DESIGNING CLINICAL DATA PRESENTATION USING COGNITIVE TASK ANALYSIS METHODS

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Despite the many decades of research on effective use of clinical systems in medicine, the adoption of health information technology to improve patient care continues to be slow especially in ambulatory settings. This applies to dentistry as well, a primary care discipline with approximately 137,000 practicing dentists in the United States. One critical reason is the poor usability of clinical systems, which makes it difficult for providers to navigate through the system and obtain an integrated view of patient data during patient care.

Cognitive science methods have shown significant promise to meaningfully inform and formulate the design, development and assessment of clinical information systems. Most of these methods were applied to evaluate the design of systems after they have been developed. Very few studies, on the other hand, have used cognitive engineering methods to inform the design process for a system itself. It is this gap in knowledge – how cognitive engineering methods can be optimally applied to inform the system design process – that this research seeks to address through this project proposal.

This project examined the cognitive processes and information management strategies used by dentists during a typical patient exam and used the results to inform the design of an electronic dental record interface. The resulting 'proof of concept' was evaluated to determine the effectiveness and efficiency of such a cognitively engineered and application flow design. The results of this study contribute to designing clinical systems that provide clinicians with better cognitive support during patient care. Such a system will contribute to enhancing the quality and safety of patient care, and potentially to reducing healthcare costs.

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1.0 INTRODUCTION

1.1 BACKGROUND

In its landmark report *"The Computer-Based Patient Record: An Essential Technology for Health Care"*, the Institute of Medicine (IOM) eloquently formulated a vision for electronic health records (1). Several subsequent reports have addressed how health information technology (HIT) can reduce medical errors and increase health care quality (2, 3). To improve patient safety and quality of care, the IOM recommended two strategies: 1) improve access to accurate and timely information about the patient, and 2) make relevant information available at the point of care. At this time, the US has committed significant resources to a headlong pursuit of the national implementation of health information technology. While this strategy promises significant benefits and opportunities going forward, it is less clear whether the current design of HIT applications actually fulfills the IOM's vision for the adequate support of health care providers' clinical decision-making.

Recently, several scientific reports suggested that simply implementing state-of-the art clinical information system does not improve the quality of patient care, patient safety or even time efficiency (4-10). Computerized provider order entry system, the most commonly implemented and studied systems have been shown to reduce medication errors and increase patient safety. However, reports also suggest that these systems sometimes facilitate unintended consequences and adverse events such as new kinds of medication errors, new work for clinicians, unfavorable workflow issues, negative emotions and untoward changes in communication and practices. Poorly designed interface components such as cluttered screens, fragmented data across different screens, dense pick lists and complex application flow designs, are major reasons for these unintended adverse consequences. As a result, these systems fail on their objective, users become dissatisfied and they are withdrawn from use (11-13).

One major flaw in the design of interfaces is a mismatch between the visual presentation of information and the actual information processes of the clinicians' as they formulate a patient's problem. Previous studies indicate that information acquisition and decisions are strongly influenced by the way the content is presented (14). Errors occur due to poor information design because the person who is viewing the data has to concentrate not just on the content but also on locating the information. This additional work causes a strain in the cognitive processes of perception, attention and memory, increases the chances of making errors and omissions, and users becomes frustrated with performing their tasks. Empirical research indicates that information designs based on the clinicians' cognitive and information processes could result in effective and efficient systems that provide cognitive support during patient care and thus have the potential to improve the quality and safety of patient care (15). Therefore, there is a growing need for health informatics research to focus not just on "outcomes-based evaluation, but also on analyzing usage behavior to reveal the cognitive, behavioral and organizational factors that led to sub-optimal results and caused many HIT implementations to fail" (16). In a study conducted by The Committee on Engaging the Computer Science Research Community in Health Care Informatics (2009)(17), the investigators identified the challenge of presenting clinical data that facilitate the clinicians' formulation of a patient's problem as a critical component for improving patient care through HIT. Considering the impact of well-designed interfaces on the effectiveness and safety of patient care, I want to devote my research to improving the interfaces of clinical information systems in order to provide effective and efficient patient-centered cognitive support at the point of care.

1.2 PROBLEM DESCRIPTION

Despite the many decades of research on effective use of clinical systems in medicine, very little is known about developing and implementing effective systems in ambulatory settings, where most health care is delivered. This applies to dentistry as well, a primary care discipline with approximately 137,000 practicing dentists in the United States. The adoption of health information technology to improve patient care continues to be slow and limited even though more than 95% of dental offices use HIT for administrative purposes. One critical reason is due to the poor usability of dental clinical systems (18-23) that makes it difficult for providers to navigate through the system and obtain an integrated view of patient data during patient care and decision-making activities. The objective of this project was to evaluate empirically whether performing cognitive engineering methods prior to design can help improve the interface of an electronic dental record. The overall research question was, “Will a prototype designed on the basis of the cognitive engineering methods supports the clinicians' review, diagnosis and treatment planning of a patient case better than a system that is not designed using such methods?” To answer this question, the cognitive processes and information management strategies used by dentists during a typical patient exam were studied and the results used to inform the design of an electronic dental record interface. The resulting 'proof of concept' system was comparatively evaluated to determine users' perceptions of information organization, navigation and usability against a commercial electronic dental record system used in academic institutions (henceforth referred as cEDR in the document). The following three research questions were answered during the three phases of this project.

1. What is the pattern of information review, processing and decision-making when dentists examine new patient cases?
    a. What information sources do dentists retrieve and in what sequence when examining patient cases of varying complexities?
    b. What information do dentists use to make clinical decisions and how do they use it?
    c. What cognitive processes characterize a dentists’ information management and decision-making activities when examining patients?
2. What is the sequence of activities and roles of the dental team members during data acquisition, data entry and retrieval?
3. How does the DMD Prototype differ from cEDR in supporting clinicians' review, diagnosis and treatment planning of a patient case with regard to information organization, navigation and usability?

1.3 SIGNIFICANCE OF THIS RESEARCH

Cognitive science methods have shown significant promise to meaningfully inform and formulate the design, development and assessment of clinical information systems and decision support technology. Most of these methods were applied to evaluate the design of systems after they have been developed (24-40). Very few studies, on the other hand, