

2. 4. 4. Clinical Decision Support Systems in Restorative Dentistry:

This section is dedicated to review widely used clinical decision support systems that have bee developed and implemented in the area of restorative dentistry. This core specialty is one of other branches and sub-branches that relatively combined together to form the dental specialties. The clinical decision-making of whether to retain or extract a questionable tooth is the most important in the area of restorative dentistry since all decisions and options depend on it to outline the final case treatment plan. This section will briefly discusses that strength and weak points of systems that are used in this field gives a justification to support our proposed system and how such a system could assist clinicians upon clinical decision-making of whether to retain or extract questionable natural dentition using a user-friendly, interactive and predictable computer based-interface that take into account evidence based data, clinician's expertise and patient's desires or preferences.

The field of restorative dentistry is undeniably a complicated specialty that relates to many rehabilitative, reconstructive and life changing decisions in the field of dentistry. Upon case examination treatment planning, a prosthodontist is a specialist that guides all other specialists through this process owing to his/her extensive knowledge, artistic and clinical skills and critical thinking to obtain informed and accurate clinical decisions. To date, the decision of whether to retain or extract remains a dilemma for clinicians, especially for novice ones. A complex decision-making of this magnitude requires careful and coordinated treatment planning process in conjunction with development of sequential treatment steps protocol that would be outlined and followed accurately. Such process is in fact necessary to achieve multi-faceted care, however clinicians need to understand that such sophisticated approach would necessitates extra chair side-sessions and solid background and knowledge in the fields of prosthodontics, periodontic, and endodontic disciplines. This retention-extraction decision-making can be extremely challenging, as any judgmental errors on the part of the dentist might be irreversible to a level that cost the patient more funds and lengthen the overall treatment time. In general, a heroic attempt to retain non-salvageable teeth or extraction of salvageable ones could results in the same negative outcomes relative to treatment cost and time. The area of restorative dentistry, namely retention or extraction decision-making, has never been discussed nor investigated before regardless of its crucial importance as one of the most critical factors upon treatment planning and execution. On the other hand, several other sub-braches under restorative dentistry have been explored enormously. Unarguably so, viable decision support systems for the purpose of consultation upon treatment planning sessions, particularly in such sensitive decision-making, can notably improve decision-making process and therefore assist in generating predictable and well-informed outcomes. RaPiD is one of the knowledge-based systems that has been designed and implemented to assist prosthodontists in the process of designing removable partial dentures (RPDs). This system presents graphical representation of partial denture components that can be directly designed and modified by end-user, a general dentist or prosthodontist, in order to obtain the required denture design that satisfies all biomechanical, functional, and esthetic principles. In such interface, clinicians have the ability to modify arch forms, represent available and missing teeth and plan RPD framework in virtual manner with complete control. This system is also advantageous in its ability to assist with removable partial denture design by dynamically determining the size, shape and position of the variable RPD components to comply with the shape of abutment teeth and surrounding soft and hard tissues when run in automated mode. However, running in critiquing mode, this system uses rule-based expert clinical knowledge to scrutinize the proposed design, recommend specific modifications and allow complete control in changing the proposed design to meet the aforementioned requirements. These expert rules are in fact beneficial to act as idealistic design template for comparison and early warning for the end-user to avoid possible faulty points while designing the RPD case in hand. The final computer-generated RPD design could then be communicated with the dental laboratory to guide technician upon design and fabrication of the denture framework. Such feature is extremely crucial for accurate construction of removable partial dentures often times gets miscommunicated between dentists who provide such treatment modality and dental technicians.[263, 285, 286]

In addition, White[216] reported two other systems that assist with removable partial denture (RPD) design. These two systems utilize algorithmic decision-tree based processing interface to help clinicians through the design process. The first system is MacRPD that was introduced by Beaumont[287, 288], this system enables design modifications that are based on patient-specific information and helps in generating a printed design chart that can be used by the dental technician upon laboratory denture fabrication. The second system was developed by Wicks and Pennell's[289], this system was more informative and user-friendly than its predecessors, in which it interacts with the end-users to ascertain required information including but not limited to available and missing teeth, periodontal parameters (e.g. PD, CAL, mobility and furcation), condition of the residual ridge, patient's functional and esthetic concerns, and occlusal considerations. The system then generates a proposed RPD design that can be manipulated by end-users as required and then sent to the dental technician along with the models.

Moreover, Finkeissen *et al*, [33] designed an Artificial Intelligent Dental Agent (AIDA) system to assist in adequate decision-making relative to treatment planning in prosthetic dentistry. The system was developed based on rule-based expert knowledge that are able to recommend a main ideal treatment option and viable alternatives that are arranged in logical order. Such system is could present predictable outcomes upon decision-making with rationale and conceivable logics to dental students, novice or experienced dentists and patients as well. The system's recommendations are implemented in XML, which can be accessed on the Internet or other healthcare systems such as dental electronic heath records and appropriately presented to the end-users and their respective patients. An extensive evaluation of this system revealed that up to 68% of the Artificial Intelligent Dental Agent (AIDA) system's suggestions were accurate and acceptable to evaluating dental experts.

Treatment planning decisions and options in the field of prosthetic dentistry are presumably complex due to the fact that they include probable risk that is continuous over time, and that time-related changes are crucial dental care. Nonetheless, restorative dentists may pose as the main dental specialists to decide whether a questionable tooth worth retention or that extraction may be the treatment of choice in specific clinical scenarios. Retention and restoration of fairly poor or hopeless teeth is time and cost consuming as failure followed by extraction may occur short-term after treatment completion. To address such an issue, Umar[249] proposed utilization of Markov Model to develop prognosis models for clinical conditions or diseases with ongoing risk and unpredictable patterns or probabilities over time. This proposal was introduced as continuation to the existing probabilistic causal approach that was utilized to design the Dental Clinical Advisory System (DCAS). [248] DCAS was developed as a decision support and treatment-planning tool for prosthodontics purposes. Such systems utilized effective diagrams to model relationships between specific predictors and their respective outcomes related to the prosthodontic decision-making process, Bayesian networks to encode existence of probabilistic influences and joint probability distribution over domain's variables, enhanced entity relationship (EER) diagrams for knowledge representation, and relational databases for storage and retrieval of clinical data needed to perform necessary modeling calculations.

Such system proposed the relative risk of a specific patient to becoming partially or completely edentulous based on the patient's present condition within the prosthetic cycle. Furthermore, the algorithms that were developed by Hollenberg[290] were efficient to estimate the financial cost or effectiveness of being in a specific condition(s) for a single or multiple prosthetic cycles. Regardless of the promising results that were presented in Hollenberg research work, the current literature lacks information on implementation, adoption and effectiveness of such system in meeting its intended purposes.

As an example of shared decision-making model, Park *et al* [34] suggested an ontology-based clinical decision support system for prosthodontics treatment planning. Park and colleagues proposed that the use of such approach helps to improve clinician-patient communication during the treatment planning phases and therefore enables patient-centered dental care. This system incorporates ontologies of prosthodontic treatment planning and alternatives to form a shared decision-making model that possess the required clinical knowledge for optimal prosthetic management. In this instance, the patient desires and preferences are involved in the model using Analytic Hierarchy Process (AHP) [291, 292] to assist in identifying the treatment priorities. This sophisticated system was brought into service as an Internet-based system that could generate evidence-based treatment recommendations and options that are weighted and ordered based on their predictability and long-term success. Initial evaluations of the system revealed advanced developments, quality improvements, enhanced dental care, and patients' satisfaction.

The CDSSs, that were discussed previously, have satisfied many outstanding needs in the field of clinical decision support relative to diagnosis, prognosis and prosthodontics treatment planning. Despite of the number and effectiveness of the presented systems, none of them have focused on the aspect of decision-making relative to retention or extraction of questionable natural teeth based on collective prosthodontic, periodontic and endodontic factors. Such decision is often complex due to the number of factors involved in decision-making process. The complexity of treatment planning questionable teeth is influenced by enormous number of dependent and interdependent factors, which may result in erroneous decision-making and poor treatment outcomes. Therefore, the sole aim of this study is to design a clinical decision support system that is based on clinical expert knowledge and evidence-based guidelines to form a standard decision trees that help in accurate treatment planning of questionable teeth. Furthermore, the proposed system is also utilizing shared decision-making approach in which the patient desires preferences are included in the scoring algorithm that controls the final treatment outcomes, alternatives and recommendations. The current literature showed that documenting patients' current and historical symptoms, desires and preferences could help clinicians in gaining better understanding of patients' perspectives and therefore provide more effective, patient-centered care.[293]

2. 5. Efficacy of the Available Computer-Based Technologies in Dental Education:

The current advancements in dental research have led to ever-increasing body of knowledge that mandated dental researchers and clinicians to collaborate in gathering such knowledge and control the flow of information reasonably and in productive manner. It is undeniably difficult to neither retain this enormous flow of new information nor instantly access it at the point of care; this calls into question the need for development and improvement of the current computer-based technologies that could facilitate an effective and expedited use of this knowledge meaningfully towards patient clinical management. In other word, the modern dental education favors the development of skills in accessing relevant knowledge over the memorization of an ever-increasing body of facts. Therefore, dental professionals are obligated to find the effective way to undertake evidence-based decision-making approach utilizing patient-specific information for the purpose of diagnosis and treatment planning of a given clinical scenario. For the above-mentioned reasons, an extreme need is being placed to develop such helpful technological tool to assist in computer-based learning (CBL). The current literature proposed that CBL improves learning and provides the clinician with key information that is required for adequate decision-making at the point of care when managing patients.[294]

In fact, clinical decision support systems (CDSSs) are the best way to enhance CBL due to the fact that they are capable of presenting structured questionnaires, proposed diagnoses, prognosis, treatment plans, recommendations, alternatives, textual information, and visual aids on demand. Regardless, these systems are not meant to take over traditional education, but rather adjunctive for self-directed or group studies. Moreover, these systems also have the ability to strengthen conventional methods of learning and make chances to present clinical scenarios or conditions in user-friendly, simplified and interactive ways. The learning process, utilizing these technologies, has the potential to assist dental students to develop adequate skills and knowledge in the interest areas of experts and decision support systems. Schittek *et al* [294] reviewed the advantages of CBL and they proposed three advantages to include: (1) It facilitates self-paced learning for students which means students can take their own time to go over the learning material, (2) It is not judgmental if the student makes mistakes in the learning process which means students can learn from their mistakes without embarrassment, and (3) Student can go over the learning material any number of times without computer getting tired. Furthermore, the anonymity of CBL interface such as CDSSs can be helpful in guiding users through diagnostic, prognostic, treatment planning and therapeutic stages of patient management in user-friendly, simplified and interactive ways per the level of user's knowledge and experience without being judgmental about the user. These systems are aimed to standardize health-related terminologies, diagnoses and prognoses; consequently improving consistency in managing cases among clinical users.[216]

Due to the enormous advantages of utilizing CDSSs as tools for CBL in dental education, our proposed CDSS is aimed to facilitate evidence-based decision-making approach for diagnosis, prognosis and treatment planning (i.e. retention and restoration or extraction and replacement) of questionable natural teeth. Our system is also aimed to improve learning process for undergraduate dental students and novice dentists. Our system was designed to direct the end-user through the steps of treatment planning process and generates alerts, diagnosis, prognosis, treatment recommendations and alternatives. In this designed system, the end-users are required to provide the system with patient-relevant information to obtain useful treatment recommendations and guidance in return. Due to the fact that this is a computer-based system, the end-users can walk through the steps of the treatment planning process at own-pace and number of times needed. This could help the end-users to go the entire process at ease without the fear of being judged or critiqued. Our proposed system will assist the end-users to learn how the expert made a particular treatment recommendation due to the fact that the system gives explanations for each proposed treatment option. The sole advantage of such system is the ability of combining evidence-based information and experts' opinions to provide the users with accurate and cutting-edge clinical recommendations avoiding the hassle of seeking information at the point of care. Although this might often be hidden from the users, they can also learn about the different factors that are critical in the decision-making process and how each factor weighs-in on the suggested treatment option and its associated outcome. While the current aim is to develop the proposed system only, this system is expected to result in fewer errors in the decision-making process following implementation to enhance patients' healthcare.

Chapter 3: Development and Implementation of the Proposed System:

The clinical decision support system that we proposed is an expert system that aimed to assist clinicians to achieve appropriate clinical decision throughout diagnosis, prognosis and treatment planning (i.e. retention and restoration or extraction and replacement) of questionable teeth. CDSSs can be defined as "computer programs that emulate the interaction that a person would have with a human expert for advice or a recommendation". [295] The majority of clinically relevant decision-making processes can be broken down into several smaller steps to which a human expert can efficiently processes each step in mind to arrive at reasonable conclusions or solve complex problems. This intuitive rule-processing methodology is a second nature to the human experts making clinical decisions that become evident at complicated scenarios where the rationale for the decision is explained to someone else. The rules that are used by experts upon decision-making process are heuristics or rules of thumb. While each rule of thumb may not be sufficient or meaningful to make any final conclusion, series of these heuristic rules, based on given patient-specific facts or information, can assist in making the final clinical decision. For the purpose of adequate training, the experts should guide non-experts throughout the heuristics factors that are involved in the decision-making process. Nevertheless, this knowledge-sharing learning process could be time-consuming, requires tremendous effort, complex, and unreasonable to repeat for large groups of non-experts individuals that needed to be trained. Furthermore, the capability of the trained individuals to recall all heuristic factors that are involved in decision-making at a specific point of time and particular point of care is questionable, which may contribute to major decision-making errors. In fact, this is an example in which the true value of expert systems can be clearly realized. For the above-mentioned reason, the expert systems are targeted to eliminate the urge to remember all the rules that an expert learns and develops over an extended period of time based on experts' field and value of experience. For instance, a clinician may develop an understanding of a particular class of diseases based on their signs and symptoms. Part of this understanding is gained upon formal training and education in the same area of interest and the remaining is gained through anecdotes, continuing education courses and shaped over the years of practice following graduation. A properly designed expert system is able to capture this remarkable knowledge and experience in its knowledge database. This advantageous feature allows the following key applications and virtues of expert systems[296]:

1. Help the under-experienced clinicians to quickly make adequate conclusions: Although these expert systems have enormous advantages and applications at any healthcare setting, their sole advantage is the ability to assist clinicians to efficiently derive adequate conclusions at the exact point of care without the need of novice clinicians to remember all relevant heuristic factors. These systems can automatically guide the targeted individuals throughout the decision-making process and ensure that they are following the rules, according to their designed sequential processing, to avoid possible risks of personal biases and decision-making errors.

2. Improve learning environment and knowledge, while reducing effort and cost: as mentioned earlier in this section, since these systems are computer-based, they can assist in delivering knowledge to a large groups of individuals in a consistent fashion despite of their varying location or time of delivery. These systems are not judgmental, and therefore end-users would feel comfortable using them at own-pace as many times as needed. They can be very efficient for training and assist in testing acquired skills.

3. Transformation of knowledge into codified rules to assist in decision-making process: the majority of clinical experts do not have free time to document all their knowledge, experience and key rules that they use to solve specific problems and make accurate clinical decisions. Therefore, developing a unique expert system that captures this knowledge, experience and key rules can assist in retaining knowledge for future use and avoiding the risk of losing experts' knowledge and experience.

4. Combine the knowledge, experience and skills of experts in a particular field of interest: these systems are also targeted to reinforce the practice of evidence-based healthcare and gathering the knowledge of many experts, in the same field of interest, to structure decision support rules that could assist in eliminating individual biases to leading to completely objective decision-making approach.

Our proposed system has the capability to fulfill all experts' roles that were described above and assists in addressing an critical gap in the area of automated decision support tools for teeth retention or extraction clinical decision-making. In the following sections, we describe in details the proposed system's architecture, process flow, rule-based knowledge management approach, and logical system components to clarify the process that is followed to design the system.

3. 1. System Architecture:

Our proposed CDSS for retention or extraction clinical decision-making is designed using a three-tier architecture model. The system's components are sectioned into three tiers of services, namely presentation tier, logic tier, and database tier. The proposed tiers do not correlate with the methodology followed upon distribution of system components in a physical arrangement, but rather to order them in logical sequence or layers of the application. Figure 3-1 shows each of the three proposed tiers and the components included in each tier:

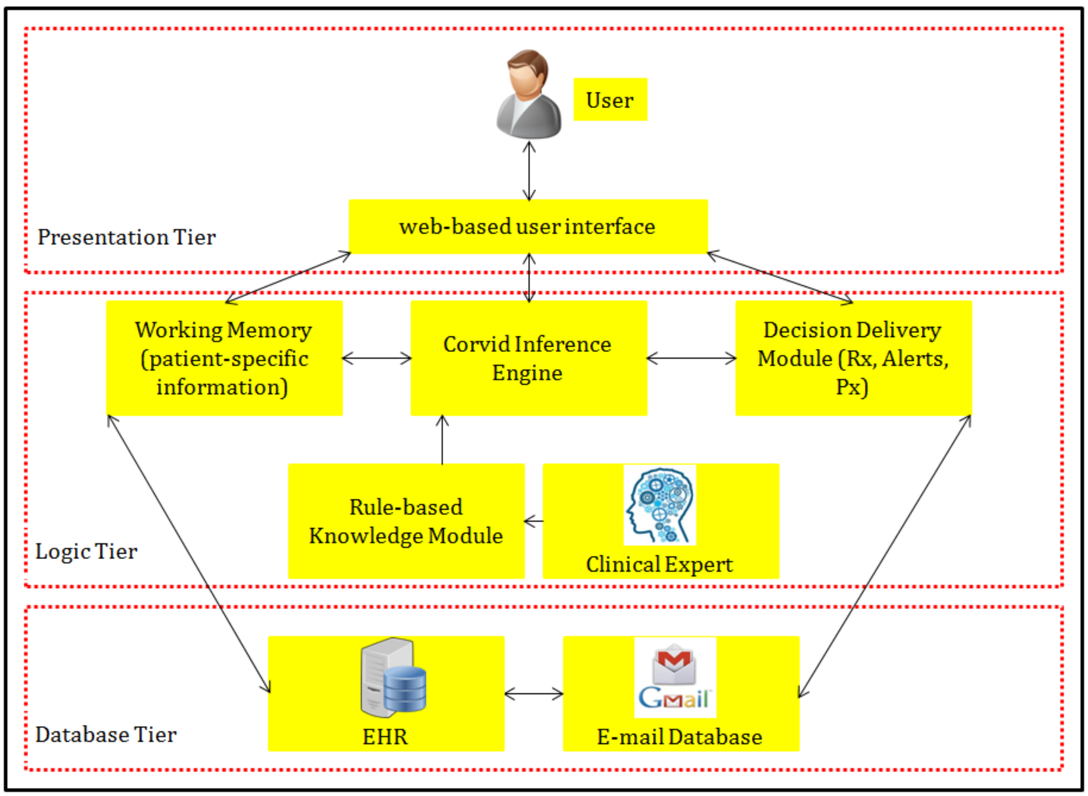


Figure 3-1. Graphic representation of the system's components designed for retention or extraction clinical decision-making. It shows the variable tiers involved and the main working components of the system.

1. Presentation Tier:

The purpose of this tier is to provide the end-users with access point to our proposed CDSS. Although there are many users' interfaces available, three main interfaces are commonly used to suit such system to include: HTML, JavaScript and J-Query programming languages that can be accessed using any Internet-based browser. The user-side of this system is narrow due to the fact that all decision support logics and rules are structured within the logic tier. This feature allows easy maintenance and/or upgrade of this tier avoiding the needs to re-programmed the rules within the knowledge database or the decision support service components.

2. Logic Tier:

This tier contains all heuristic factors that are crucial to form the core of decision-making capability for our system. Comparable to other knowledge-based CDSSs, it has four principal components: knowledge base, inference engine, working memory, and decision delivery module. Exsys Corvid software have been chosen and programmed to represent the proposed expert system framework that was utilized to implement this layer. The following section of this chapter presents the reasons for choosing Exsys Corvid framework to implement this layer. The section will include thorough descriptions of Exsys Corvid concepts of variables, logic blocks, action blocks and command blocks. These varying blocks are essential to structure the logic tier to which they are needed to store and process patient-relevant information (input), outcomes for the decision delivery module (output), viable rules for the knowledge database, and specific commands that guide the inference engine upon processing the given information. These system's elements can be hosted on a chosen application server that is supported with Apache Tomcat Servlet container.

3. Database Tier:

The database tier permits easy storage and retrieval of information needed by the expert system upon clinical decision-making to provide alerts, treatment options and relevant recommendations. In fact, this feature is intended to save clinician's time especially when treatment planning needed to be done for a patient that was seen previously. The capability of saving system's generated treatment options and recommendations is beneficial to refer back to clinical decisions that were made previously. This tier utilizes data-access components that conceal the complexity of interacting with designed databases away from the previous tiers. However, sometimes integration with complex databases (e.g. Oracle) required special skills, additional cost and multi-steps access procedure each time a treatment plan file is required for review. In our project, the system was designed to email the results to providers, patients or both. This email could then be converted to PDF format and uploaded to electronic health system (e.g. Axium) as an expert consultation report. This option is more efficient, less costly and clinically applicable to store patient's report directly in EHR for future reference. Since the results is codified with provider and patient identification numbers only, both are protected against data preach and HIPPA violations. A future attempt is needed to facilitate direct interface between current expert and electronic health record systems that contains the actual case information. Several connection models have been proposed for storing and retrieving data relevant to actual clinical cases along with their respective treatment options, plans and clinical recommendations. Future developments are needed to interface the expert systems with a real-world databases that could facilitate versatility of clinical use and improve the targeted healthcare system.

This well integrated 3-tier strategy, which is utilized for system architecture as part of our proposed system, presents enormous advantages such as system's flexibility, ease of maintenance, scalability, and better management of application environment. The applications and elements within each one of those tiers can be structured and implemented with tremendous flexibility that could cope with changing the current and future requirements. Moreover, the ability to update the structural elements within each one of those tiers avoiding the need to re-write the system is an indication for limitless structural maintenance. These tiers can also allow limitless scalability to satisfy users' needs and desires.

The capacity and interaction of the system's components and concepts are further discussed below:

3. 2. Rules and Knowledge Database:

In continuation to what has been explained in chapter 2, there are many types of knowledge representation methodologies that can be used to build clinical expert systems (i.e. CDSSs). The clinical decision of retention or extraction of questionable teeth can be very challenging even for expert clinicians. To choose the most accurate decision in this aspect of dentistry, a clinician needs to develop an extensive knowledge of all factors that govern it based on available literature as well as long trail of clinical experience in this field of dentistry. Similar to the controlling factors of which clinical experts use to make accurate decisions and formulate appropriate treatment plans, the knowledge database of our proposed expert system is programmed to simulate expert clinicians who process such factors upon decision-making process. This decision-making process can be converted to Exsys Corvid software language in the form of 'if/then' rules. For instance, a simple 'if/then' rule-based clinical decision-making would be represented as:

If

Overall tooth prognosis is hopeless

Then

Tooth extraction is indicated. Consider either implant, FPD or RPD for replacement, if needed.

To build our knowledge database, all relevant clinical and radiographic-based rules must be identified and codified in a simple and logical way that allow their use upon building the system. Therefore, the simple rules were kept in their format while the complex rules were decomposed into simpler and smaller steps in attempt to facilitate codification in the form of simple if/then rules. These rules are then combined to maintain the functionality of the decision-making process using varied operations such as 'AND', 'OR', 'NOT', and relational operations such as less than, less than or equal to, greater than, greater than or equal to, equals, not equals, and approximately equals. The following sections will provide additional explanations with regard to the methodology used for rules representation based on logical system flow.

3. 3. Inference Engine:

The function of this sophisticated component of our system, CDSSs in general, is to analyze knowledge that was stored in the knowledge database and incorporate it with the patient-relevant information to generate adequate outcomes that are related to diagnostic or treatment decision-making domains. Our proposed system utilizes Exsys Corvid inference engine to rationalize throughout the rules that are stored in the knowledge-database of the system. Our proposed system operates in a way in which series of multiple choice questions are presented to the end-users. It then analyses the provided case-specific information in order to determine what additional information is needed to make final decisions. This engine will ascertain if there is a way to process or calculate the data from rules in the knowledge database, so that unnecessary questions are not presented to the end-users. Nevertheless, the engine will make sure that all respective areas are examined in details in order to collect adequate information to decrease the number of applicable choices that poses solutions to domains in hand. Once all required data is presented to the system, it will reach definitive conclusions relative to specific domains that may include several treatment recommendations that are ranked in the order according to their suitability and fulfillment of a given patient needs and preferences along with treatment-specific expected prognosis. Due to this engine capability of logical reasoning that makes it more unique relative to other traditional programming languages, such systems are posed by far the most effective and maintainable tools for knowledge storage, processing and delivery in the field of clinical decision-making. This engine operates the rules in series of backward chaining, forward chaining or combination of both, which will be explored in details in the following sections.

3. 4. Backward Chaining vs. Forward Chaining Inference Techniques:

The term 'backward chaining' is an inference technique that can be defined as a goal-driven processing technique in way the system operates backwards from its destined goals. Problem-solving methodology that requires setting of appropriate goals or hypotheses and working in retrospective approach to meet them, is in fact a part of clinical experts' problem-solving armamentaria. Therefore this method was adopted to develop machined expert systems. Usually, these proposed high-level goals or hypothesis are viable answers to specific domains that need solving several other low-level goals or hypothesis to reach final answers or outcomes. The inference engine is responsible for analysis of relevant data and determines whether or not the data is sufficient to achieve high-level goals to provide adequate answers to the end-users that address specific clinical domains. In case the existing data is not sufficient, the system will retrieve additional data (i.e. rules) from external sources such as databases and spreadsheets or by asking the end-users some additional questions.

For instance, let's assume that the clinical goal is to determine if a tooth is retainable or not. The inference engine will go through the stored rules to find the one that would be pertinent to making this decision:

If

Overall tooth prognosis is hopeless

Then

Tooth extraction is indicated. Consider either implant, FPD or RPD for replacement, if needed.

Even tough the inference engine may found the most applicable rule to proceed to the following step, it needs more supportive data before such a rule can be utilized. For logical data processing in backward chaining, the system processes the data to know if "Overall tooth prognosis is hopeless". In this instance, determining whether this statement is true or not become the new goal of the inference engine. Nonetheless, the definitive goal is not dismissed; it is just replaced temporarily by the new goal. The Inference engine will then scrutinize all relevant rules that control the overall tooth prognosis. It finds the following rule:

If

Crown-to-root ratio is 2:1, Furcation lesion is Class IV, Detected mobility is Grade III etc.

Then

Overall tooth prognosis is hopeless

For this rule to be utilized, the inference engine deduces the overall tooth prognosis following series of analytical processing of the given patient-relevant information (i.e. crown-to-root ratio, furcation involvement, mobility, patient's needs and desires, tooth involvement in final treatment option and oral hygiene status). Addressing these low-level goals individually becomes the new goal, in which necessitate answers or input from the end-users. Consequently, backward chaining is defined as a goal-oriented method that processes rules in backward direction going through a chain of goals starting from the highest to the lowest level repeatedly until lower level goals are satisfied or eliminated from the chain as data becomes available from user end, and moving upward to achieve high-level goals and provide relevant recommendations or instructions to the end-users. Due to the fact that the list of goals controls which rules to be chosen and utilized, this inference methodology is described as goal-driven.

Furthermore, while backward chaining was described earlier as goal-driven inference methodology, forward chaining methodology is in fact data-driven. It begins with small amount of data and utilizes the programmed inference rules to gain more data moving forward, from both the rules and the end-user, to arrive at final recommendations. The term 'forward chaining' drives from the fact that the system begins with small amount of data, utilizes given logic or rules to evaluate it and rationalizes its way to the conclusions. Amongst the advantages of forward chaining in contrast with backward chaining is that availability of new data directs the process to new inferences, which might be beneficial for problems with dynamic nature in which conditions are expected to change over time. [297] In the contrary, backward chaining is adequate for clinical domains that may have many unknowns at the start that should be carefully investigated to arrive at valid conclusions. In dental settings, forward chaining is more applicable and user-friendly in contrast to its counterpart, especially to undergraduate dental students, novice dentists and recent specialty graduates due to the fact that all clinical, radiographic and investigational data are readily known to end-users given that the system is pointing them in the right direction through series of logically sequenced and easily structured multiple-choice questions to ensure system's objectivity. Although backward chaining can simulate the way that experts use to solve difficult domains, its complex structure and types of questions involved might be challenging to the main targeted population. Since such inference methodology operates with too many unknown at the starting point, the system that utilizes such approach might be questioned about the subjectivity of its conclusions.

For this reason, our user-friendly expert system utilized forward chaining inference methodology to provide adequate treatment plans, alerts and recommendations relative to clinical decision-making for retention or extraction of questionable teeth. The rules in our proposed system were structured in a unique and clinically relevant approach to avoid redundancy. Therefore, our proposed system utilizes forward chaining inference technique only to ensure its simplicity and objectivity and avoid potential complexity and possible subjectivity of its outcome.

3. 5. Corvid Variables, Logic and Command Blocks:

Corvid variables, despite of their different types, are considered the building blocks that are utilized to develop Exsys Corvid expert systems. They are used to delineate the rules within the logic block, execute commands in command block, set outcomes for the proposed system and store data within the working memory upon execution of variable rules structured within the system.[296] In our system that is focused on retention versus extraction decision-making, we have outlined all relevant variables to represent numerous concepts within restorative dentistry (prosthodontics), periodontal and endodontic clinical domains and terminologies. These variables are utilized to structure all possible if/then rules within the logic block and system's commands within the command block. In fact, a system without well-written command to guide logic processing, the system will not serve as intended.

The logic blocks are building units that outline, order and structure several rules into logically inter-related blocks. These rules may either be defined in the form of tree diagrams or listed as independently isolated rules. They also can be distributed among inter-related levels or joined together utilizing logical operators. As an illustration for this concept, Figure 3-2 (A) depicts a screenshot obtained from our system in which the logic block was structured to identify the medical status of the patient in questions. The values 'Yes' and 'No' were assigned to identify whether the patient is medically fit or not as identified by the end-user. Similarly, Figure 3-2 (B) shows another logic block that is aimed to identify the type of the tooth and the area of the arch in question where 'Anterior Tooth' and 'Posterior Tooth' was assigned as values. The location of the tooth in the dental arch is crucial due to the fact that posterior teeth received higher masticatory stress when compared to anterior teeth. The location is therefore affecting the assigned score significantly. Cumulative prognosis score is a confidence variable in which selected mathematical functions can be applied upon as the system proceeds through the subsequent rules and logic blocks to produce final recommendations based on the result of this calculation. Each variable could also be accompanied by recommendations or alerts that instruct providers on how to proceed in dental management and what to avoid upon clinical intervention. Commands could also be added to any logic block to control the flow of processing within each block and between them.

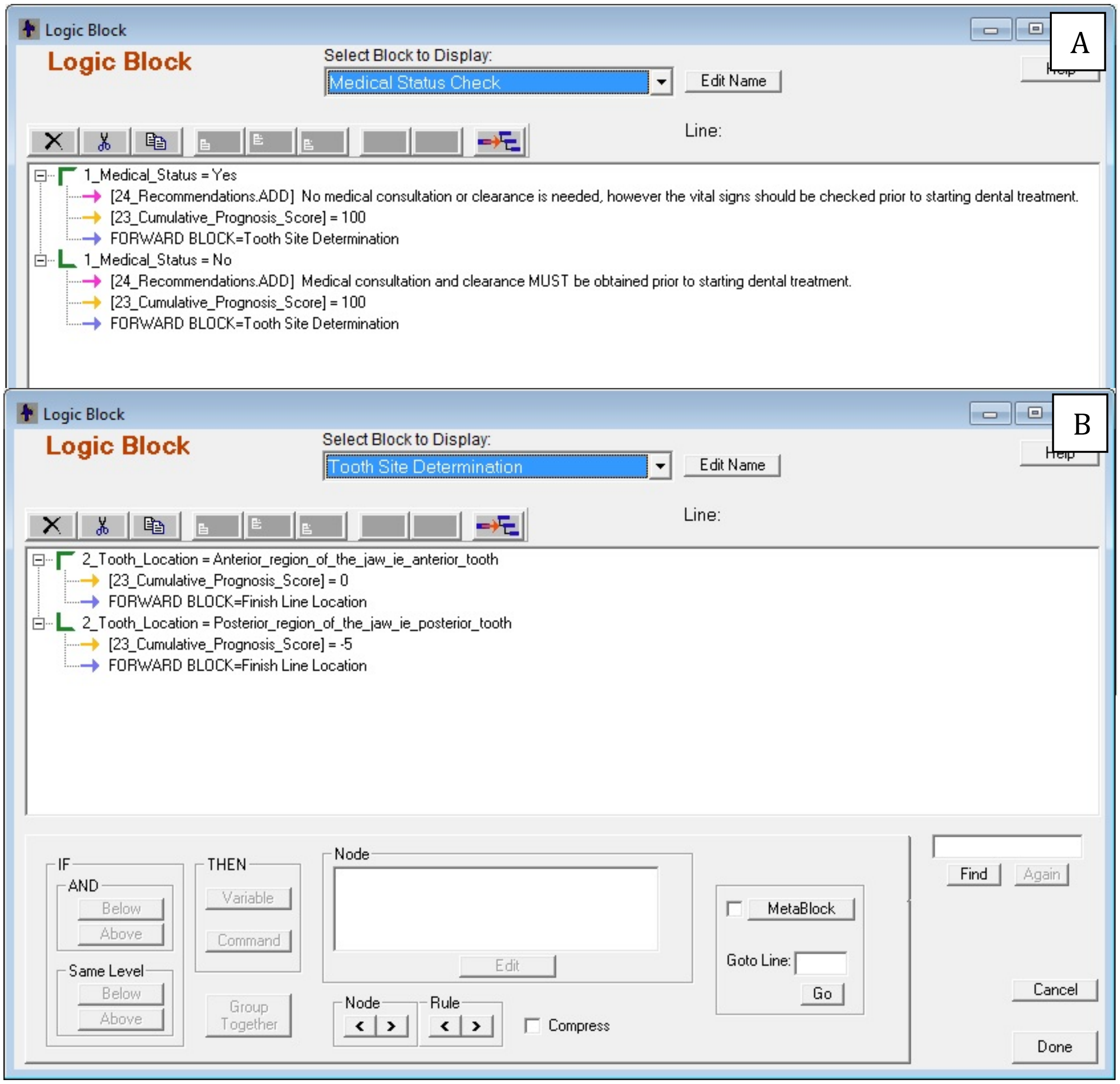


Figure 3-2. Screenshot of Logic blocks (A) to determine medical status of the patient and (B) to determine the location of the tooth relative to the dental arch (i.e. anterior or posterior tooth). This figure also indicates the variables that were used to define the if/then rule in both logic blocks.

While logic blocks, in Exsys Corvid systems, are focused on the variables and their arrangement into specific rules, command blocks are the elements that are responsible to control the procedural flow of the expert system. Moreover, the logic blocks involve the heuristics factors that are required for clinical decision-making, while the command blocks involve the commands that govern the actions and flow of variables within the logic blocks to derive data as outcomes. Whether the inference engine runs in backward chaining or forward chaining mode is also controlled through Command blocks. These blocks also govern the presentation mode and format of intermediate and/or final outcomes. Figure 3-3 shows an example of a command black that was designed to derive information with regard to overall tooth prognosis, display a custom-made title screen and display results at the end of the session. This block was designed to tell the inference engine to process all the rules in forward chaining mode to explore the logic block that contains specific rules to derive specific variable's value.

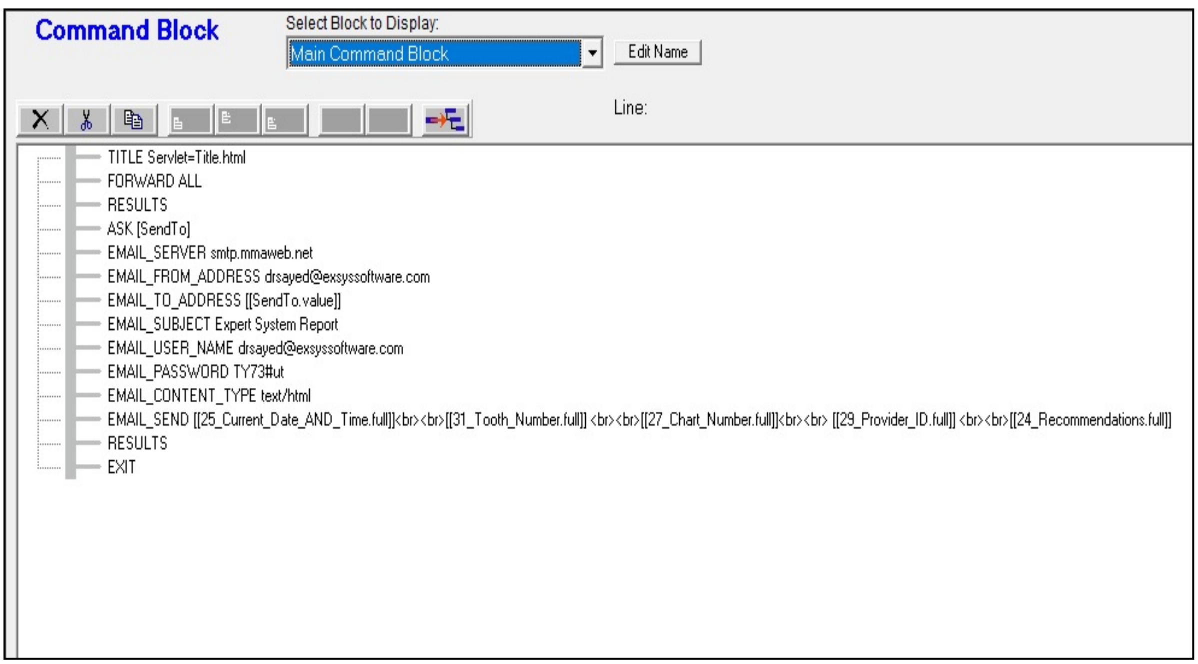


Figure 3-3. Screenshot of the main command block that sets the title screen in Servlet, run logic blocks in forward chaining mode, show the system's results at the end of the session and email the results to providers, patients or both.

3. 6. Working Memory of CDSSs:

The function of 'working memory' component of any clinical decision support system is to allow storage and future access and retrieval of patient-related information. This information includes but not limited to medical history, dental history, current tooth status or conditions, parafunctional jaw activities or personal habits, and patient's desires and preferences. The previous information is stored in the system's working memory. This information is retrieved and utilized when the end-users report a clinical scenario to receive treatment plan options and recommendations. Upon planning of a new clinical scenario, the system will ask the end-user to input necessary patient information, so that it can be stored and retrieved in future for planning the same or related cases. When the Command block activates the inference engine, necessary information is either retrieved from the system's working memory or gained from the end-user in case such information is not available in the memory. The retrieved information is then stored in the memory as variable values to be used by relevant logic blocks as the system move through the rules. It is critical for the system to have this memory well integrated and in coordination with the designed logic and command blocks to maintain harmonious flow of procedures.

3. 7. Results Presentation Platform:

As mentioned earlier, the inference engine moves through the logic blocks as instructed by the commands blocks in order to display outcomes to end-users in the form of treatment plans, options and recommendations pertinent to specific case in hand. The system also ranks the outcome options relative to the final score attached to each one of them. The scoring methodology that we have developed factors-in patient's desires, preferences and anticipated prognoses of the proposed treatment options prior to reaching final recommendations. In the result screen, a rationale will also be displayed to the end-users in the form of medical status or tooth-related alerts, definitive diagnosis and prognosis relative to the patient or tooth in questions and final treatment recommendations based on previous information. The idea behind this intellectual and rationalized interaction between expert systems and end-users is to teach the targeted population on how experts make decisions.

3. 8. Rationale for Utilizing Exsys Corvid to Build our Proposed System:

Exsys Corvid software is uniquely able to provide a robust and versatile framework for computer-based CDSSs. In previous sections, we have discussed the ability of such software to store knowledge data, arrange logic rules and perform variable procedural steps as needed by system's designers. The logic rules, which are used by clinical experts for diagnosis and treatment planning, can be methodically indexed into the expert system in an approach that makes them easy to read, understand and maintain. Upon completion of knowledge base development, the inference engine that is supported by the system's framework simulates the clinical experts in the way they perform critical thinking and processing of challenging clinical domains. The framework permits development of an Internet based interactive platform in which end-users can consult it as if they were talking to a clinical expert. The systems that adopted this mode of technology have a great potential to educate and train end-users to think and practice at the level of clinical experts in delivering medical and/or dental care and therefore enhance treatment outcomes.

The following are the design features that justified selection of Exsys Corvid to implement our proposed system:

1. Permits goal-oriented structural design: Exsys Corvid utilizes goal-oriented approach for designing expert system for particular intended purposes. The logic rules, within the system, can be specified utilizing a list of variables that have common properties and/or indications. This feature gives so many advantages to expert systems designers since it permits easy structural process, reduce time needed to complete desired tasks and integrate many variables together for versatility of use. Although programming such software may often be complex, per complexity of the desired system, the complexity remains hidden from end-users.

2. The software posses a robust inference engine: Exsys Corvid posses powerful and competent inference engine that can efficiently process all the logic rules that are integrated within the CDSSs. This engine endorses forward, backward chaining and combination of both approaches to allow maximum benefits and flexibility of use. It can also endorse a probabilistic data processing approach that is considered fundamental for clinical scenarios with many unknowns that needed to be taken into consideration upon decision-making process.

3. The software is applicable in probabilistic as well as certainty conditions: Exsys Corvid permits its variables to contain several confidence or certainty factors that permit various levels of confidence in attempt to provide adequate recommendations to solve specific domain. The software could support backward chaining for probabilistic conditions with multiple unknowns and forward chaining for certainty conditions where fair amount of facts are available at the start of decision-making process. This feature permits finding the most applicable clinical solution by logical ordering of multiple possible solutions. This approach is in fact simulates that way that experts solve their challenging real-word problems.

4. The software can be well integrated with the Web and other forms of databases: Exsys Corvid's posses a unique ability integrate with different forms of databases that permits the system to be efficiently connected with the current information technology environments and satisfies the outstanding needs for developing new practical environments. This feature is enormously helpful for expert systems' developers whom do not present interests to structure complex logic rules due to the fact that system's integration with variable databases is supported by the framework itself.

5. The software is user-friendly and provides versatile interactive platform: Exsys Corvid supports a simple, user-friendly and unique ability to accept future developments. The process of clinical decision-making is logically codified in the form of If/Then rules that are easy and permissible to be written. These rules are developed English language and simple algebra that render them easy to read, understand, and maintain. Such feature allows effortless maintenance of the system's structures and functions and facilitates uncomplicated update as well. The given ability to maintain and update the expert systems is necessary taking into account the amount of new knowledge being generated in the field of dentistry in general and factors governing the clinical decision of interest in specific.

3. 9. Users-system Interactions and Flow of Process:

The interaction model between our proposed system and the end-users (i.e. clinicians) is presented in Figure 3-4 as a swim lane diagram.

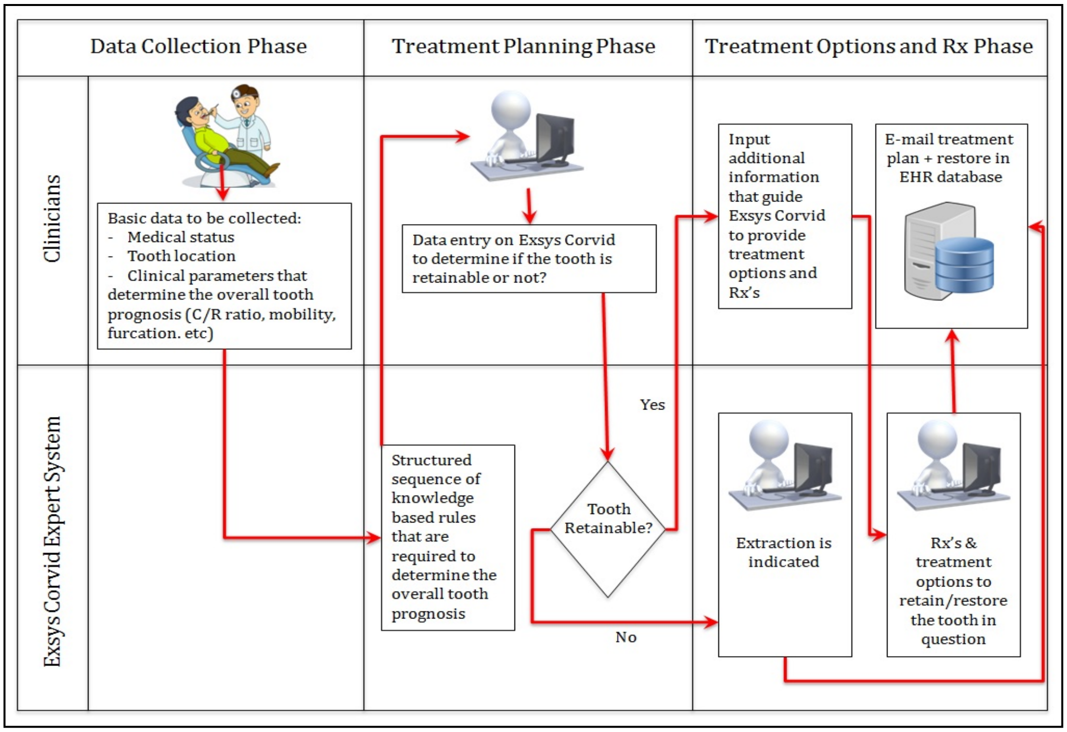


Figure 3-4. Swim lane diagram shows the process flow of interactions between the end-users and expert system. The system will interact with users to gain knowledge relative to the clinical case in hand and present appropriate outcomes.

Dental clinicians, whether undergraduate dental students, general dentists or specialists, could utilize our proposed system for assistance in terms of diagnosis, prognosis, treatment planning of questionable teeth in hand. Treatment planning in this instance relies on the overall tooth prognosis in which treatment recommendations include: retention and restoration, extraction and replacement along with patient and tooth related alerts and additional recommendations. The first step in this multi-phase process starts when the patient is being examined in which the provider review medical history and current status, dental history, location of the tooth in question along with some tooth-related clinical parameters such as C/R ratio, location of finish line, mobility and furcation in multi-rooted teeth. The following step in this process is for the system to process series of rules within the knowledge database to ascertain whether or not this tooth worth retention and restoration according to case-specific data that was entered by the end-user. In the basic data that was entered in the first phase is not sufficient for adequate decision-making, the system will automatically ask the user to provide further relevant information that is necessary to provide definitive recommendations based on patient's specific condition and rules that was outlined within the knowledge base. This additional information may include but not limited to oral hygiene status, risk tolerance and presence of parafunctional habits.

In some clinical scenarios, extraction may present as the treatment of choice especially in advanced cases of dental caries where surgical or orthodontic corrective procedures are not applicable or may result in poor long-term prognosis. Extraction is also indicative in cases of advanced periodontal disease where clinical attachment loss is far exceeded the ability to re-generate the lost tissue and maintain the tooth. In these clinical conditions, the system will provide recommendation for extraction as the most viable treatment plan option along with options to restore the space using implant or tooth supported restorations or prostheses. However, when the tooth in question is in fact retainable, the system will ask the end-user to provide further relevant information to include oral hygiene, parafunctional habits such as bruxism, patient's desires and preferences with regard to prescribed treatment option such as acceptance/refusal of tooth extraction, risk tolerance and financial ability in order to develop a predictable treatment plan that suits the patient with favorable long-term prognosis. This flow of process presents various possibilities in which the system assists clinical users in providing adequate treatment plan and recommendations in an interactive heuristic approach for optimal decision-making process. Due to the fact that our system can be easily implemented at the clinical operatory, clinicians can plug-in all patient-relevant data into the system in the same way as it is being collected at the point of healthcare with the patient in dental chair.

In clinical scenarios of retainable teeth, our system uses logical and rule-based inference approach to propose case-specific diagnoses, prognoses, alerts and adequate treatment plans and recommendations information. The proposed information is in fact based on clinical expert knowledge, evidence-based data, and patient desires and preferences that were made into logic rules and indexed into the knowledge database. The system evaluates these rules utilizing a scoring algorithm that weighs between several treatment plan options and recommendations while meeting patient preferences taking into consideration the present diagnosis and prognosis of clinical presentation. Since the system uses a heuristic probability approach, it has the ability to rank the treatment plan options based on the overall resultant score and present them as an overall tooth prognosis information accompanied with recommendations to dental clinicians. The system will also present alerts, if any, in case there is a negative implication related to the treatment option that may affect case management or treatment outcomes. The last step in this process flow is for the end-user to store the system generated outcomes into the database for future references.

The data that was used to process the logic rules and make decisions with regard to treatment plan are retained within the system variables. These values are either set by forward chaining, which was the adopted chaining approach for our proposed system, or by presenting additional questions to the end-user in case those values cannot be scrutinized by the available logic-inference methods. Our proposed system was designed to intuitively proceed through logic rules and present optimal outcomes relevant to case-specific information in a unique approach for clinical decision-making process that simulate the way that dental experts would traditionally perform during problem-solving sessions to achieve optimal clinical outcomes. This problem-solving approach is therefore ideal to teach dental clinicians, at all career levels, the way that experts think upon treatment planning to make viable clinical decisions. Targeted dentists may utilize such helpful technology either in clinical operatory or distant locations at their own pace and time convenience. The following section provides details on the system design and implementation.

3. 10. System Structural Design and Implementation:

3. 10. 1. Development of Definitive Logic Rules and Pre-programming Validation:

In Chapter 2, detailed literature review and discussion was undertaken to identify the clinical factors that are crucial upon treatment planning of questionable teeth. These factors were categorized into: medical status factor, tooth level factors, intra-/inter-arch level factors, and patient level factors that include factors used for shared decisions. Twenty-eight simulated clinical scenarios were used to initially test the validity of these factors to arrive at optimal treatment plan options with regard to retention or extraction decision-making of these simulated cases and to develop a tentative scoring mechanism that reflect the weight and importance of each factors amongst the others. The factors and scoring method were tested by two expert prosthodontists and found adequate to achieve appropriate treatment recommendations. They were documented and codified in preparation to be used later for programming our proposed expert system. The following sections will present these factors along with their scoring contributions based on their effect and importance for clinical decision-making in this particular aspect of dentistry. Without comprehensive evaluation of these factors, clinicians may experience treatment errors and failure.

3. 10. 2. Logic Flow of Phases Within the Proposed Expert System:

The approach that we used to enter the logic rules in the knowledge database and the sequence in which the rules are processed by the inference engine, that is an integral part of

CDSSs, for the purpose of treatment planning of questionable teeth, can be summarized into three well-defined phases as presented in Figure 3-5.

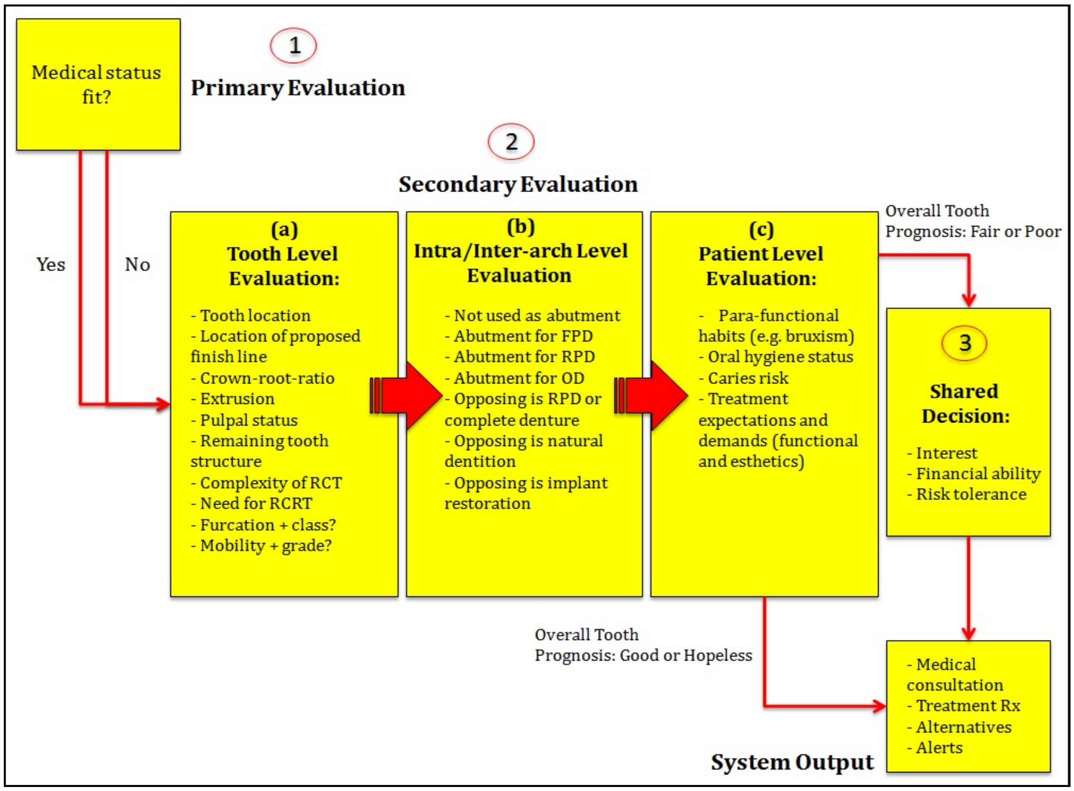


Figure 3-5. Swim lane diagram shows the logic flow in which our system utilizes to process given clinical scenarios proceeding through three well-defined phases to present the most accurate treatment recommendations.

Moreover, we have achieved goal-oriented programming concept that ensures high cohesion and loose coupling by codifying the expert knowledge, evidence based data, patient's preferences and desires into logic rules that were distributed among specific logic blocks within one of the three phases of process flow. The concepts of coupling and cohesion were developed by Constantine, more than four decades ago, while he was investigating for adequate programming concepts that would help to minimize upgrading and maintenance costs.[298] In the field of computer science, cohesion was defined as "the extent of which the components of a module belong together”. [299] This term was traditionally defined as “binding or the measure of cohesiveness of a module”. [300, 301] However, coupling was described as “the measure of strength of association established by a connection from one module to another”. [300] To understand the relation between these terms, these terms are actually contradicting where loose coupling is associated with high cohesion, and vice versa. To ensure robustness and proper functionality of any developed expert system, it should be designed to satisfy high cohesion criterion. Such characteristic is required to ensure strong inter-relationship between the components inside each block that in turn ensures specific function to be executed well. Likewise, loose coupling as a criterion is fundamental to make sure that developed logic blocks can work in an independent environment in order to reduce the cascading effect of changes in one block that would necessitate changes in other blocks as well. In summary, high cohesion is necessary to advocate software’s durability and conceivability, while loose coupling is fundamental for ease of read and maintenance.

The next sections will discuss in details the relationship between the three phases mentioned above and all the logic factors that were involved in building the system. These three phases were ordered in a way to simulate clinical experts’ logical thinking workflow upon evaluation and treatment planning of questionable teeth to determine their fate of retention and restoration or extraction and replacement. This logical thinking workflow starts with collection of all patient-relevant data with medical status being the most critical, followed by serial evaluation of all critical factors relative to tooth, intra-/inter-arch, patient levels and shared decision, follows up with shared decision-making between dentist and patient and eventually presenting relevant recommendations to include medical request for consultation if needed, tooth related alerts, the most suitable treatment recommendation and alternative treatment options in case the first option deemed difficult in respect to the dentist, patient or both. The designed system utilizes a unique, robust and comprehensive methodological approach to provide accurate clinical recommendations.

3. 10. 2. 1. Title Screen:

To maintain copyrights of our proposed system, a custom title screen was designed using Photoshop software that include the title of the system, diagrammatic representation of our knowledge-based system that are supported by the three pillar of evidence-based dentistry (literature data, clinical experience and patient's desires/preferences), the name of the developer and year in which the system is developed, and a declaimer was added to notify the public that such system should only be used by dental students, general dentists and specialists only following online implementation (Figure 3-6).

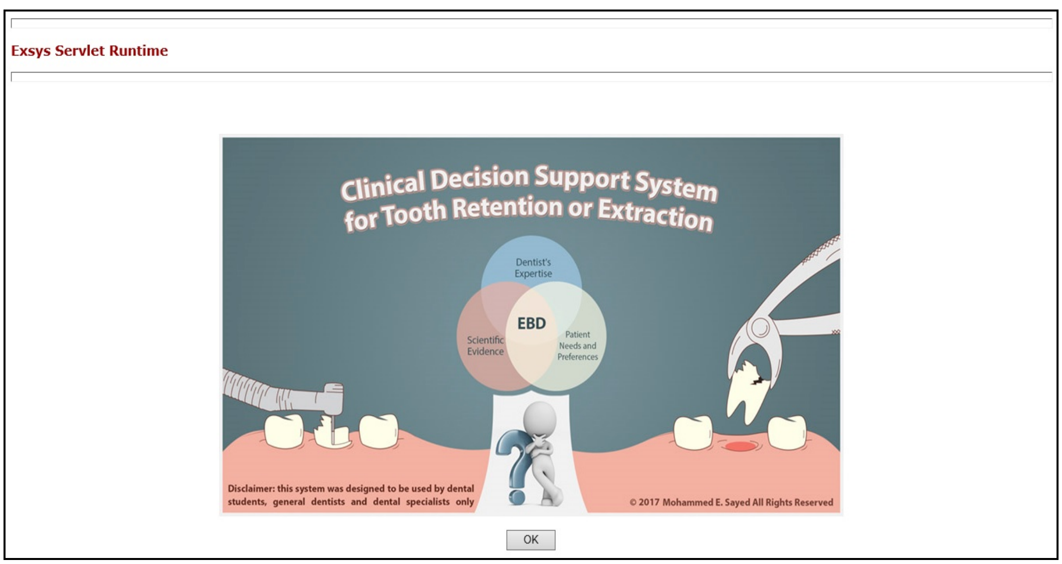


Figure 3-6. Title screen was designed to match our system's objectives and promote critical thinking process upon treatment planning of questionable teeth.

The screen was designed with "OK" button to initiate the system when the user is ready. To be able to add this screen, a specific command was added as the first command in the command block to be able to start the system with the title screen as shown in Figure 3-3. This feature is only available on Servlet runtime. The command for this feature is: TITLE Servlet=Title.html.

3. 10. 2. 2. Primary Evaluation Phase (Data Collection):

The primary and the foremost evaluation phase in treatment planning of a questionable tooth is data collection that focuses on patient's current medical status and history. The patient is questioned regarding his/her current medical status in which available answers are either medically fit or not. In this instance, a provider is instructed to check basic vital signs prior to each treatment visit in case of a fit patient, or refer the patient to a physician for medical consultation and request for medical clearance in case a medical condition is reported and potential risks or complications are anticipated before, during or after dental treatment visits (Figure 3-7).

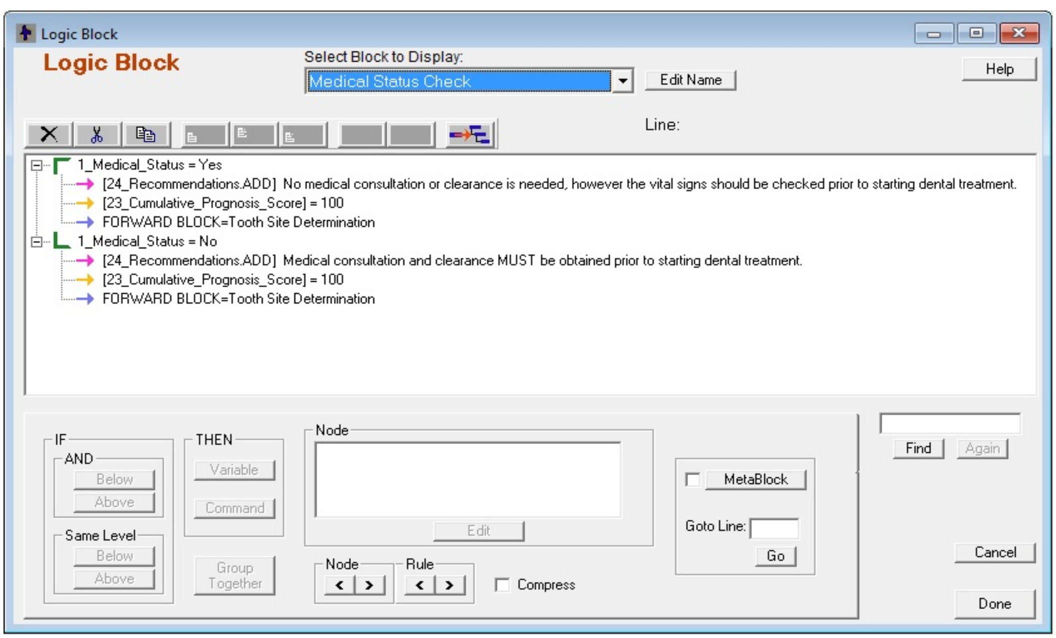


Figure 3-7. Screenshot of logic block representing data collection phase of treatment planning relative to medical status.

The system starts with cumulative prognosis score of 100. It is empirical that medical condition should be stabilized prior to treatment planning and intervention, however the condition itself (if present) doesn't not affect tooth prognosis per say. Therefore, a cumulative prognosis score of 100 was given to both options. The following section will present a multi-level secondary evaluation phase of treatment planning that include factors relative to the tooth itself, intra-/inter-arch, patient in general.

3. 10. 2. 3. Secondary Evaluation Phase (Treatment Planning):

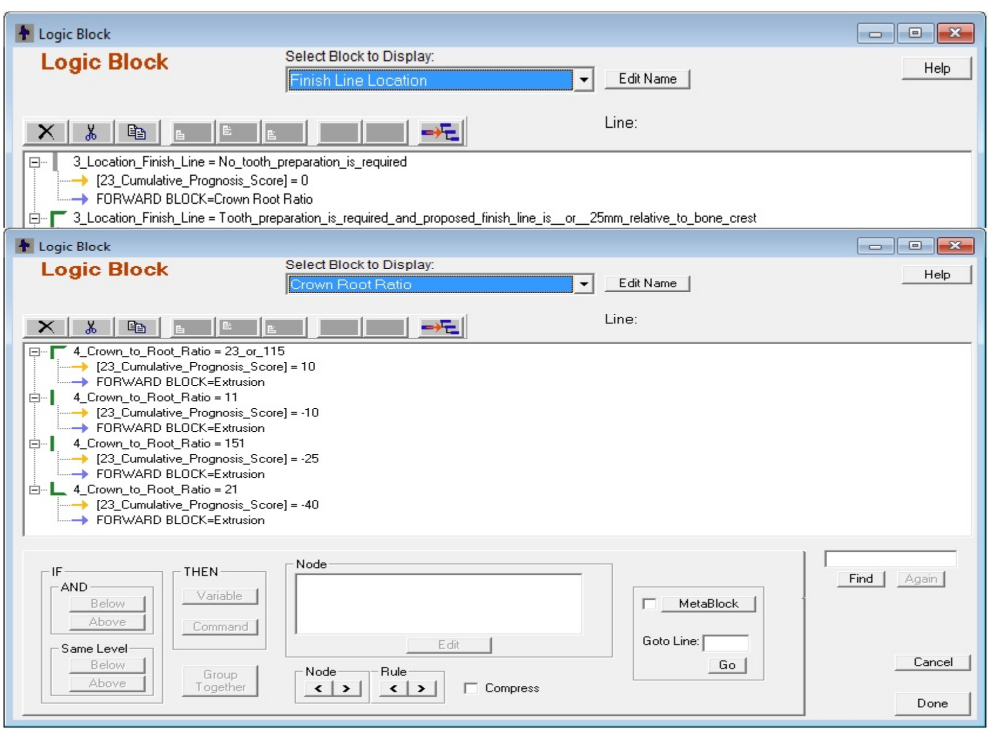
The sole objective of this phase is to whether or not the tooth in question is retainable based on comprehensive evaluation of numerous clinical parameters relative to the tooth itself, intra-/inter-arch, and patient in general. This evaluation process will result in accurate treatment recommendations. The rules relative to the tooth-level evaluation include: tooth location within the dental arch, location of the proposed finish line relative to bone crest, crown-to-root ratio, extrusion relative to occlusal plane, pulpal status, remaining tooth structure, complexity of RCT, need for root canal re-treatment, and presence of furcation and mobility along with their class and/or grade. Further, intra-/inter-arch level evaluation includes factors relative to: utilization of the tooth in question as an abutment to support planned dental prosthesis and the nature and type of opposing occlusion. The last level in this phase is patient-level evaluation. The factors involved in this level are: presence of parafunctional habits (bruxisim), oral hygiene status (plaque control), caries risk, treatment expectations and demands (functional and esthetics). The system proceeds through these levels in forward chaining mode and calculates the cumulative (overall) prognosis based on data entry to each rule and level. The importance, classification, influence of these factors on tooth prognosis has been thoroughly discussed in literature review section of chapter 2.

Each rule is associated with a score, recommendation, alert and command to proceed to the following logic block.

1. Tooth-level evaluation:

This sub-secondary phase include all the factors that should be evaluated relative to a tooth under question. The sequential order of these factors represents its weight and importance in clinical decision-making relative to tooth retention or extraction. The provider is required to perform careful clinical and radiographic examinations to be able to accurately respond to the system's prompts in this step of evaluation.

In fact, the majority of dental students, general dentists, and recent specialty graduates are trained adequately to collect information in this regard. Inaccurate data collection during this phase may results in misinterpretation and faulty treatment recommendation outcomes (Figure 3-8).



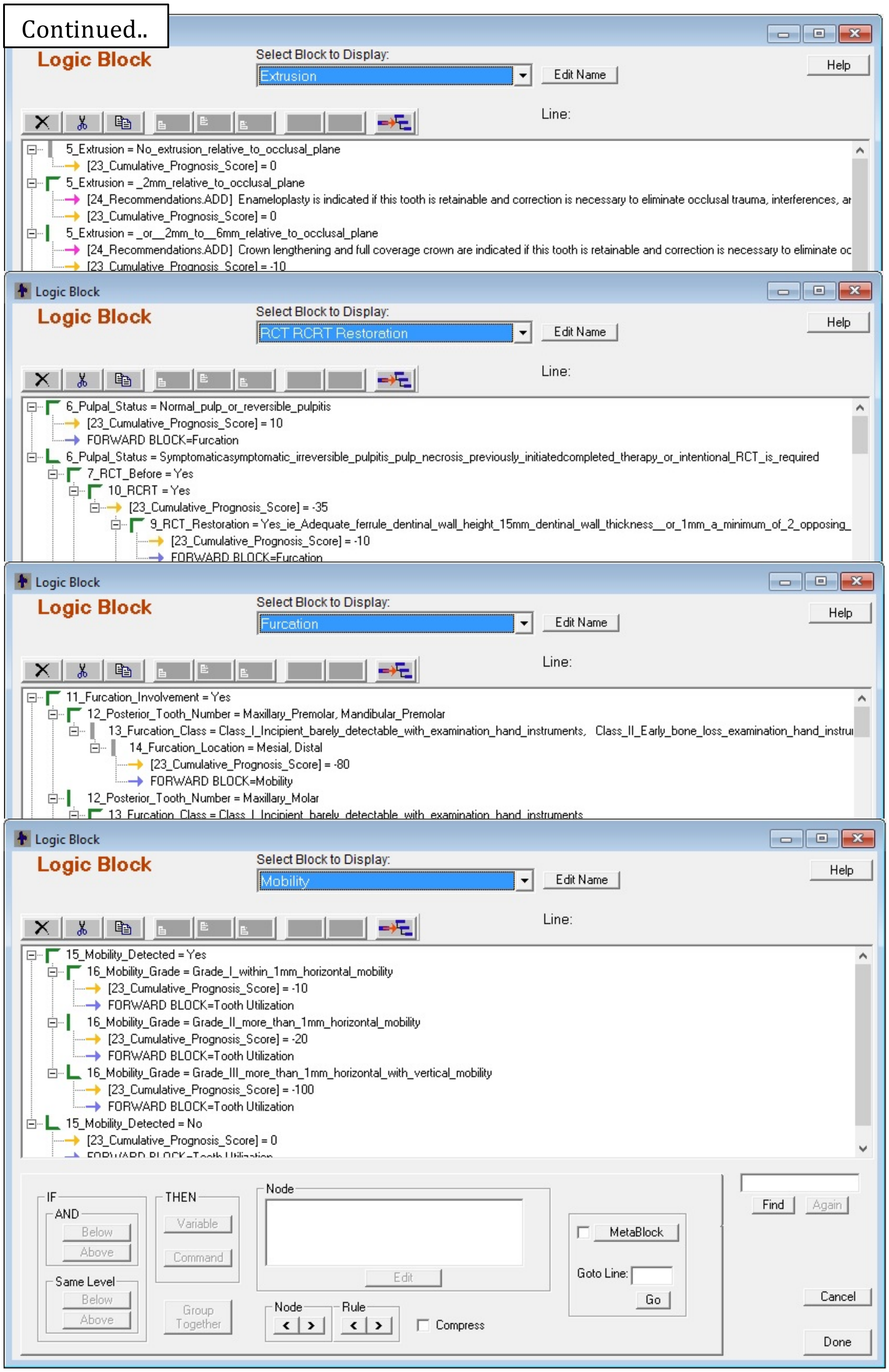


Figure 3-8. Screenshot of logic blocks representing tooth-level step of secondary evaluation phase.

2. Intra-/inter-arch level evaluation:

This sub-secondary level of evaluation includes factors relative to: utilization of the tooth in question as an abutment to support planned dental prosthesis and the nature and type of opposing occlusion. It represents the relation of the tooth in question with the adjacent and opposing dentition and/or occlusion. Consideration of these factors is crucial in accurate determination of optimum treatment recommendations. Figure 3-9 shows the logic blocks that are involved in this sub-categorical level of evaluation.

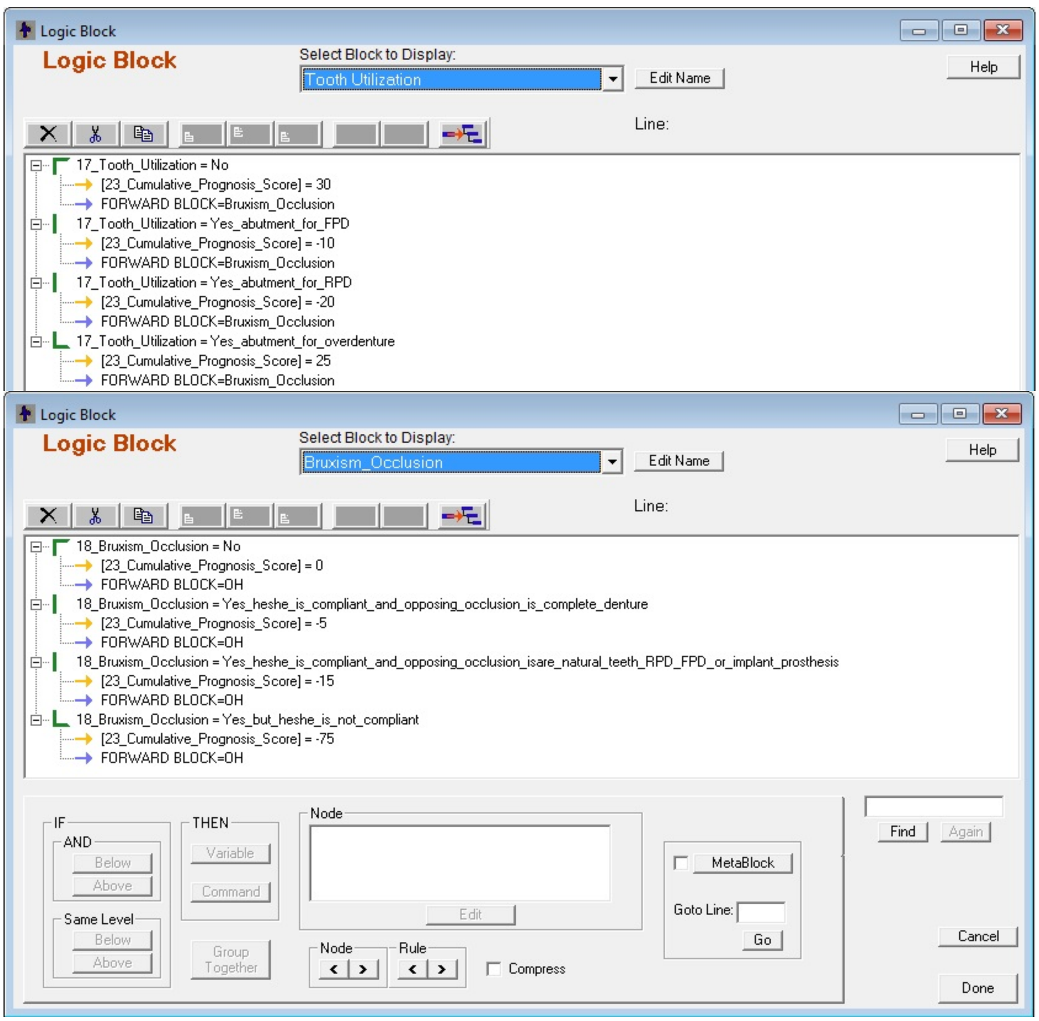
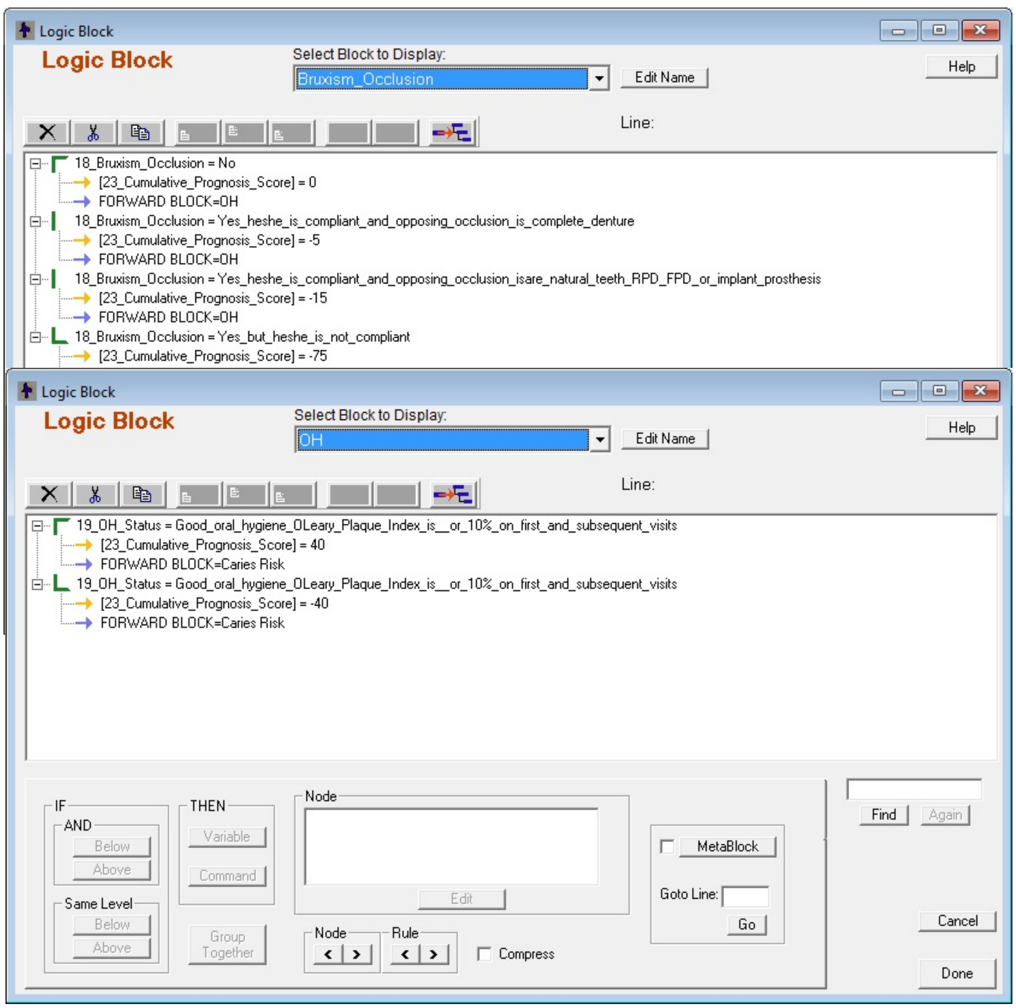


Figure 3-9. Screenshot of logic blocks representing Intra-/inter-arch level step of secondary evaluation phase.

3. Patient level evaluation:

This sub-categorical evaluation involves patient-related factors that influence individual tooth prognosis. The factors in this level include: presence of parafunctional habits (bruxisim), oral hygiene status (plaque control), caries risk, treatment expectations and demands (functional and esthetics). Figure 3-10 represents the logic blocks that are involved in this sub-categorical level of evaluation. For instance a non-bruxer patient with good oral hygiene, low caries risk and low demands or expectations would have favorable tooth prognosis than a non-compliant bruxer patient with poor oral hygiene, extreme high caries risk and high treatment expectations.



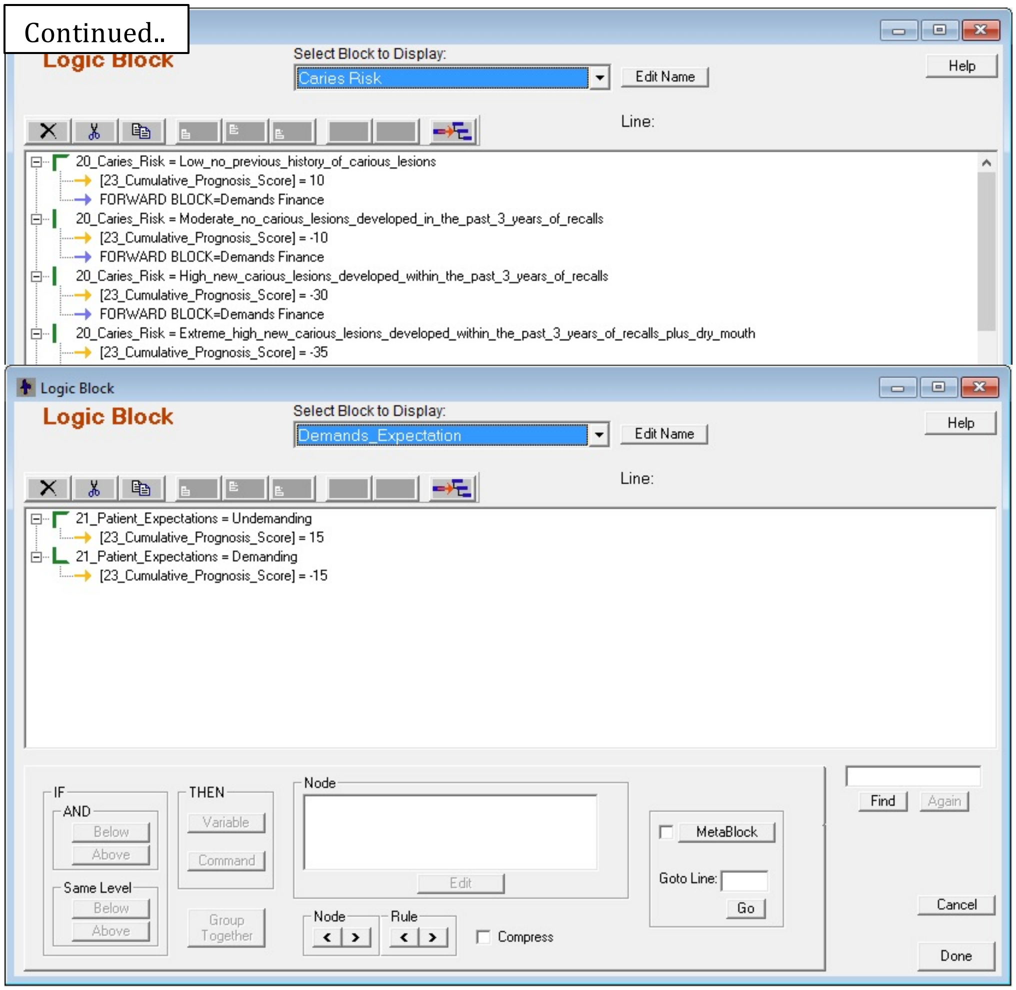


Figure 3-10. Screenshot of logic blocks representing patient level step of secondary evaluation phase.

3. 10. 2. 4. Shared Decision-Making Phase of Treatment Planning:

This phase of treatment planning is important since the patient is responsible for making the final decisions whether or not to follow care provider's recommendations. The ideal treatment plans or recommendations are those tailored to satisfy patient's needs, desires and preferences. In fact, evidence-based dentistry approach values this aspect upon clinical decision-making. After processing of all rules in the secondary evaluation phase, the system will arrives at two possible routes of overall tooth prognosis. Clear route when the system arrives at good or hopeless overall tooth prognosis. In this instance the system will advice the provider to retain and restore the tooth in question, if needed, in case of good overall tooth prognosis, while hopeless overall tooth prognosis predicated tooth extraction and replacement with either implant, tooth-supported restorations/prostheses or RPD based on case presentation. In this route the patient has minimum intervention since decision-making is clear and straightforward. The other route is unclear where the system arrives at fair or poor overall tooth prognosis. In this route the patient's input is extremely valuable to reach final treatment recommendations. In this scenario, patient's interests, financial ability and risk tolerance are factored-in as the final step prior to making definitive treatment plans and recommendations. This 'shared-decision' approach is crucial to ensure patient's participation in clinical decision-making process and therefore satisfaction with the final treatment outcomes. Figure 3-11 represents the logic block for shared-decision making phase of diagnosis and treatment planning.

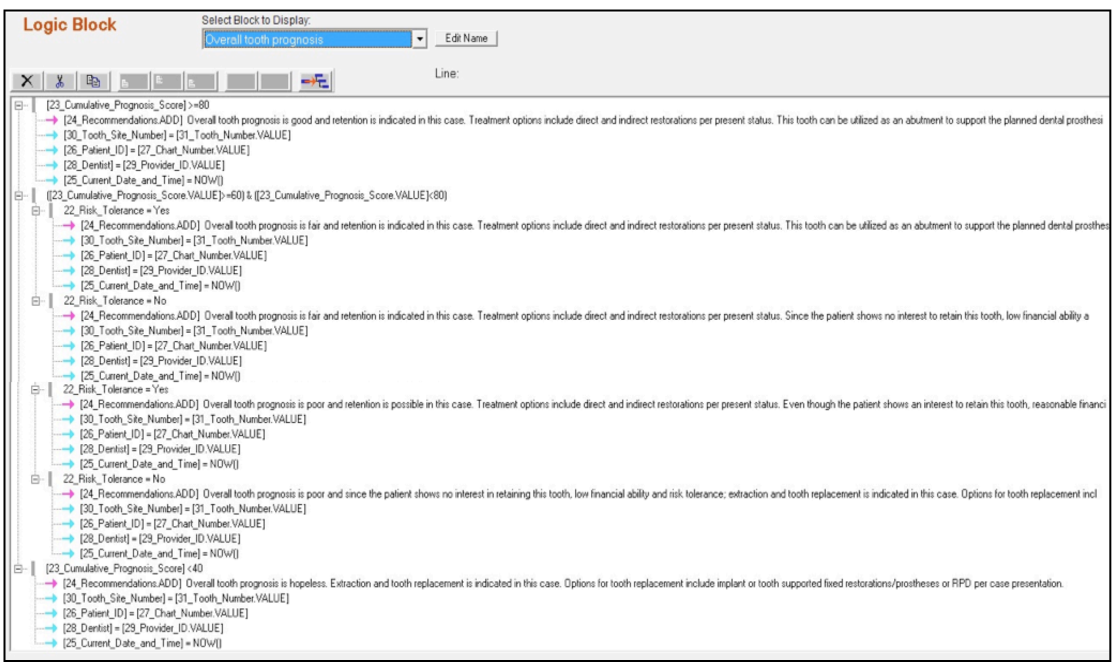


Figure 3-11. Screenshot of logic block representing shared-decision making phase as an integral part for determining the overall tooth prognosis.

3. 10. 2. 5. System Results:

Following a comprehensive evaluation process of rules and logics, the system is designed to ask the provider to input: the exact tooth number, patient ID or chart number, and provider ID number for documentation purposes. The objective of the results screen is to allow thorough review of prompts along with user's inputs/answers and help to justify the given patient and tooth-related alerts, definitive treatment plan, options and recommendations since they are all presented in one platform. Tooth number, patient ID number, provider number and date and time of the current treatment planning session are aimed for documentation. Figure 3-12 represents an example of the results screen generated by the expert system at the end of treatment planning session.

Is the patient medically stable? No

What is the location of the tooth in question relative to the dental arch? Anterior region of the jaw (i.e. anterior tooth)

If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest? Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest

What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required? 2:3 or 1:1.5

What is the amount of tooth extrusion relative to the occlusal plane? No extrusion relative to occlusal plane

What is the pulpal status of the tooth in question? Normal pulp or reversible pulpitis

Does the tooth in question show signs of furcation involvement upon clinical or radiographic examination? No

Does the tooth in question show signs of mobility upon clinical examination? Yes

What is the grade of tooth mobility that was detected upon clinical examination? Grade I: within 1mm horizontal mobility

Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis? No

Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion? No

What is the present or anticipated oral hygiene status of the patient in question? Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]

Where does the patient fit in the following caries risk categories? Low: no previous history of carious lesion(s)

How would you describe the patient's treatment expectations from esthetics and functional standpoints? Undemanding

Tooth Prognosis Score Conf=170.0

Recommendations: Medical consultation and clearance MUST be obtained prior to starting dental treatment. Overall tooth prognosis is good and retention is indicated in this case. Treatment options include direct and indirect restorations per present status. This tooth can be utilized as an abutment to support the planned dental prosthesis, maintaining the principles of abutment selection, in case replacement of adjacent missing tooth/teeth is indicated.

Current Date and Time: January 26, 2017 10:01:53 AM EST

Chart Number/Patient ID: 12222

Provider ID: 21111

Tooth Number: 8, 9

Figure 3-12. Screenshot of the results screen generated by the proposed expert system at the end of treatment planning session.

3. 10. 2. 6. Storage and Provider-Patient Communication:

In the final step of the workflow, the provider is able to store the system's report in a protected email account such as Gmail and later convert this report into PDF format file and upload it into the electronic health record available at the clinical operatory. The provider is also able to share this report with the patient utilizing personal email address. Even though the modern email accounts carriers have applied rigorous security against theft and data breach, the emailed report is encrypted using provider and/or patient ID numbers along with treatment recommendations, tooth number, data and time of the current treatment planning session. The use of database interfaces, such as Oracle and others, are very complicated to setup and required high skills and training to utilize them efficiently. They are highly depended on the type of database and its configuration and security issues on the used server. On the contrary, using email account is much easier and probably more effective to use than a database. It is comparatively easy to send an email with system data either to the end user, patients or both. This only requires an email account, not the complexity of an installed database and SQL. It also proactively provides the user (i.e. providers) with the data without them having to go through the steps to access the database. If the system is ever fielded on a production server with IT resources, a database interface could be added later if there are some reasons to do so. Figure 3-3 shows the list of commands that are required to activate the email feature of our Corvid-based system. Figure 3-12 represents the prompt that asks end-users to provide an email address to send the report to destinations of interest.

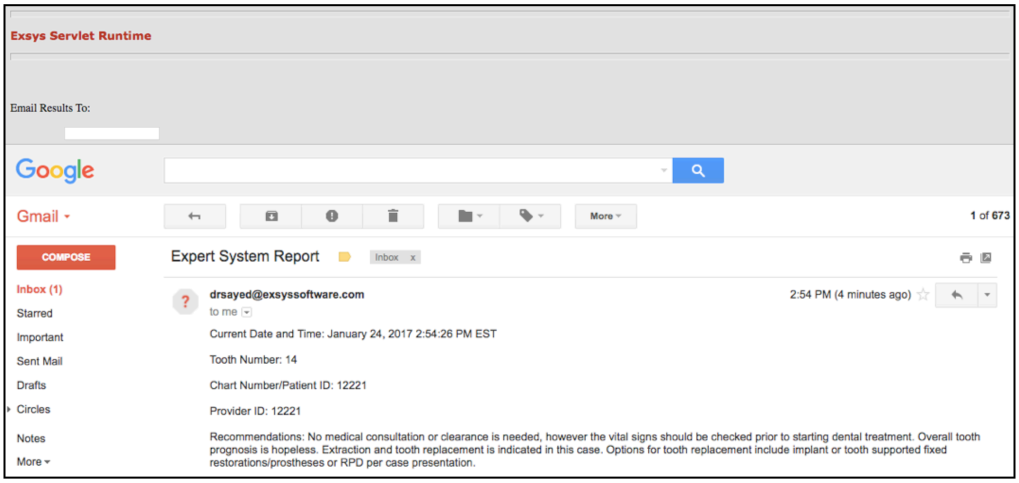


Figure 3-13. Screenshot of the prompt that asks end-users to provide an email address to send the report and the email that is received at the intended destination

3. 10. 3. Rule-Based Knowledge Representation:

In the previous section, the logical process and workflow within our proposed system ware discussed in details in order to provide the most adequate treatment plan options and recommendations with regard to retention or extraction clinical decision-making. The current section will discuss in details the factors that are involved in this aspect of decision-making. These factors were codified into categorical and sub-categorical rules and were assigned positive or negative numerical values based on their impact on the overall tooth prognosis and treatment outcomes. The scoring system used was highly dependent on the concept of evidence-based dental practice guidelines where clinical expert, literature knowledge and patient's desires were taken into considerations. This system was designed to perform forward chaining only to maintain simplicity and objectivity of the system and its outcomes.

Although we have adopted a complex and multi-factorial comprehensive evaluation approach, we were able to tabulate the set of rules and criteria that must be considered for accurate treatment recommendations in this aspect of decision-making. The rules and criteria were classified into 'basic' category, which is highlighted in the dark-grey area of table. This category requires input of information from end-user side based on review of medical status, clinical and radiographic examination. The other category is 'shared-decision' category that is highlighted in the light-grey area of the table. This category is not applicable in all clinical situations, but only under unclear and complex situations where the basic set of criteria do not provide a deterministic treatment option. In this situation, patient's interests, financial ability and risk tolerance are factored-in as the final step prior to making definitive treatment plans and recommendations. Table 3-1 represents the rules and criteria that were used to develop our proposed expert system.

Prompts	***Options***	***Score Contribution***
Is the patient medically stable?	Yes	+100
	No Medical consultation should be obtained prior to tx	+100
What is the location of the tooth in question relative to the dental arch?	Anterior region of the jaw (i.e. anterior tooth)	0
	Posterior region of the jaw (i.e. posterior tooth)	-5
If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest?	No tooth preparation is required	0
	Tooth preparation is required and the location of the proposed finish line ≥ 2.5mm above the bone crest	+5
	Tooth preparation is required and the location of the proposed finish line < 2.5mm relative to the bone crest The user should factor the amount of root in bone, How far below the current osseous crest to the proposed finish line (i.e. the need for crown lengthening)	-10
What is the proposed crown-to-root ratio of the tooth in question following crown lengthening, if required?	The proposed crown-to-root ratio is 2:3 or 1:1.5	+10
	The proposed crown-to-root ratio is 1:1	-10
	The proposed crown-to-root ratio is 1.5:1	-25
	The proposed crown-to-root ratio is 2:1	-40
What is the amount of tooth extrusion relative to the occlusal plane?	No extrusion relative to occlusal plane	0
	Extrusion is less than 2mm relative to occlusal plane Extrusion correction is necessary? If so, the user should consider enameloplasty	0
	Extrusion relative to occlusal plane is 2mm to less than 6mm Extrusion correction is necessary? If so, the user should consider CL and full coverage crown	-10

	Extrusion relative to occlusal plane is 6mm to less than 11mm ⚠ Extrusion correction is necessary? If so, the user should factor the need for root canal treatment, CL and full coverage crown	-40
	Extrusion relative to occlusal plane is 11mm or more ⚠ Extrusion correction is necessary? If so, the user should factor the need for surgical crown lengthening, the post-operative C/R ratio and furcation involvment?	-100
What is the pulpal status of the tooth in question?	Normal pulp or reversible pulpitis	+10
	Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required	0
Has the tooth in question been root canal treated previously?	Yes	0
	No	0
If no, what is the grade of root canal treatment complexity?	Complexity of root canal therapy is low[1,2]: * Single/multiple root canals with curvature <15° to the root axis that are considered negotiable from radiographic or clinical evidence through their entire length * Easily isolated * Closed apex * No root canal obstruction or damaged access * Incision and drainage	0
	Complexity of root canal therapy is moderate[1,2]: * Single/multiple root canals with curvature >15° but <40° to the root axis that are considered negotiable from radiographic or clinical evidence through their entire length * Moderately difficult to isolate * Teeth with incomplete root development * Open apex within 1.5mm	-10
	Complexity of root canal therapy is high[1,2]: * Single/multiple root canals with curvature >40° * Single/multiple root canals that are NOT considered negotiable from radiographic or clinical evidence through their entire length * Extremely difficult to isolate * Open apex more than 1.5mm * Surgical root canal treatment	-25
If yes, Does the tooth in question require root canal re-treatment?	Yes	-35
	No	0
Does the tooth in question meet the minimum requirements to restore root canal treated teeth?	Yes (i.e. Adequate ferrule [dentinal wall height >1.5mm], dentinal wall thickness > or =1mm, a minimum of 2 opposing dentinal walls)	-10
	No (i.e. Inadequate ferrule [dentinal wall height <1.5mm], dentinal wall thickness <1mm, one or no dentinal walls)	-20
Does the tooth in question show signs of furcation involvement upon clinical or radiographic examination?	No	0
	Yes	0
You have indicated earlier that the tooth in question is located in the posterior region of the jaw; please specify the tooth type among the following categories?	Maxillary premolar	-80
	Mandibular premolar	-80
	Maxillary molar	0
	Mandibular molar	0
What is the class of furcation lesion(s) relative to the tooth in question?	Class I furcation involvment[3]	-10
	Class II furcation involvment[3] or combination of class I and II	Locations?

	Class III furcation involvment[3] or combination of class II and III	-80
	Class IV furcation involvment[3]	-80
Where is/are the location(s) of furcation lesion(s) relative to the tooth in question?	Buccal	-20
	Mesial	-40
	Distal	-40
	Mesial and Distal	-80
	Buccal and mesial or distal	-60
	Buccal, mesial and distal	-100
	Lingual	-20
	Buccal and lingual	-40
Does the tooth in question show signs of mobility upon clinical examination? If yes, what is the grade of tooth mobility that was detected upon clinical examination?	No mobility	0
	Mobility grade I	-10
	Mobility grade II - The user should factor the initial C/R ratio	-20
	Mobility grade III	-100
Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis?	No	+30
	Tooth will be utilized as abutment for FPD	-10
	Tooth will be utilized as abutment for RPD	-20
	Tooth will be utilized as abutment for Overdenture	+25
Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion?	No	0
	Patient is bruxer but compliant with wearing of night guard or opposing occlusion is complete denture	-5
	Patient is bruxer but compliant with wearing of night guard or oppsoing occlusion is natural teeth, RPD, FPD or implant	-15
	Patient is non-compliant bruxer	-75
What is the present or anticipated oral hygiene status of the patient in question?	Oral Hygiene Index (Plaque Index)[3] Plaque accumulation counted on 4 surfaces for each tooth (B, L/P, M and D) for all available dentition. [Plaque Index = The number of plaque containing surfaces / The total number of available surfaces X 100] PI ≤ 10% PI >10% but reduced to ≤ 10% on subsequent visits after OHI	+40
	PI >10% and remain the same on subsequent visits	-40
Where does the patient fit in the following caries risk categories?	Low: no previous history of carious lesion(s)	+10
	Moderate: no carious lesion(s) developed in the past 3 years of recalls	-10
	High: new carious lesion(s) developed within the past 3 years of recalls	-30
	Extreme high: new carious lesion(s) developed within the past 3 years of recalls plus dry mouth	-35
	Highest: is the same as extreme high category plus exposed roots	-50
How would you describe the patient's	Undemanding	+15

treatment expectations from esthetics and functional standpoints?	Demanding	-15
Is the patient interested in retaining the tooth in question, financially able and willing to take the risk of the tooth retention decision? (Unclear route)	Yes	0
	No	0
Tooth Number:	Users (providers) are required to enter a string value for documentation purposes	None
Chart Number/Patient ID:	Users (providers) are required to enter a string value for documentation purposes	None
Provider ID:	Users (providers) are required to enter a string value for documentation purposes	None
Current Date and Time:	Exsys Corvid will refer to time and date information indicated by destination PC	None
Cumulative Prognosis Score:	Results (Good >=80, Fair >=60 and <80, Poor >=40 and <60, hopeless <40)	None
Recommendations:	According to options selected and cumulative prognosis score	None
Email Results To:	Users (providers) are required to enter email address value(s) to send the results to providers, patients or both	None

Table 3-1. Represents the rules and categories that were used to constructs the logic blocks of our proposed system.

The rules were organized in the table according to their importance in clinical decision-making.

The last category, which is highlighted in the light-green area of the table, has no actual contribution in the overall tooth prognosis score and was added specifically for the purpose of triggering results and clinical recommendations, request of personal identification and communication of the result to destinations of interest. It should be identified that the system starts with a cumulative prognosis score (confidence variable) of 100, proceeds through series of robust rules processing and calculations and end-up with a score that determines the definitive treatment plan, options and alerts that are intended to guide providers for taking the most suitable clinical decisions. Each variable in the system was accompanied by an image for clarification.

3. 10. 4. Post-Programming Evaluation and Validation:

To validate our proposed following development, the simplified questionnaire was developed utilizing the same clinical case-scenarios that were used for pre-programming validation. Inclusion criteria for survey participants predicated that participants should carry certification from the American Board of Prosthodontics or fellowship of the Royal College of Dentists of Canada in prosthodontics or certification from both entities. The range of years in practice was not determined in specific, although it was used as a parameter upon data analysis and interpretation. The American Board of Prosthodontics maintains an online and readily accessible database for its diplomats, which include their names, degrees, address and contact information. This database was accessed on October 2016 to retrieve diplomats contact information, specifically those who are located in the tri-state area for convenience. A total of 84 diplomats were contacted via emails, asked to participate in this survey and return their response either electronically or via mail. Twenty diplomats responded to this survey providing a response rate of 23.8%. The Canadian counterpart keeps its fellows' information confidential; therefore contact was made with the fellows who graduated from the graduate prosthodontics program at Rutgers School of Dental Medicine only, where two participants were additionally included in this survey.

Twenty-two expert prosthodontists have responded to questions relative to 28 clinical scenarios of varying complexity. Each participant gave each scenario a prognosis rating and corresponding treatment. These scenarios were also run through our proposed CDSS, in which prognosis rating and corresponding treatment were also documented for each clinical scenario. This process was done utilizing double-blinded approach among the participants and our proposed system. The prognosis is a four point Likert scale of ratings ranging from good (1), fair (2), and poor (3) to hopeless (4). The corresponding treatment includes options of retention and restoration (1) and extraction and replacement (2). The data was codified accordingly and entered in an Excel Spreadsheet in preparation for statistical analysis. SAS was used for statistical testing and analysis.

The number and percentage of agreement for prognosis and treatment between each prosthodontist and CDSS were calculated. Weighted Kappa was used to measure the level of agreement for the ordinal data of prognosis, while Kappa was used to measure the level of agreement for treatment between each prosthodontist and CDSS. Subsequently, the average of Weighted Kappa for prognosis and average of Kappa for treatment were calculated. Pearson correlation coefficients were used to identify if the years in practice of prosthodontists were correlated with the levels of agreement for prognosis and treatment. The percentages of agreement between each prosthodontist and CDSS are presented in table 3-2.

Participants	***Prognosis***		***Treatment***	
	# of agreement	% of agreement	# of agreement	% of agreement
Prosthodontist 1	8	28.6	23	82.1
Prosthodontist 2	18	64.3	25	89.3
Prosthodontist 3	20	71.4	21	75.0
Prosthodontist 4	21	75.0	23	82.1
Prosthodontist 5	22	78.6	24	85.7
Prosthodontist 6	16	57.1	22	78.6
Prosthodontist 7	21	75.0	25	89.3
Prosthodontist 8	17	60.7	23	82.1
Prosthodontist 9	18	64.3	24	85.7
Prosthodontist 10	20	71.4	25	89.3
Prosthodontist 11	23	82.1	24	85.7
Prosthodontist 12	17	60.7	24	85.7
Prosthodontist 13	16	57.1	23	82.1
Prosthodontist 14	18	64.3	24	85.7
Prosthodontist 15	15	53.6	22	78.6
Prosthodontist 16	17	60.7	24	85.7
Prosthodontist 17	18	64.3	20	71.4

Prosthodontist 18	19	67.9	23	82.1
Prosthodontist 19	16	57.1	23	82.1
Prosthodontist 20	26	92.9	26	92.9
Prosthodontist 21	20	71.4	25	89.3
Prosthodontist 22	16	57.1	22	78.6
Average	**18.3**	**65.3%**	**23.4**	**83.6%**

Table 3-2. Number and percentage of agreement between each Prosthodontist and CDSS.

Weighted Kappa and Kappa between each faculty and CDSS are shown in table 3-3.

Participants	***Prognosis***	***Treatment***
	Weighted Kappa	Kappa
Prosthodontist 1	0.31	0.64
Prosthodontist 2	0.63	0.79
Prosthodontist 3	0.61	0.50
Prosthodontist 4	0.71	0.63
Prosthodontist 5	0.79	0.71
Prosthodontist 6	0.51	0.56
Prosthodontist 7	0.68	0.78
Prosthodontist 8	0.59	0.64
Prosthodontist 9	0.59	0.71
Prosthodontist 10	0.69	0.78
Prosthodontist 11	0.81	0.71
Prosthodontist 12	0.51	0.71
Prosthodontist 13	0.49	0.64
Prosthodontist 14	0.61	0.72
Prosthodontist 15	0.53	0.57
Prosthodontist 16	0.59	0.71
Prosthodontist 17	0.57	0.43
Prosthodontist 18	0.65	0.64
Prosthodontist 19	0.50	0.64
Prosthodontist 20	0.93	0.86
Prosthodontist 21	0.63	0.79
Prosthodontist 22	0.63	0.57
Average (SD)	**0.62 (0.13)**	**0.67 (0.10)**

Table 3-3. Measure of agreement (Kappa) between Prosthodontists and CDSS.

The results of statistical analysis reveal the following:

1) Average percentage of prognosis and corresponding treatment agreement between the prosthodontists and CDSS were 65.3% and 83.6%, respectively.

2) Average Kappa for prognosis and corresponding treatment between the prosthodontists and CDSS were 0.62 and 0.67, respectively, indicating a substantial agreement for both prognosis and corresponding treatment between the prosthodontists and CDSS.

3) Average of years in practice for prosthodontists was 16.6 with a standard deviation of 15.7. There was no correlation between years in practice and measure of agreement for both prognosis ($r=-0.062$, $p=0.785$) and corresponding treatment ($r= -0.202$, $p=0.368$).

3. 10. 5. System Fielding and Induction into Clinical Operatory:

Our proposed system was temporarily fielded on an Exsys production server in coordination with IT support to simulate an induction scenario into clinical operatory. This technical support is usually provided by Exsys to users for monthly or annually set fee. The support is required to maintain the system workability, resolve issues that may happen upon initial implementation into any destination of interest and continues thereafter. Exsys takes care of system fielding and provides users with an html link that either be converted into desktop icon or saved in favorite list for future reference. The URL link to our proposed system is: Expert System for Tooth Retention or Extraction Decision-Making

Figure 3-13 shows a desktop icon that contains the URL link to our proposed system on the Web server. This URL link or icon could be adapted on PCs, laptops, and smart devices to be accessed at any desired destinations within the clinical operatory area or distant locations.

Figure 3-14. Screenshot of Lap-top desktop showing the system icon identified by Exsys logo.

<u>Chapter 4: Simulated Clinical Scenarios and Case Studies</u>

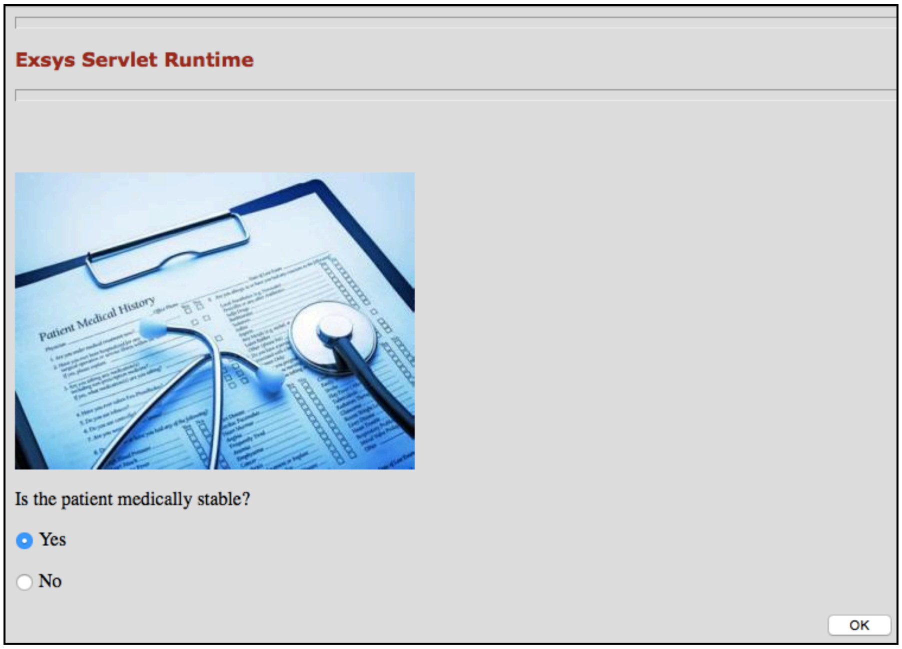
In this section, we will run few clinical case scenarios through the system to show the process and steps in which providers are supposed to go through upon induction of such system in the real-world clinical setting.

4. 1. Clinical Scenario#1 (posterior tooth, no shared-decision):

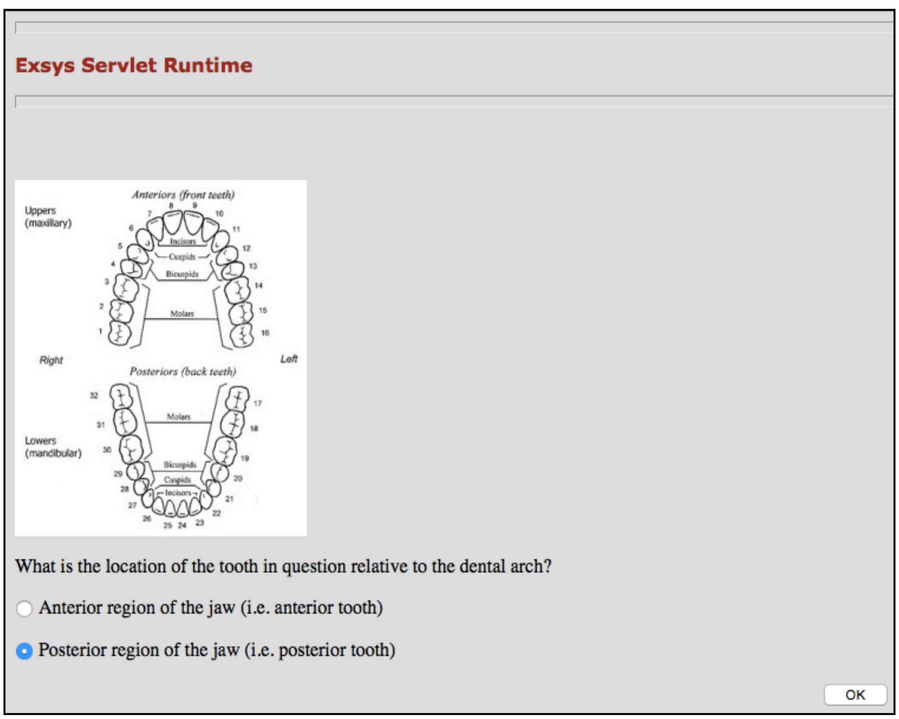
History and findings: This patient presented to the dental office with severe lingering pain related to tooth #18. A review of medical status revealed non-significant findings. Extensive mesial carious lesion was detected on clinical and radiographic evaluation with pulpal involvement. The tooth in question meets the minimum requirements to restore RCT teeth. The patient is missing teeth #19-21 and third molars, while the maxillary arch remains intact. The proposed C/R ratio is 1:1.5 while the proposed finish line is more than 2.5mm from bone crest. No extrusion, mobility or furcation lesions were detected. No carious lesion(s) was detected or developed on all teeth, except for tooth #18 in the past year. Canal is reduced in size and its curvature is 40° to the long axis of the tooth. Crown morphology moderately complicates isolation for endodontic procedures. He has reasonable treatment expectations or demands, high-risk tolerance and reasonable financial ability. He showed good oral hygiene and compliance to instructions. Missing teeth # 19-21 will be restored with RPD. Therefore, tooth #18 will be utilized as a terminal abutment to support/retain RPD prosthesis. He is a non-compliant bruxer and opposing occlusion is natural maxillary dentition.

CDSS Steps Showing Decision-Making Process and Final Treatment Plan Recommendation:

Step 1:

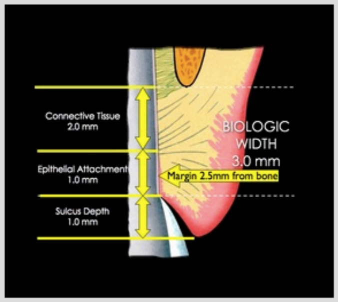


Step 2:



Step 3:

Exsys Servlet Runtime



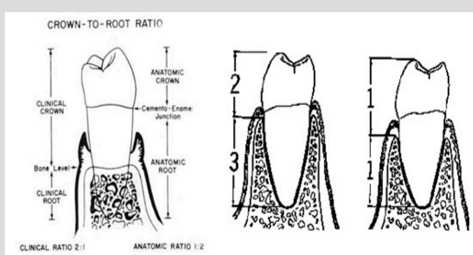
If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest?

- ○ No tooth preparation is required
- ● Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest
- ○ Tooth preparation is required and proposed finish line is < 2.5mm relative to bone crest

OK

Step 4:

Exsys Servlet Runtime



What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required?

- ● 2:3 or 1:1.5
- ○ 1:1
- ○ 1.5:1
- ○ 2:1

OK

Step 5:

Exsys Servlet Runtime

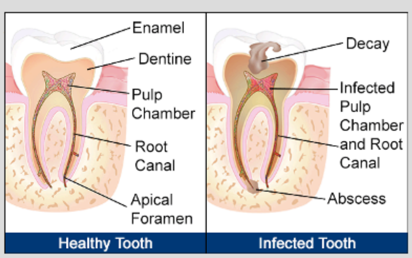
What is the amount of tooth extrusion relative to the occlusal plane?

- (●) No extrusion relative to occlusal plane
- ( ) < 2mm relative to occlusal plane
- ( ) = or > 2mm to < 6mm relative to occlusal plane
- ( ) = or > 6mm to < 11mm relative to occlusal plane
- ( ) > 11mm relative to occlusal plane

OK

Step 6:

Exsys Servlet Runtime

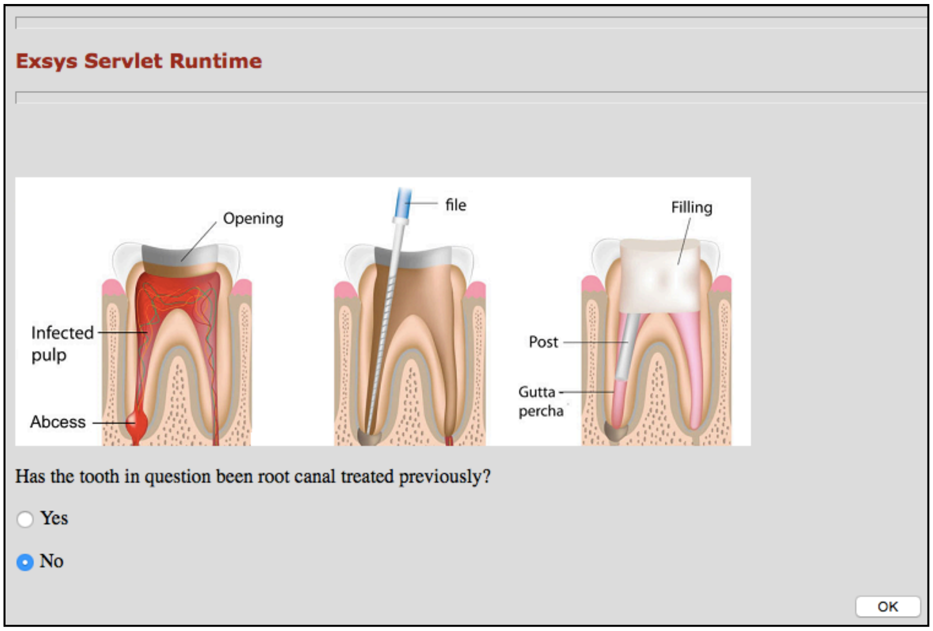


What is the pulpal status of the tooth in question?

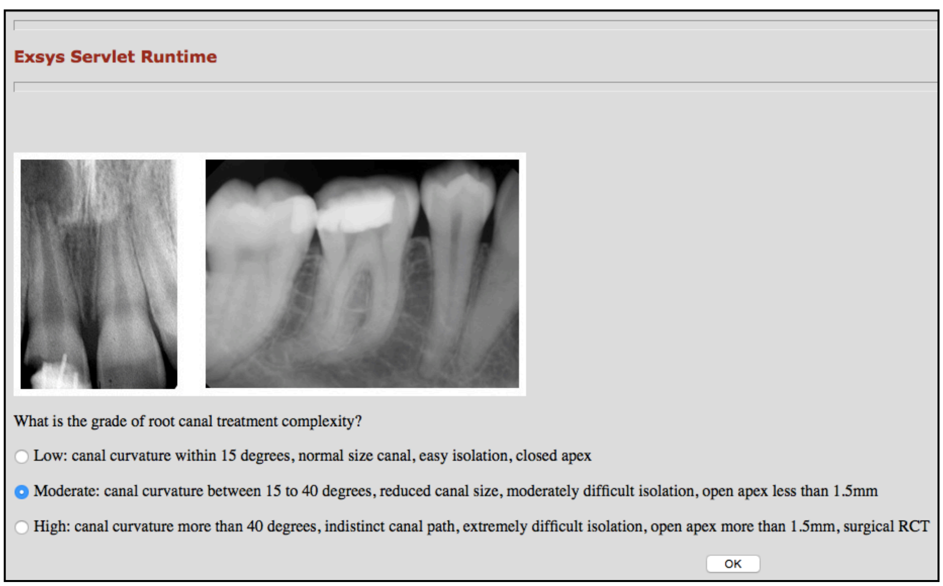
- ( ) Normal pulp or reversible pulpitis
- (●) Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required

OK

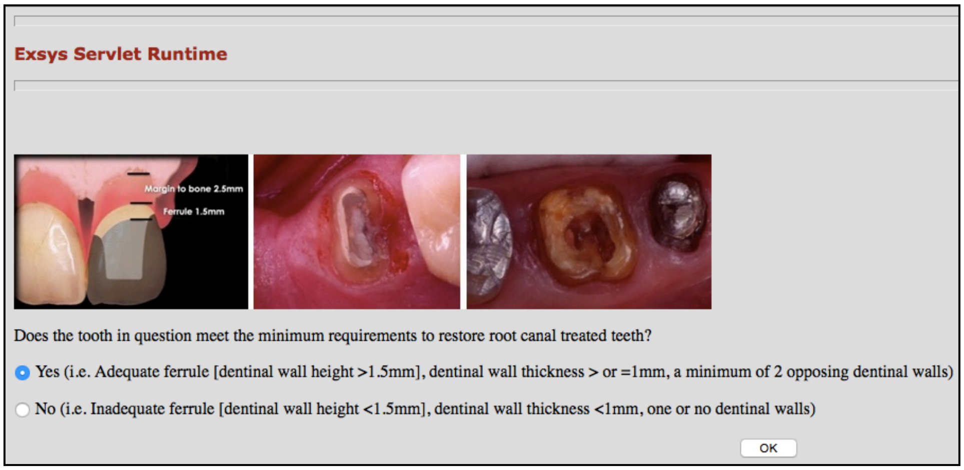
Step 7:


Exsys Servlet Runtime
Opening
file
Filling
Infected pulp
Post
Gutta percha
Abcess
Has the tooth in question been root canal treated previously?
Yes
No
OK

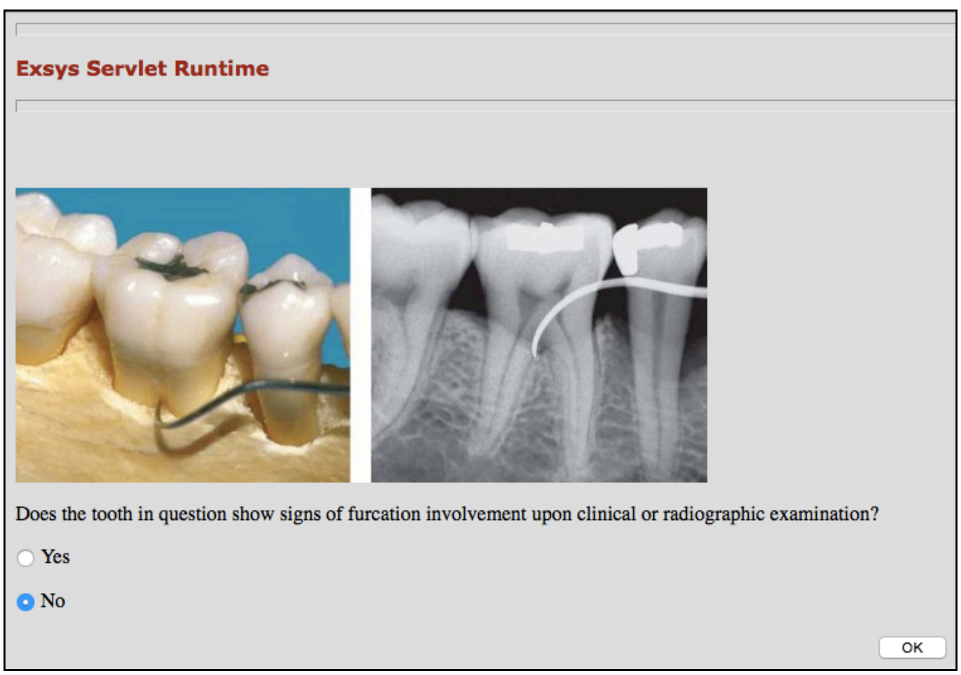
Step 8:


Exsys Servlet Runtime
What is the grade of root canal treatment complexity?
Low: canal curvature within 15 degrees, normal size canal, easy isolation, closed apex
Moderate: canal curvature between 15 to 40 degrees, reduced canal size, moderately difficult isolation, open apex less than 1.5mm
High: canal curvature more than 40 degrees, indistinct canal path, extremely difficult isolation, open apex more than 1.5mm, surgical RCT
OK

Step 9:



Step 10:



Step 11:

Exsys Servlet Runtime

Does the tooth in question show signs of mobility upon clinical examination?

- ○ Yes
- ● No

OK

Step 12:

Exsys Servlet Runtime

Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis?

- ○ No
- ○ Yes, abutment for FPD
- ● Yes, abutment for RPD
- ○ Yes, abutment for overdenture

OK

Step 13:

Exsys Servlet Runtime

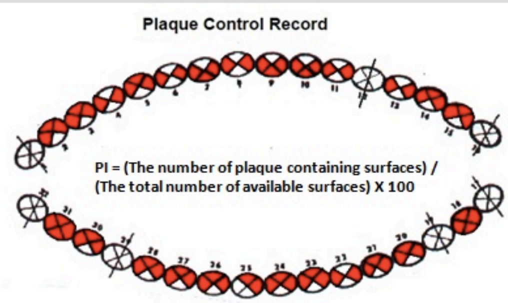
Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion?

- No
- Yes, he/she is compliant and opposing occlusion is complete denture
- Yes, he/she is compliant and opposing occlusion is/are natural teeth, RPD, FPD or implant prosthesis
- Yes, but he/she is not compliant

OK

Step 14:

Exsys Servlet Runtime



What is the present or anticipated oral hygiene status of the patient in question?

- Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]
- Poor oral hygiene [O'Leary Plaque Index is >10% on first and subsequent visits]

OK

Step 15:

Exsys Servlet Runtime

Where does the patient fit in the following caries risk categories?

- ○ Low: no previous history of carious lesion(s)
- ○ Moderate: no carious lesion(s) developed in the past 3 years of recalls
- ◉ High: new carious lesion(s) developed within the past 3 years of recalls
- ○ Extreme high: new carious lesion(s) developed within the past 3 years of recalls plus dry mouth
- ○ Highest: is the same as extreme high category plus exposed roots

OK

Step 16:

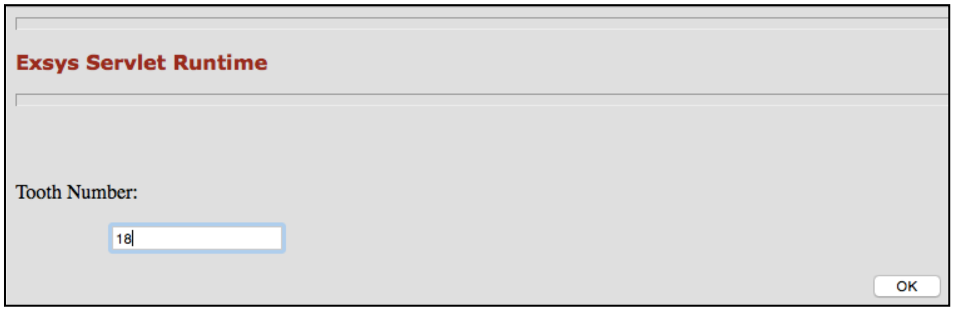
Exsys Servlet Runtime

How would you describe the patient's treatment expectations from esthetics and functional standpoints?

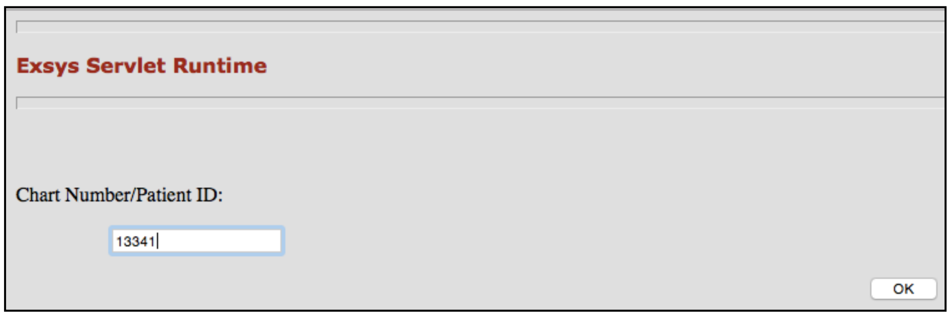
- ◉ Undemanding
- ○ Demanding

OK

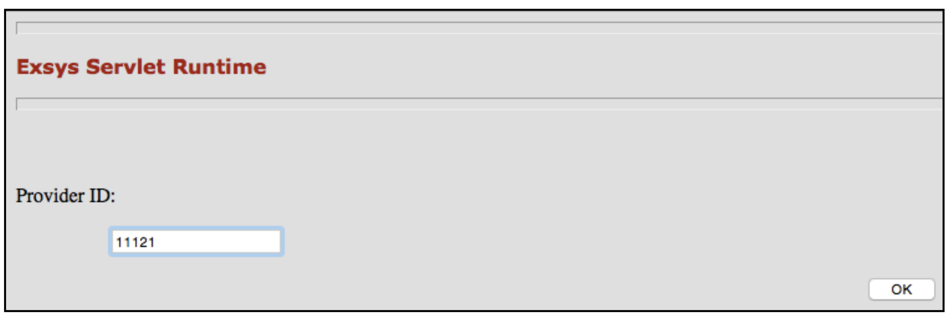
Step 17:



Step 18:



Step 19:



Results Screen:

Is the patient medically stable? Yes

What is the location of the tooth in question relative to the dental arch? Posterior region of the jaw (i.e. posterior tooth)

If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest? Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest

What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required? 2:3 or 1:1.5

What is the amount of tooth extrusion relative to the occlusal plane? No extrusion relative to occlusal plane

What is the pulpal status of the tooth in question? Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required

Has the tooth in question been root canal treated previously? No

What is the grade of root canal treatment complexity? Moderate: canal curvature between 15 to 40 degrees, reduced canal size, moderately difficult isolation, open apex less than 1.5mm

Does the tooth in question meet the minimum requirements to restore root canal treated teeth? Yes (i.e. Adequate ferrule [dentinal wall height >1.5mm], dentinal wall thickness > or =1mm, a minimum of 2 opposing dentinal walls)

Does the tooth in question show signs of furcation involvement upon clinical or radiographic examination? No

Does the tooth in question show signs of mobility upon clinical examination? No

Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis? Yes, abutment for RPD

Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion? Yes, but he/she is not compliant

What is the present or anticipated oral hygiene status of the patient in question? Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]

Where does the patient fit in the following caries risk categories? High: new carious lesion(s) developed within the past 3 years of recalls

How would you describe the patient's treatment expectations from esthetics and functional standpoints? Undemanding

Tooth Prognosis Score Conf=-20.0

Recommendations: No medical consultation or clearance is needed, however the vital signs should be checked prior to starting dental treatment. Overall tooth prognosis is hopeless. Extraction and tooth replacement is indicated in this case. Options for tooth replacement include implant or tooth supported fixed restorations/prostheses or RPD per case presentation.

Current Date and Time: January 26, 2017 9:25:44 AM EST

Chart Number/Patient ID: 13341

Provider ID: 11121

Tooth Number: 18

E-mail Address Request:

Exsys Servlet Runtime

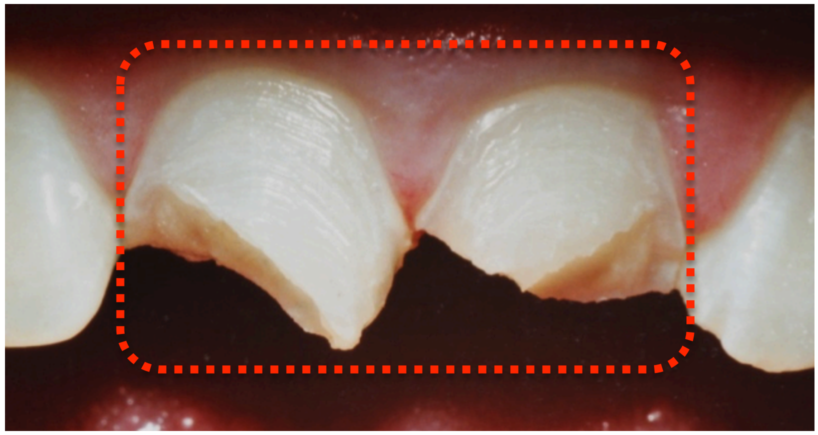
Email Results To:

drsayed203@gmail.com

OK

E-mailed System Report:

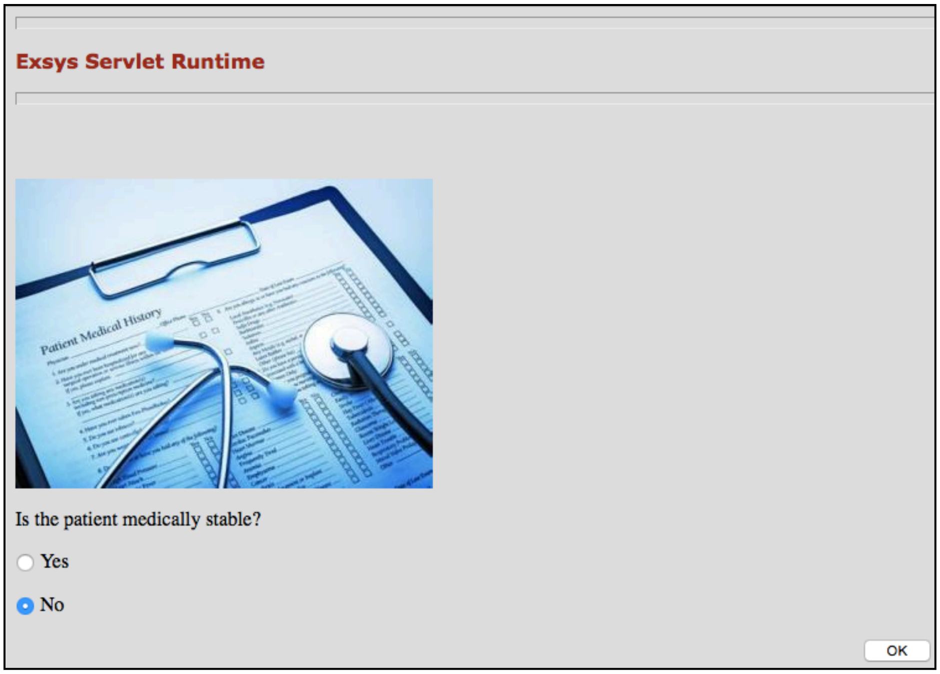
4. 2. Clinical Scenario#2 (anterior tooth, no shared-decision):



History and findings: This patient presented to the dental office for urgent care. Review of medical status revealed high blood pressure. He is seeking immediate dental management of teeth #8 and 9 that were broken due to sport related trauma. Clinical and radiographic examination revealed that teeth #8 and 9 are vital with grade I mobility and 1:1.5 C/R ratio. No extrusion was noted. The patient is caries-free. Pocket depths and bleeding on probing are within normal limits. He has reasonable treatment expectations or demands, high-risk tolerance and reasonable financial ability. He showed good oral hygiene and compliance with instructions. The proposed finish line is more than 2.5mm relative to bone crest. Teeth #8 and 9 will receive 2 all ceramic crowns and won't be utilized to support or retain any prosthesis. Neither bruxism nor parafunctional habits are present. Opposing occlusion is natural mandibular dentition.

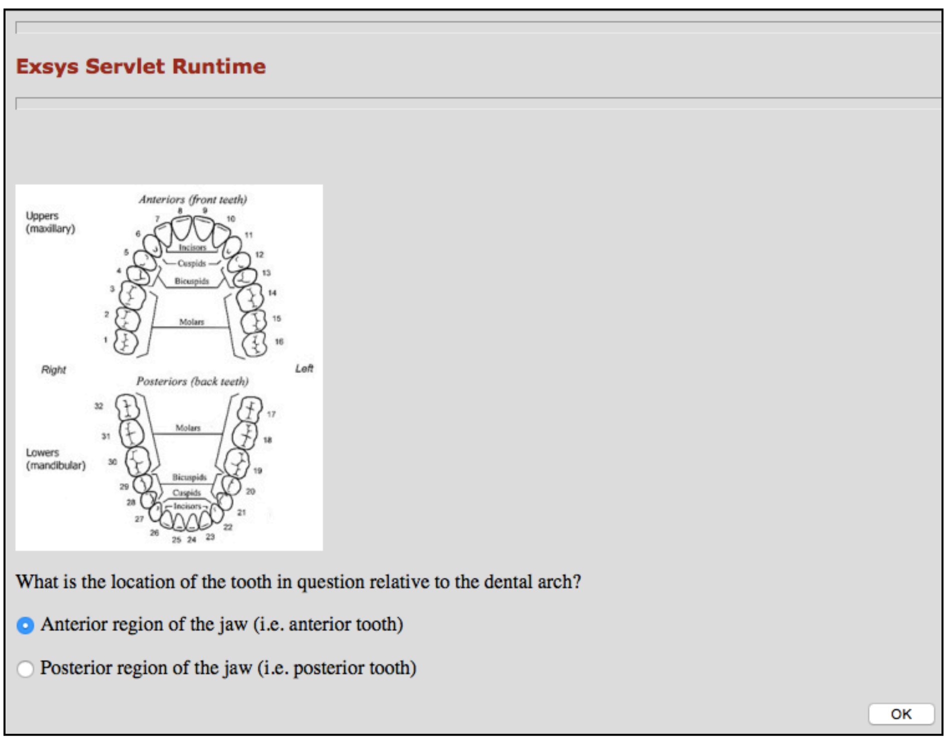
CDSS Steps Showing Decision-Making Process and Final Treatment Plan Recommendation:

Step 1:



Exsys Servlet Runtime
Patient Medical History
Is the patient medically stable?
Yes
No
OK

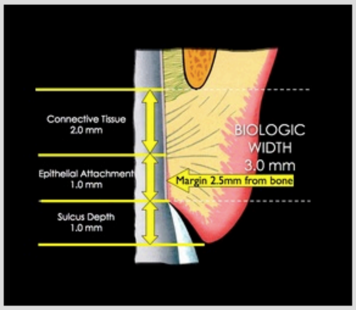
Step 2:



Exsys Servlet Runtime
Anteriors (front teeth)
Uppers (maxillary)
Incisors
Cuspids
Bicuspids
Molars
Right
Left
Posteriors (back teeth)
Lowers (mandibular)
What is the location of the tooth in question relative to the dental arch?
Anterior region of the jaw (i.e. anterior tooth)
Posterior region of the jaw (i.e. posterior tooth)
OK

Step 3:

Exsys Servlet Runtime



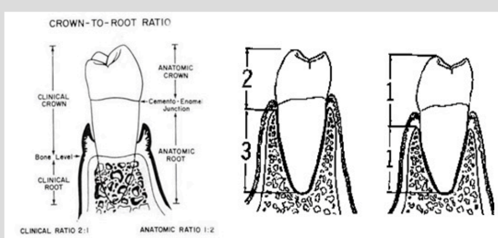
If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest?

- ○ No tooth preparation is required
- ◉ Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest
- ○ Tooth preparation is required and proposed finish line is < 2.5mm relative to bone crest

OK

Step 4:

Exsys Servlet Runtime



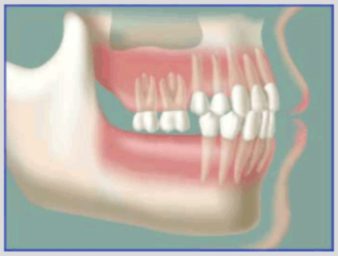
What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required?

- ◉ 2:3 or 1:1.5
- ○ 1:1
- ○ 1.5:1
- ○ 2:1

OK

Step 5:

Exsys Servlet Runtime



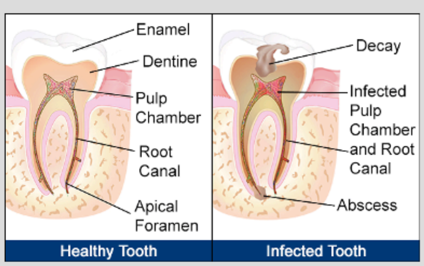
What is the amount of tooth extrusion relative to the occlusal plane?

- (•) No extrusion relative to occlusal plane
- ( ) < 2mm relative to occlusal plane
- ( ) = or > 2mm to < 6mm relative to occlusal plane
- ( ) = or > 6mm to < 11mm relative to occlusal plane
- ( ) > 11mm relative to occlusal plane

OK

Step 6:

Exsys Servlet Runtime



What is the pulpal status of the tooth in question?

- (•) Normal pulp or reversible pulpitis
- ( ) Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required

OK

Step 7:

Exsys Servlet Runtime

Does the tooth in question show signs of mobility upon clinical examination?

- (•) Yes
- ( ) No

OK

Step 8:

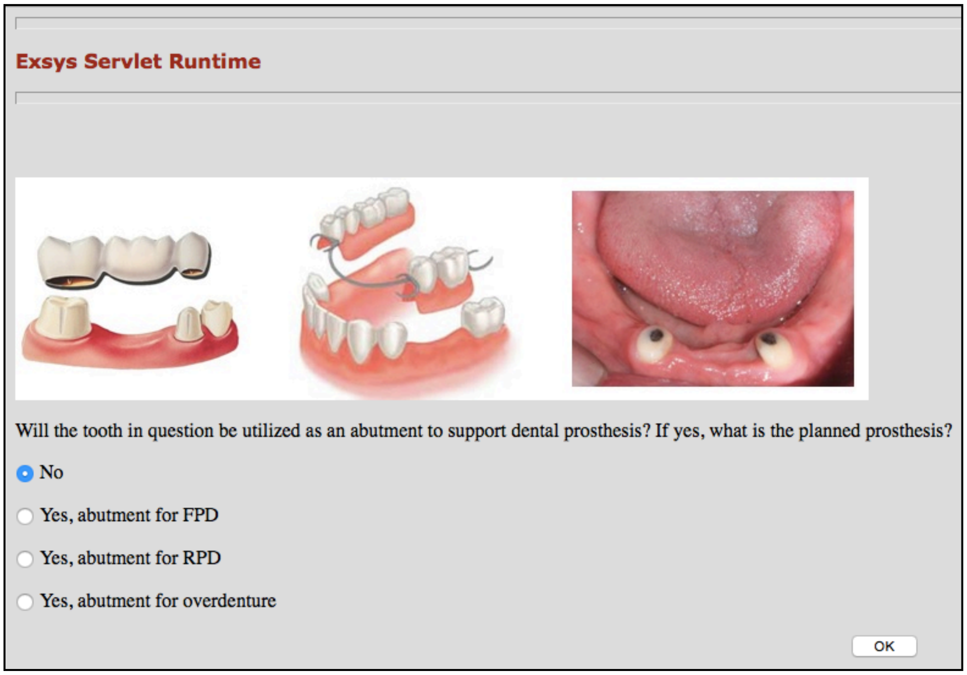
Exsys Servlet Runtime

What is the grade of tooth mobility that was detected upon clinical examination?

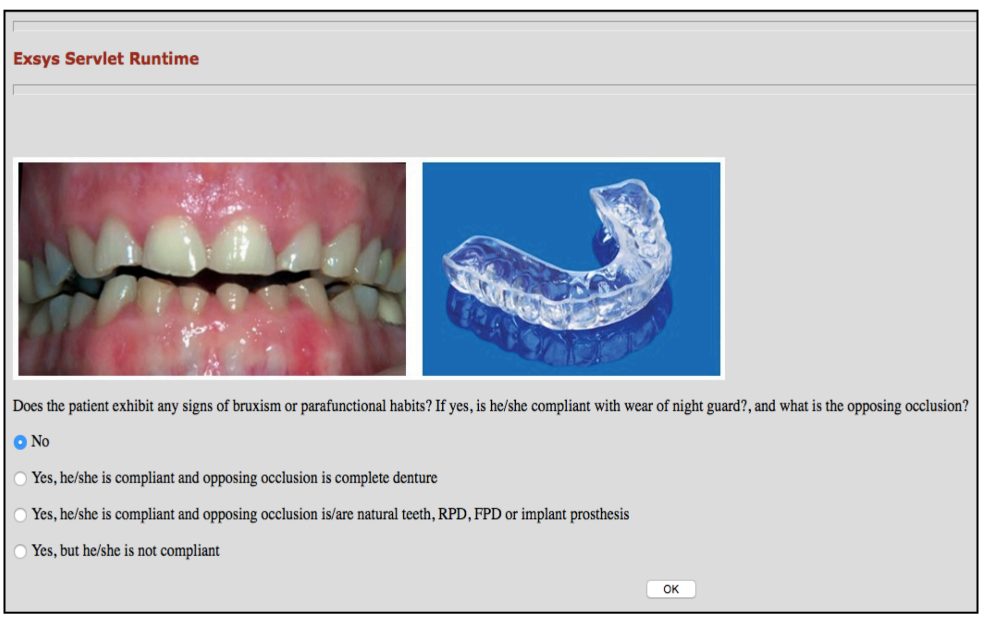
- (•) Grade I: within 1mm horizontal mobility
- ( ) Grade II: more than 1mm horizontal mobility
- ( ) Grade III: more than 1mm horizontal with vertical mobility

OK

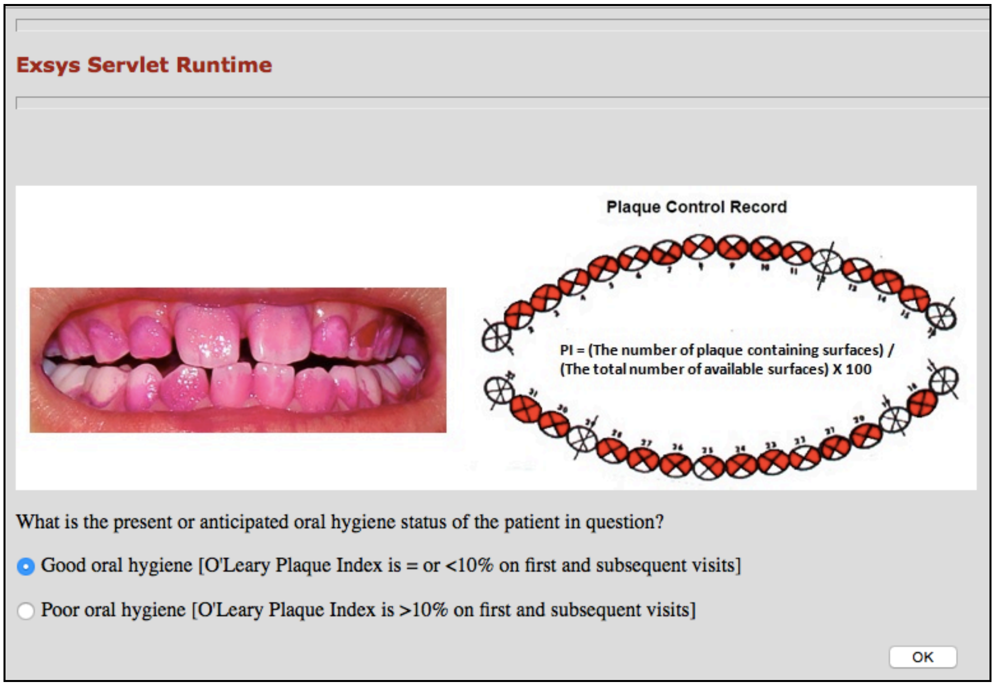
Step 9:



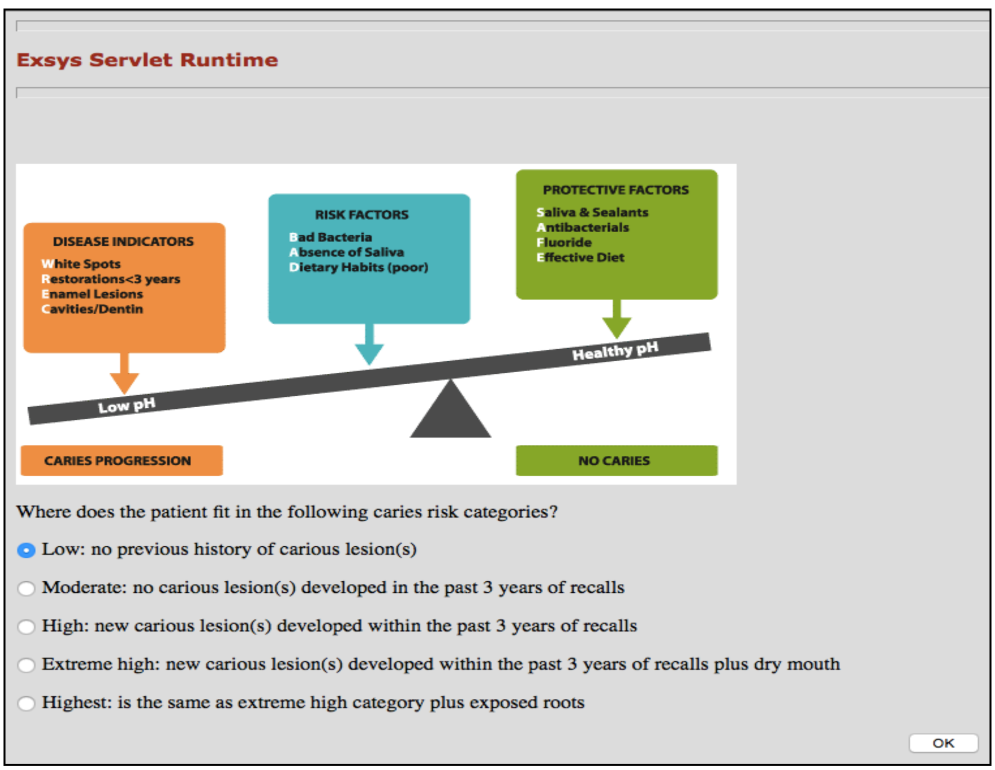
Step 10:



Step 11:



Step 12:



Step 13:

Exsys Servlet Runtime

How would you describe the patient's treatment expectations from esthetics and functional standpoints?

- (●) Undemanding
- ( ) Demanding

OK

Step 14:

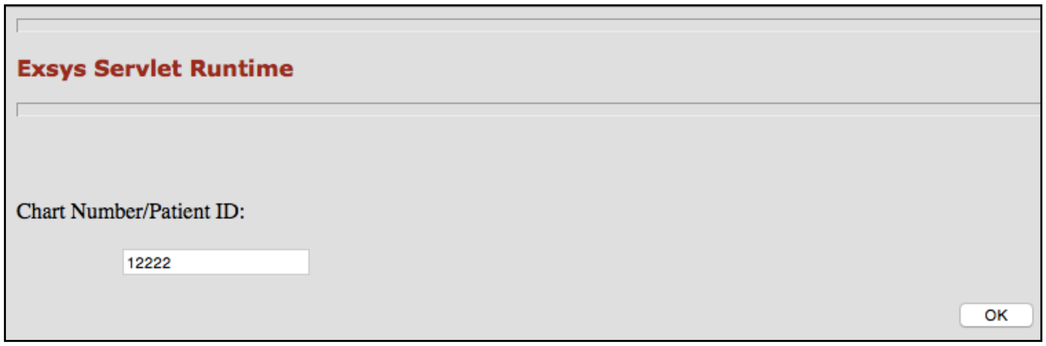
Exsys Servlet Runtime

Tooth Number:

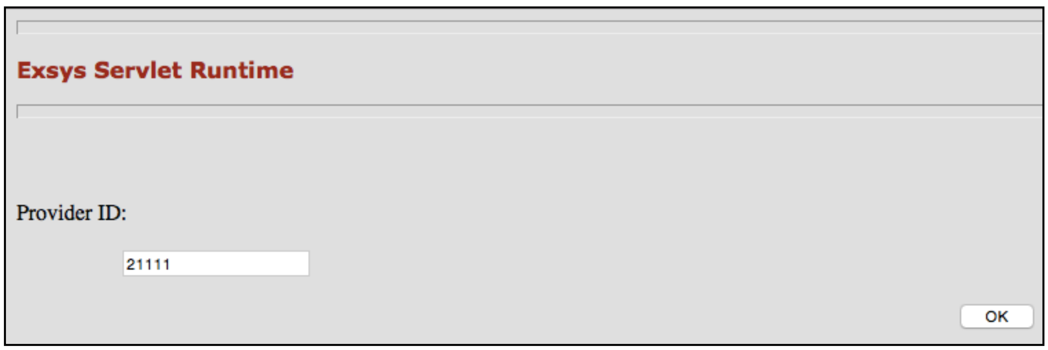
8, 9

OK

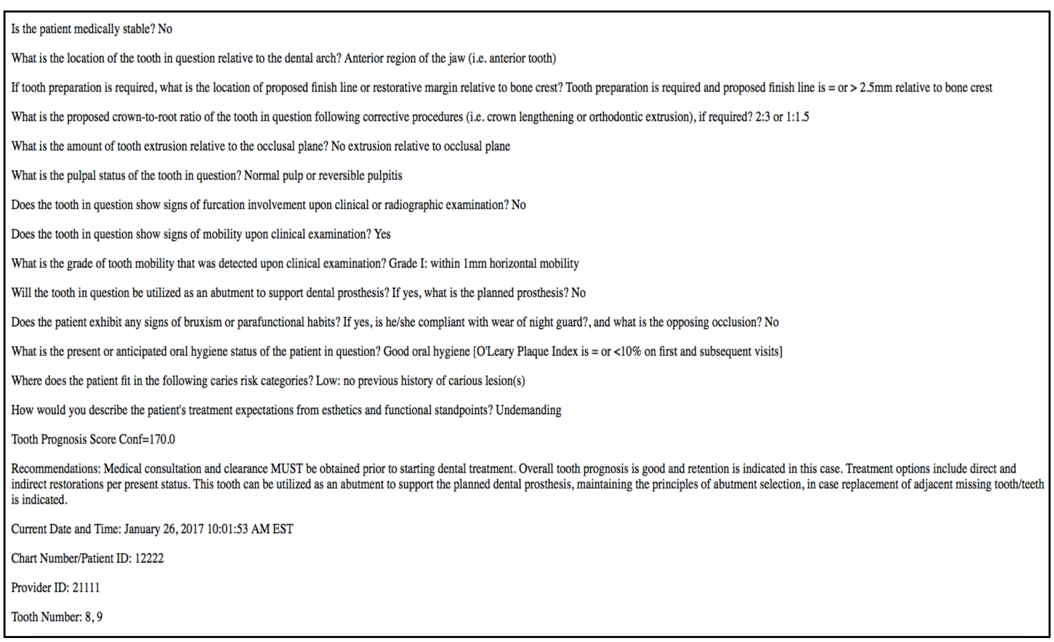
Step 15:



Step 16:



Results Screen:



Is the patient medically stable? No

What is the location of the tooth in question relative to the dental arch? Anterior region of the jaw (i.e. anterior tooth)

If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest? Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest

What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required? 2:3 or 1:1.5

What is the amount of tooth extrusion relative to the occlusal plane? No extrusion relative to occlusal plane

What is the pulpal status of the tooth in question? Normal pulp or reversible pulpitis

Does the tooth in question show signs of furcation involvement upon clinical or radiographic examination? No

Does the tooth in question show signs of mobility upon clinical examination? Yes

What is the grade of tooth mobility that was detected upon clinical examination? Grade I: within 1mm horizontal mobility

Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis? No

Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion? No

What is the present or anticipated oral hygiene status of the patient in question? Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]

Where does the patient fit in the following caries risk categories? Low: no previous history of carious lesion(s)

How would you describe the patient's treatment expectations from esthetics and functional standpoints? Undemanding

Tooth Prognosis Score Conf=170.0

Recommendations: Medical consultation and clearance MUST be obtained prior to starting dental treatment. Overall tooth prognosis is good and retention is indicated in this case. Treatment options include direct and indirect restorations per present status. This tooth can be utilized as an abutment to support the planned dental prosthesis, maintaining the principles of abutment selection, in case replacement of adjacent missing tooth/teeth is indicated.

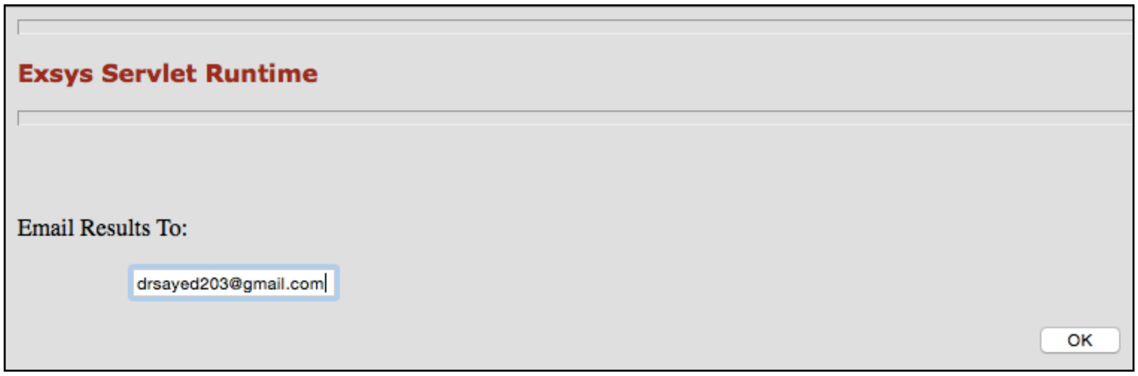
Current Date and Time: January 26, 2017 10:01:53 AM EST

Chart Number/Patient ID: 12222

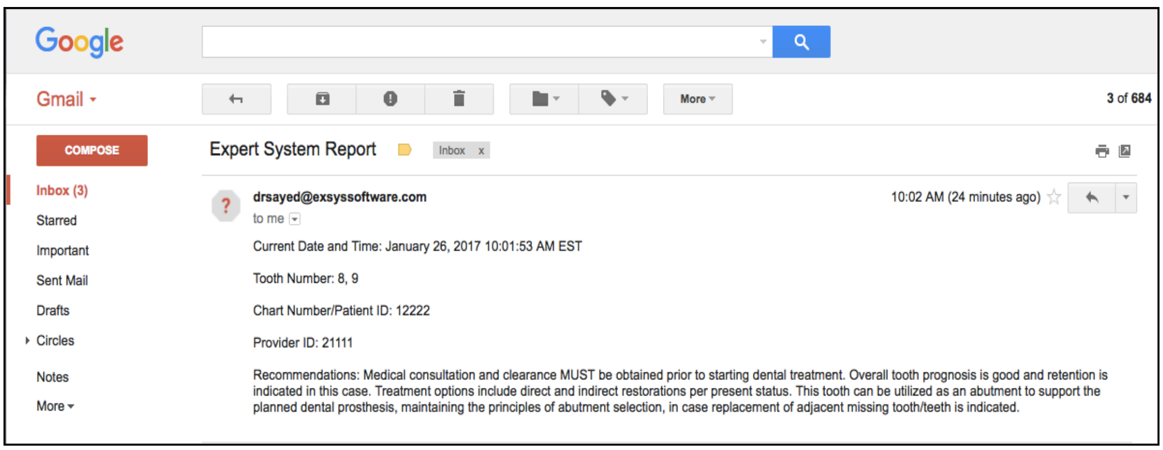
Provider ID: 21111

Tooth Number: 8, 9

E-mail Address Request:



E-mailed System Report:



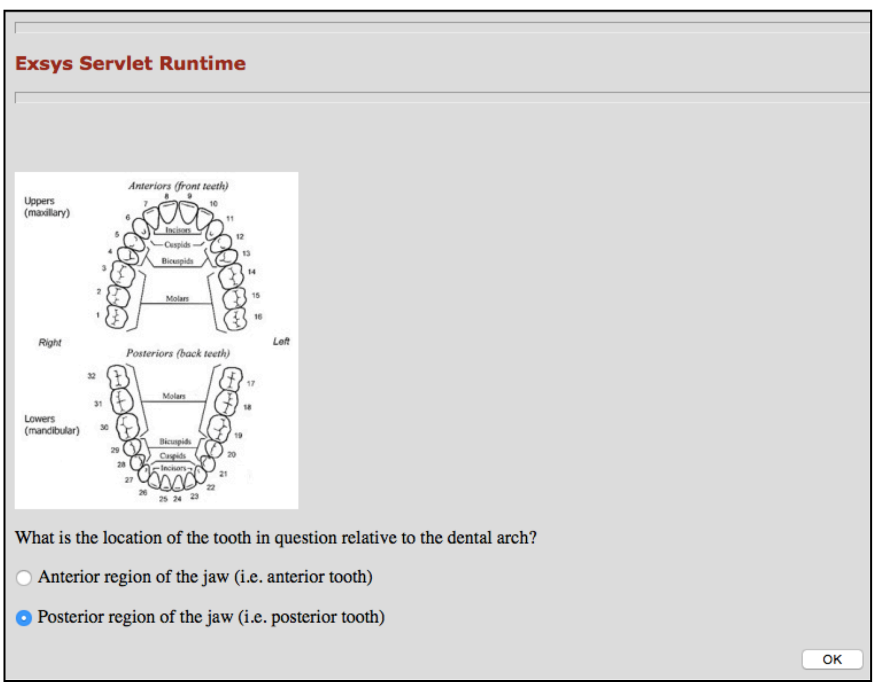
4. 3. Clinical Scenario#3 (posterior tooth, with shared-decision):

History and findings: This patient presented to the dental office for urgent care. His complaint is: "I have broken filling and want to replace it ASAP". Review of medical status revealed no significant findings. Clinical and radiographic examination revealed that tooth #19 is extensively restored and has broken MO composite restoration. It was root canal treated 3 years ago and currently showing peri-apical involvement, which indicates the need for RCRT. The tooth in question meets the minimum requirements to restore RCT teeth. The proposed C/R ratio is 1:1.5. No extrusion, mobility or furcation lesion was detected. The proposed finish line is more than 2.5mm away from bone crest. No carious lesion(s) was detected or developed on all teeth for a period of 3 years. This tooth is easily accessible and can be isolated for endodontic procedures. He has reasonable treatment expectations or demands, high-risk tolerance and reasonable financial ability. He showed good oral hygiene and compliance to instructions. Tooth #19 will be utilized to support RPD prosthesis. Neither bruxism nor parafunctional habits are present. Opposing occlusion is natural maxillary dentition.

CDSS Steps Showing Decision-Making Process and Final Treatment Plan Recommendation:

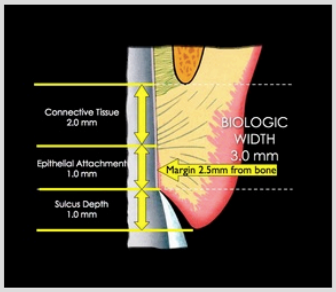
Step 1:

Step 2:



Step 3:

Exsys Servlet Runtime



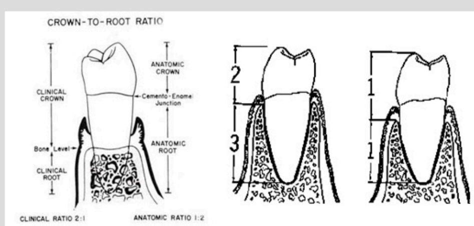
If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest?

- ○ No tooth preparation is required
- ● Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest
- ○ Tooth preparation is required and proposed finish line is < 2.5mm relative to bone crest

OK

Step 4:

Exsys Servlet Runtime



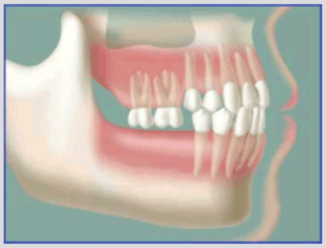
What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required?

- ● 2:3 or 1:1.5
- ○ 1:1
- ○ 1.5:1
- ○ 2:1

OK

Step 5:

Exsys Servlet Runtime



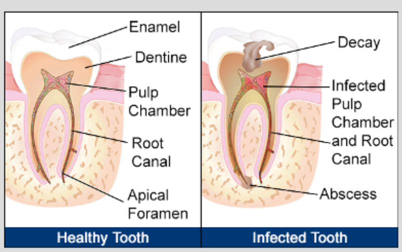
What is the amount of tooth extrusion relative to the occlusal plane?

- (●) No extrusion relative to occlusal plane
- ( ) < 2mm relative to occlusal plane
- ( ) = or > 2mm to < 6mm relative to occlusal plane
- ( ) = or > 6mm to < 11mm relative to occlusal plane
- ( ) > 11mm relative to occlusal plane

OK

Step 6:

Exsys Servlet Runtime

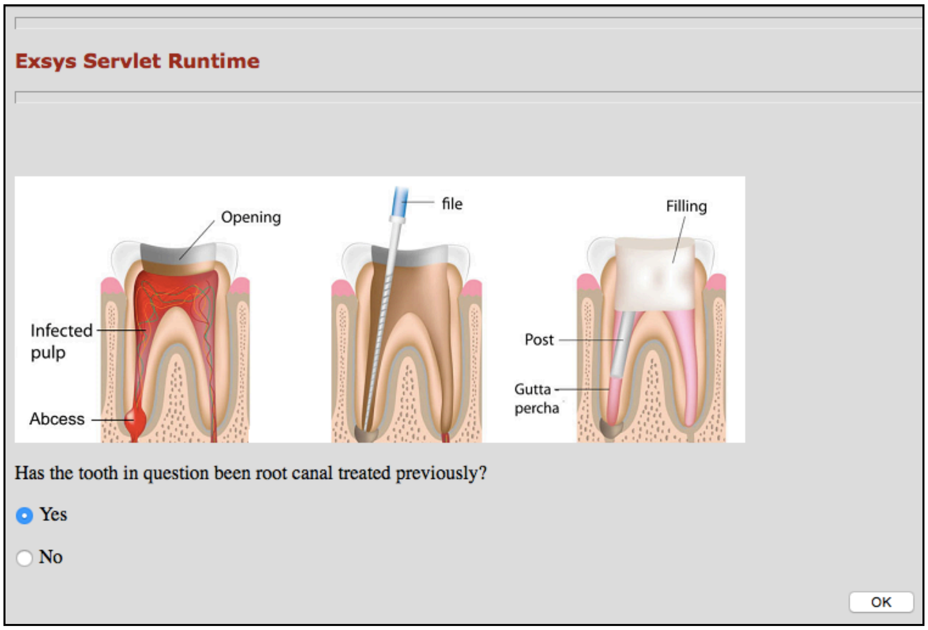


What is the pulpal status of the tooth in question?

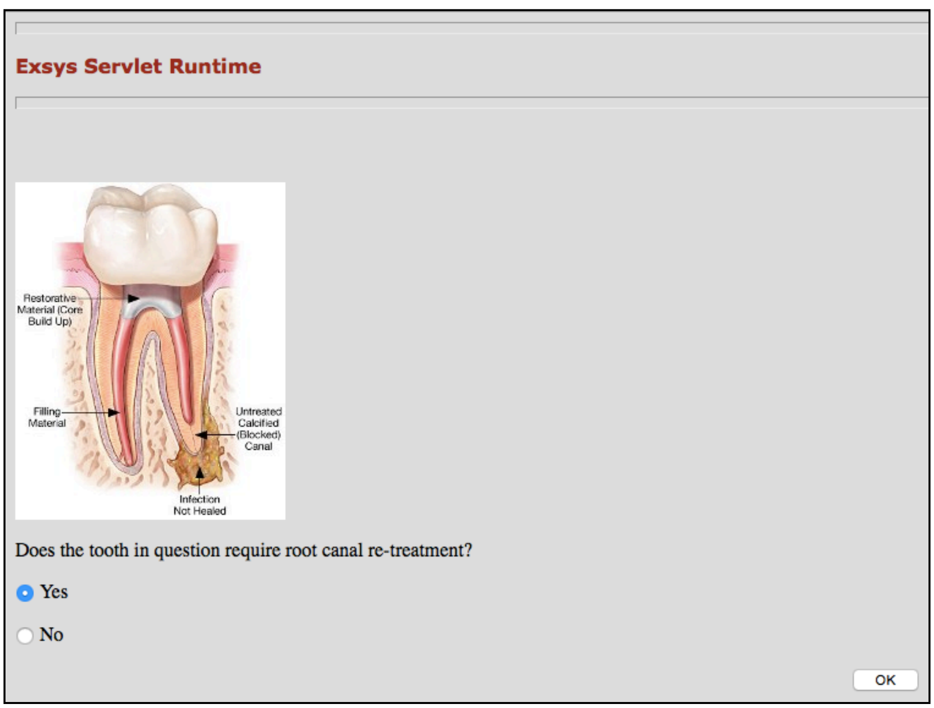
- ( ) Normal pulp or reversible pulpitis
- (●) Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required

OK

Step 7:

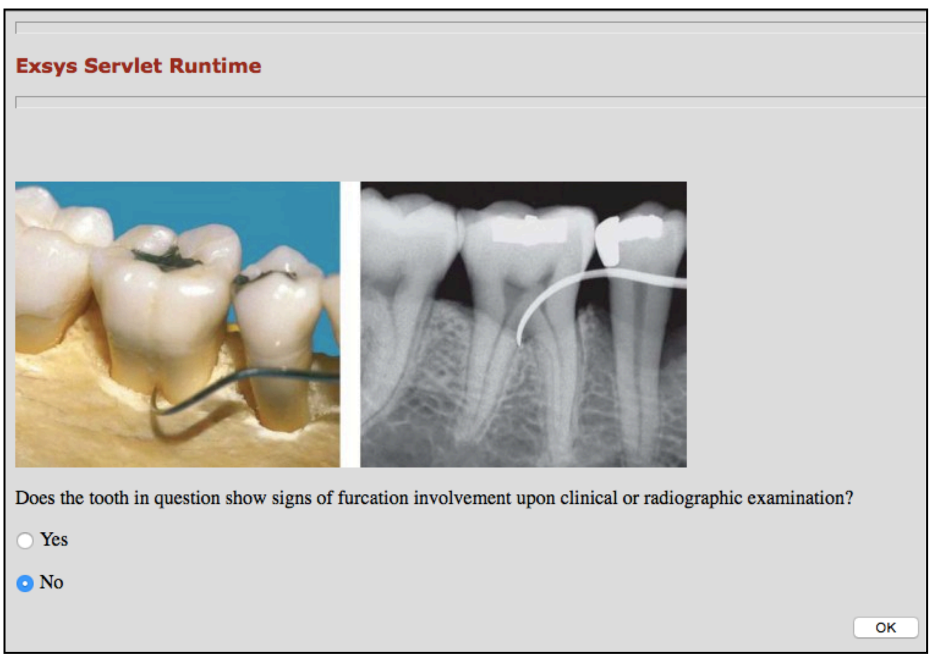

Exsys Servlet Runtime
Opening
file
Filling
Infected pulp
Post
Gutta percha
Abcess
Has the tooth in question been root canal treated previously?
Yes
No
OK

Step 8:

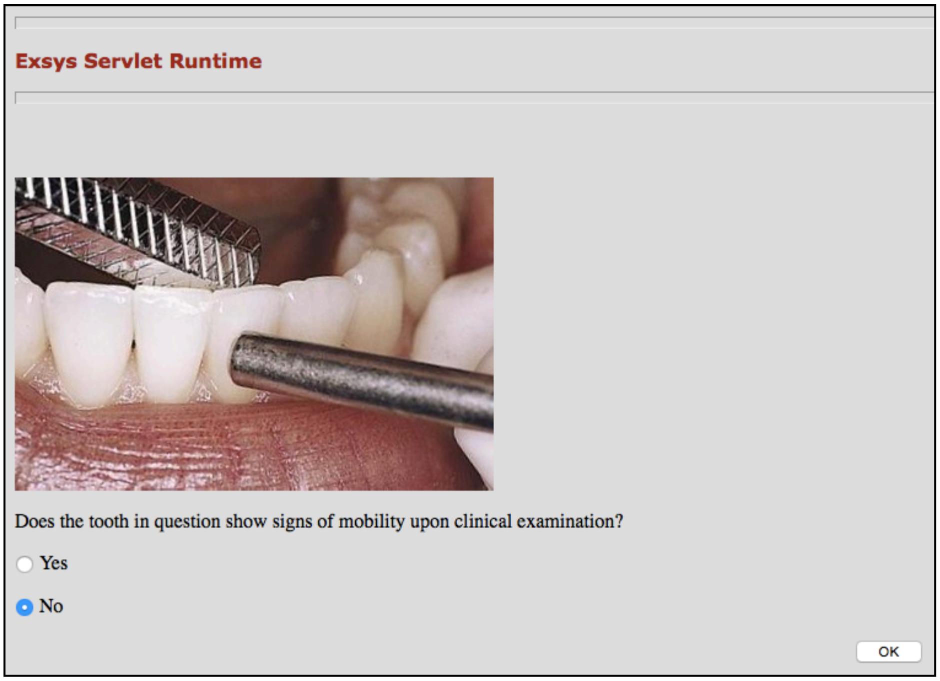

Exsys Servlet Runtime
Restorative Material (Core Build Up)
Filling Material
Untreated Calcified (Blocked) Canal
Infection Not Healed
Does the tooth in question require root canal re-treatment?
Yes
No
OK

Step 9:

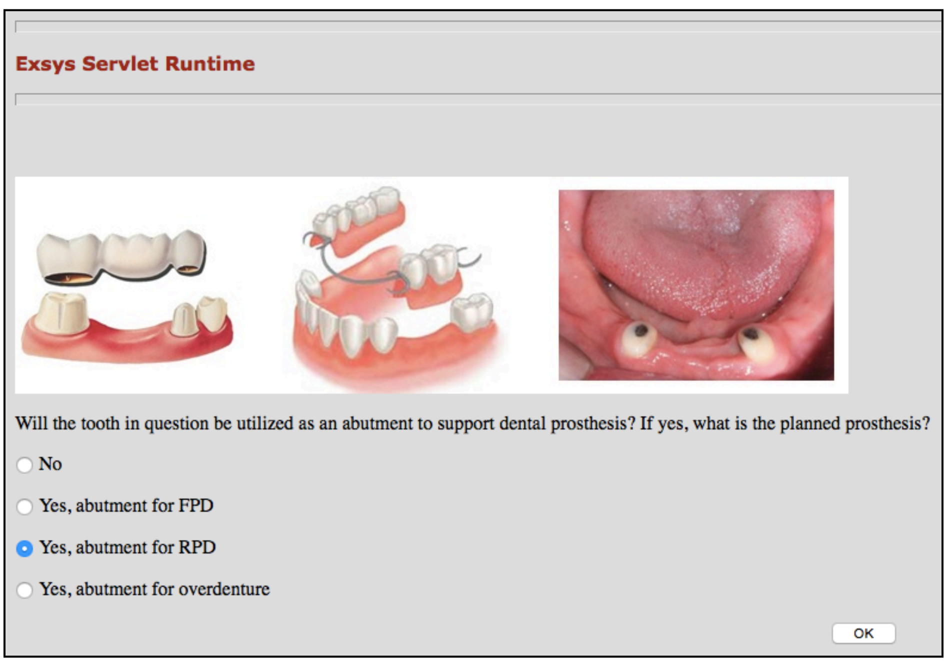
Step 10:



Step 11:



Step 12:



Step 13:

Exsys Servlet Runtime

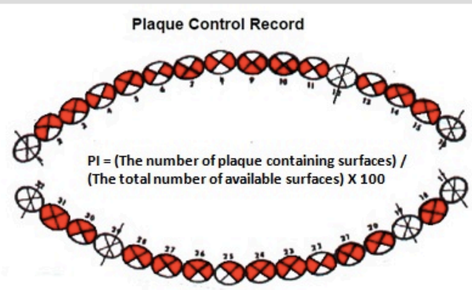
Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion?

- (●) No
- ( ) Yes, he/she is compliant and opposing occlusion is complete denture
- ( ) Yes, he/she is compliant and opposing occlusion is/are natural teeth, RPD, FPD or implant prosthesis
- ( ) Yes, but he/she is not compliant

OK

Step 14:

Exsys Servlet Runtime



What is the present or anticipated oral hygiene status of the patient in question?

- (●) Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]
- ( ) Poor oral hygiene [O'Leary Plaque Index is >10% on first and subsequent visits]

OK

Step 15:

Exsys Servlet Runtime

Where does the patient fit in the following caries risk categories?

- (●) Low: no previous history of carious lesion(s)
- ( ) Moderate: no carious lesion(s) developed in the past 3 years of recalls
- ( ) High: new carious lesion(s) developed within the past 3 years of recalls
- ( ) Extreme high: new carious lesion(s) developed within the past 3 years of recalls plus dry mouth
- ( ) Highest: is the same as extreme high category plus exposed roots

OK

Step 16:

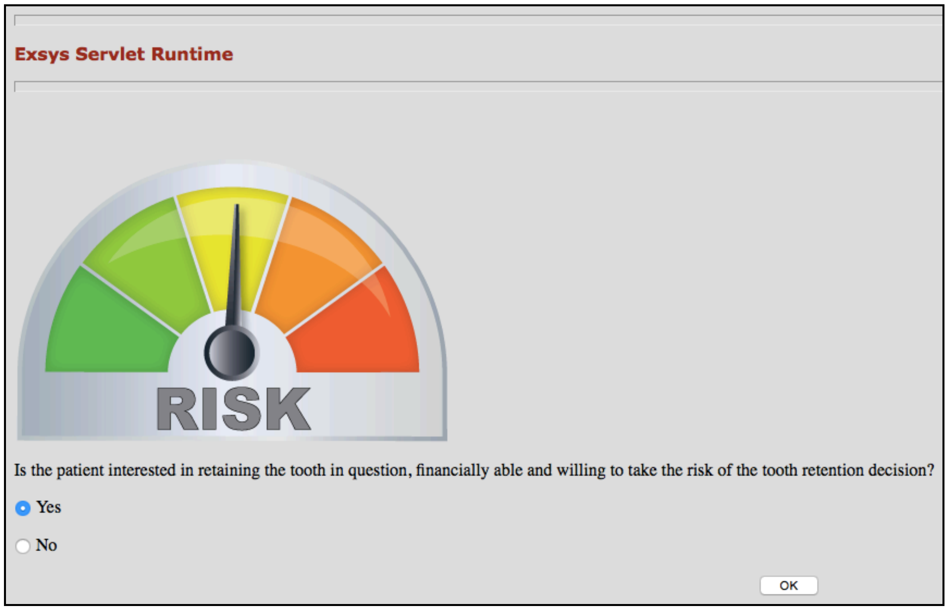
Exsys Servlet Runtime

How would you describe the patient's treatment expectations from esthetics and functional standpoints?

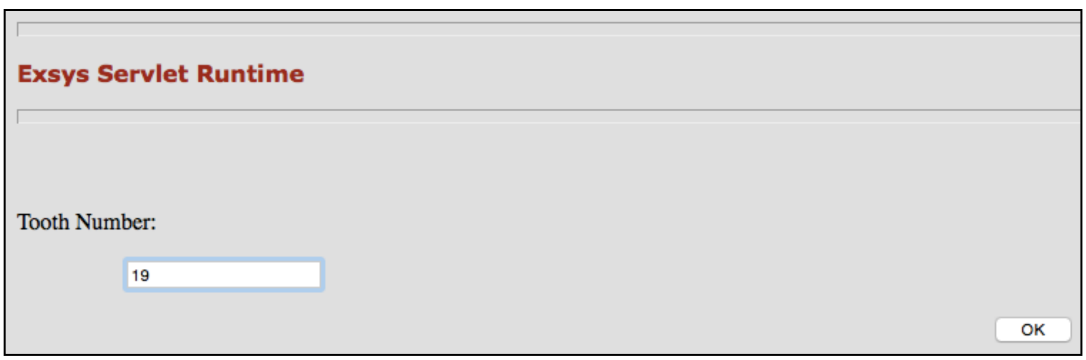
- (●) Undemanding
- ( ) Demanding

OK

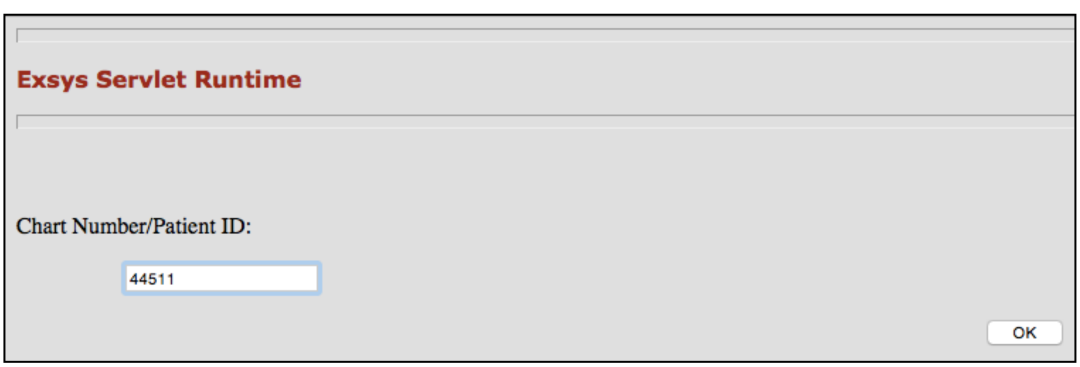
Step 17 (shared-decision step):



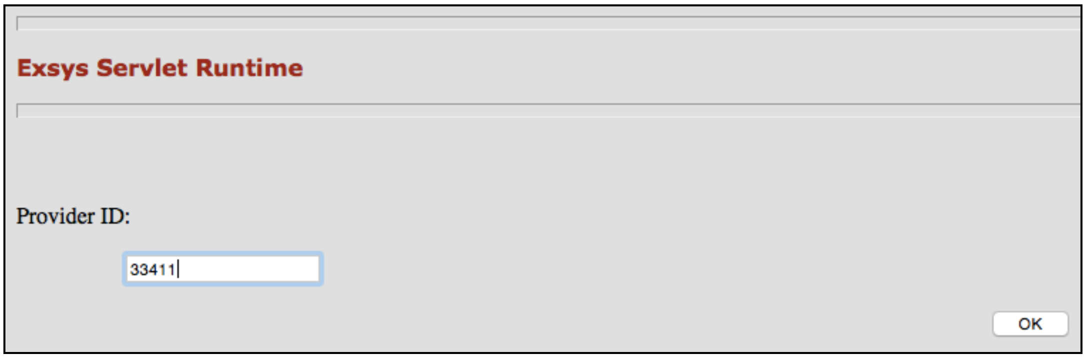
Step 18:



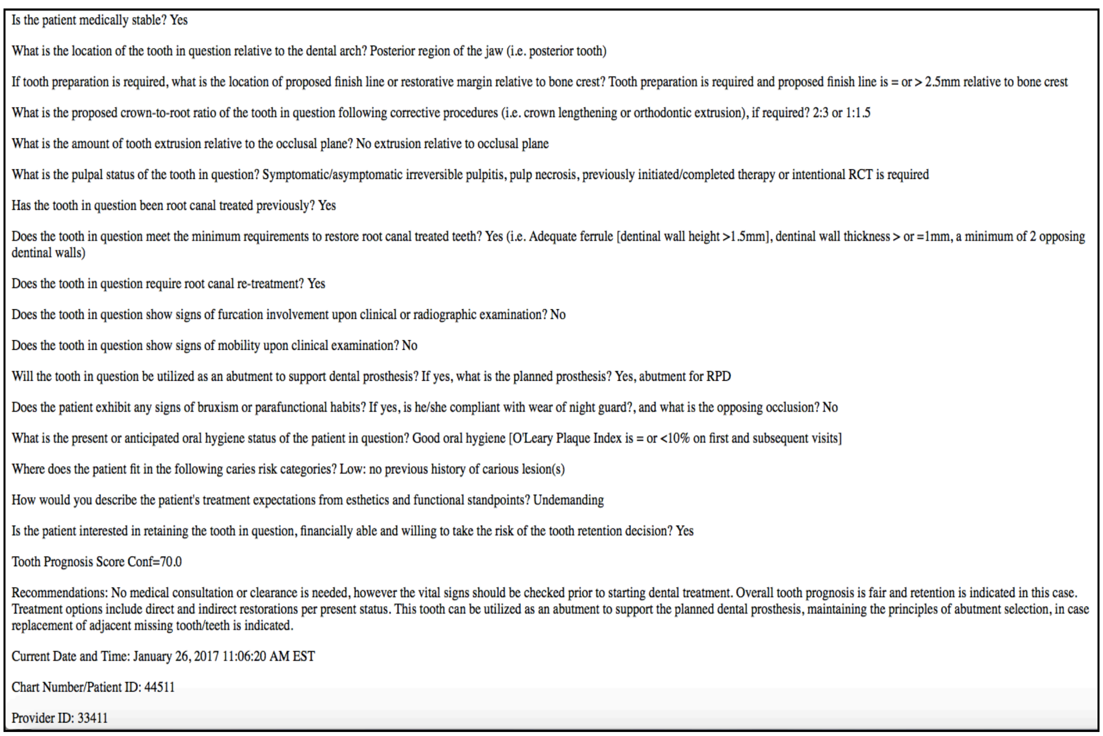
Step 19:



Step 20:



Results Screen:



Is the patient medically stable? Yes

What is the location of the tooth in question relative to the dental arch? Posterior region of the jaw (i.e. posterior tooth)

If tooth preparation is required, what is the location of proposed finish line or restorative margin relative to bone crest? Tooth preparation is required and proposed finish line is = or > 2.5mm relative to bone crest

What is the proposed crown-to-root ratio of the tooth in question following corrective procedures (i.e. crown lengthening or orthodontic extrusion), if required? 2:3 or 1:1.5

What is the amount of tooth extrusion relative to the occlusal plane? No extrusion relative to occlusal plane

What is the pulpal status of the tooth in question? Symptomatic/asymptomatic irreversible pulpitis, pulp necrosis, previously initiated/completed therapy or intentional RCT is required

Has the tooth in question been root canal treated previously? Yes

Does the tooth in question meet the minimum requirements to restore root canal treated teeth? Yes (i.e. Adequate ferrule [dentinal wall height >1.5mm], dentinal wall thickness > or =1mm, a minimum of 2 opposing dentinal walls)

Does the tooth in question require root canal re-treatment? Yes

Does the tooth in question show signs of furcation involvement upon clinical or radiographic examination? No

Does the tooth in question show signs of mobility upon clinical examination? No

Will the tooth in question be utilized as an abutment to support dental prosthesis? If yes, what is the planned prosthesis? Yes, abutment for RPD

Does the patient exhibit any signs of bruxism or parafunctional habits? If yes, is he/she compliant with wear of night guard?, and what is the opposing occlusion? No

What is the present or anticipated oral hygiene status of the patient in question? Good oral hygiene [O'Leary Plaque Index is = or <10% on first and subsequent visits]

Where does the patient fit in the following caries risk categories? Low: no previous history of carious lesion(s)

How would you describe the patient's treatment expectations from esthetics and functional standpoints? Undemanding

Is the patient interested in retaining the tooth in question, financially able and willing to take the risk of the tooth retention decision? Yes

Tooth Prognosis Score Conf=70.0

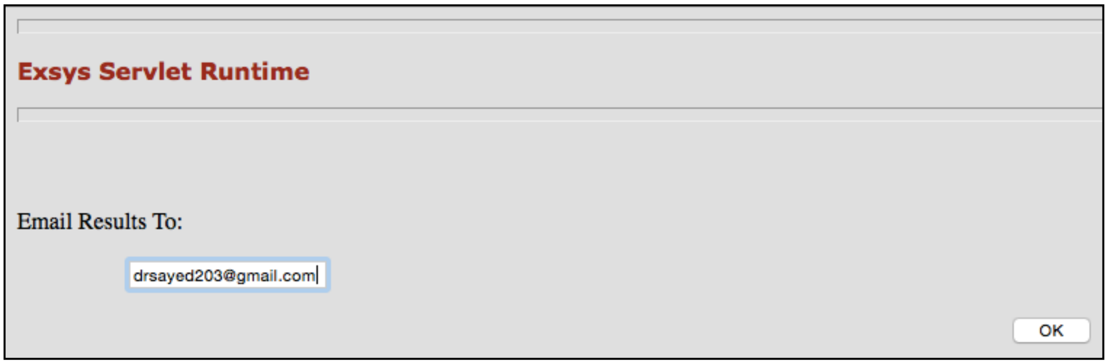
Recommendations: No medical consultation or clearance is needed, however the vital signs should be checked prior to starting dental treatment. Overall tooth prognosis is fair and retention is indicated in this case. Treatment options include direct and indirect restorations per present status. This tooth can be utilized as an abutment to support the planned dental prosthesis, maintaining the principles of abutment selection, in case replacement of adjacent missing tooth/teeth is indicated.

Current Date and Time: January 26, 2017 11:06:20 AM EST

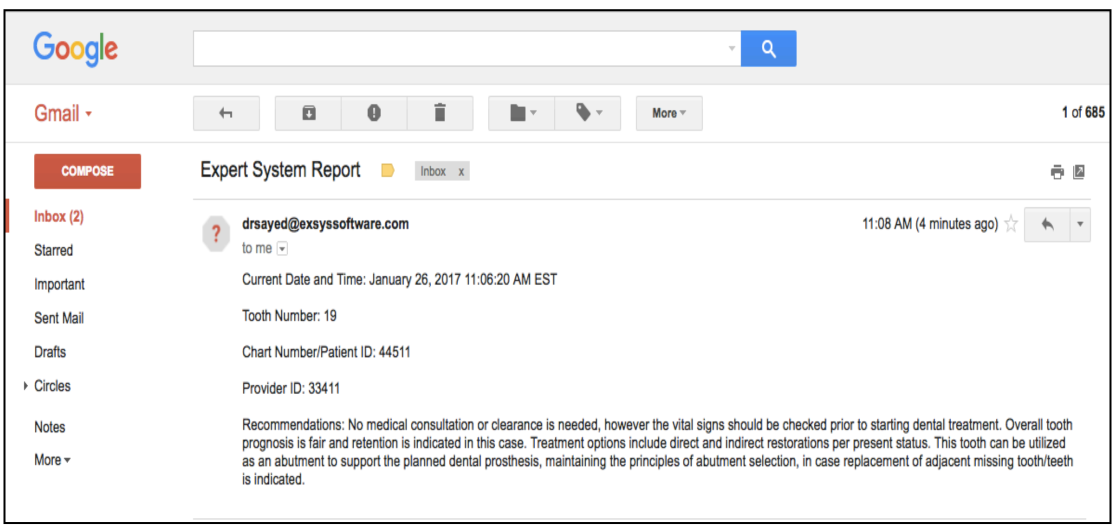
Chart Number/Patient ID: 44511

Provider ID: 33411

E-mail Address Request:



E-mailed System Report:



Chapter 5: Discussion, Conclusions and Future Directions

5. 1. Discussion:

Treatment planning is a multistep process that necessitates the analysis and evaluation of each tooth from prosthodontics (restorative), endodontic and periodontics aspects. Although, the majority of dental diseases that are affecting teeth and their surrounding tissues are mainly bacterial or infectious in nature, there are levels of etiological factors that are capable of affecting these tissues in variable degrees. Therefore, it is undeniably crucial to consider all relevant factors that may affect the individual tooth prognosis prior to intervention. Nonetheless, a clinician should keep in mind that such prognosis is often affected by the definitive treatment plan that includes the tooth itself in relation to adjacent and opposing dentition. Thus, individual tooth prognosis is not sufficient to determine the fate of the tooth in question. It is imperative for a clinician to determine the overall tooth prognosis considering all factors related to the tooth itself, whole dentition and patient in general.

The objective of our system is to organize available literature-based evidence and risk factors and combine it with the clinician's expertise and patient's desires and preferences to enable clinical decision-making as well as fast and efficient knowledge transfer to the providers and patients at the point-of-care. Our system is aimed to expand clinicians' professional expertise, not to take over and make decisions on its own. Even though the system was built with comprehensive list of factors, it is not anticipated to solve each and every clinical situation; however, it indeed extends widely to cover the majority of most common etiological and clinical factors, provides instant instructions and recommendations that are substantially consistent with clinical-experts opinions, experience and current evidence as well, and therefore it could be considered as a valuable and efficient tool for use in clinical setting.

Clinical decisions relative to retention or extraction can be very challenging, especially for dental students and novice dentists. Erroneous decision in this aspect of dentistry may lead to irreversible treatment (i.e. extraction), resulting in an increase in the cost for rehabilitating treatment, time consumption and loss of patient's trust and confidence. Heroic approach in saving non-salvageable teeth may often lead to the same outcomes indicated previously. Since our system can be implemented and accessed at the clinical operatory area, it can offer valuable assistance upon treatment planning that involves retention or extraction decision-making, especially when experts are not available on the clinical floor for consultation and guidance.

Since our system satisfies the concept of evidence-based dental practice, trailing the latest available evidence and guidelines, it can offer an educational platform to teach un-experienced dentists to think like experts, avoiding the need to memorizing all the factors and information relative to this particular aspect of decision-making. Such system teaches them to evaluate and judge challenging clinical scenarios in a holistic and comprehensive approach rather than concentrating on technical details, which in turn enhances treatment results and patient's satisfaction. The system's outcomes enable clinicians to justify each given treatment plan thus proactively helps in patient acceptance and commitment to the proposed treatment. It providers illustrative diagrams and images that facilitate ease of communication between providers and their patients. It also assists in explaining the most suitable treatment option and its corresponding outcomes. In case that proposed treatment options is not acceptable to the patient, the provider has the ability to make necessary changes in proposed treatment plan, given that these changes results in a viable plan and the patient is made aware of possible risks and long-term prognosis of the new plan. This interactive treatment planning approach ensures patient satisfaction, compliance, and commitment to the delivered dental care. Our system is proven reliable and user-friendly, which facilitate provider's acceptance and adoption into clinical practice.

Although, many CDSSs have been developed in the field of dentistry, there is still an outstanding need for an expert system that can efficiently assist in clinical decision-making with regard to retention or extraction of questionable teeth. The target for developing our system is to fulfill this outstanding need, since erroneous decisions in this area prove costly. Knowledge in dentistry emerges continuously, thus our system has the ability to continually be brought up-to-date to reflect knowledge developments.

5. 2. Conclusions:

The retention and restoration of extensively damaged or periodontally involved tooth, in comparison to extraction and prosthetic rehabilitation, is considered amongst the most challenging and multifactorial clinical decisions that dentists must make. Using the current Exsys Corvid development platform, we were able to develop an efficient and reliable computer-based tool to assist providers upon treatment planning sessions that involves retention or extraction decision-making. Our system can be launched on the web, easily accessed is on PCs, laptops, and smart devices either chair side or at distant locations. This feature allows the system to be easily integrated into clinicians' workflow. Since it is accessed from virtually all devices connected with the Internet, it can be inducted as a valuable educational tool to support and revolutionize the current academic armamentaria that are used for teaching. Such a tool helps students to develop critical thinking concepts that assist in analysis of challenging clinical problems rather than focusing on technical procedures alone to solve them. This system was designed to deliver instructions and recommendations that help to minimize decisions errors and therefore improve dental care. The results of the survey part of this project indicates that our system is in substantial agreement with experts in the field of prosthodontics who achieved the highest qualifications from the governing body of the specialty either in the US, Canada, or both. Since the system was developed by dentists for dentists, the system's outcomes are user-friendly, easy to understand, and able to provide recommendations that are applicable at the clinical setting.

Our system is flexible and scalable, allowing upgrade of the system's knowledge and rules as soon as new knowledge becomes available. Since the system utilizes a heuristic and goal-oriented approach, it analyzes the given scenarios carefully and provides the most accurate and suitable outcomes. The outcomes can be shared with corresponding patients and other healthcare providers. It can also be converted into PDF files where it can be signed and uploaded into the electronic health record system for documentation. Such documentation is important for medico-legal purposes and as an evidence for patient's understanding and acceptance. This professional conduct allows better work environment and transparent patient's healthcare process.

In addition to support in the decision-making process, our system were developed with the following features:

1. The system was designed to share the results, via email, with the patients and other healthcare providers. These results can be stored in EHR for future reference.

2. The system was developed with plenty of images and diagrams to ensure better understanding and communication between providers and patients.

3. The system was designed with custom results screen to display all case-relevant prompts along with their answers. This allows providers to review their inputs and rationalize proposed treatment options and recommendations to maintain an interactive treatment planning process between providers and patients.

4. The system was developed with a title screen that illustrates the objective of the system, year of development and specifies the targeted population who is eligible to use such a system.

5. The system was designed to automatically report the time and date of the treatment planning session and ask the end-users to input provider ID and Patient ID numbers for proper documentation and future reference.

Ultimately, the provider's experience and utilization of our system along with the common sense of the provider, is the suggested approach to guide in deciding whether to extract or retain a tooth.

5. 3. Future Directions and Recommendations:

Due to the fact that our system is both flexible and scalable, it presents a great potential for future development to address complex areas relative to the present clinical domain or other areas within the dental field to increase its adoption rate among clinicians and expand its clinical applications and versatility of use. We propose the following steps to achieve the aforementioned goals:

1. Even tough we have achieved an indirect method to connect between expert and electronic health record systems through report upload feature, a direct connection between the two systems may seems more logical and convenient. For instance, a system report can be transferred directly to the patient's account in the EHR system. Such feature will save time and help to avoid erroneous documentation.

2. Future integration of CDSSs with other image processing systems or interfaces that allow the system to read and analyze imported clinical photographs and radiographs in automatic fashion instead of manual entry of medical, dental history and current clinical findings. This integration will speed-up the decision-making process and increases adoption rates of expert systems

3. Efforts should be made to include expert systems into dental academic curriculum. Presently, developments in dental sciences are faster than ever, necessitating incorporation of this system as an efficient and user-friendly educational tool to supplement the conventional classroom-learning mode.

4. Ultimately, our system can be inducted into real-world clinical environment in order to be used by the targeted population upon treatment planning sessions that involve retention or extraction decision-making. Since validation was performed by expert clinicians only, a survey study is indicated to identify opinions and attitudes of dental students, general dentists and specialist toward the use of expert systems. A randomized controlled clinical

study is also needed investigate the efficacy of these systems to provide accurate recommendations and to compare among users and non-users clinicians.

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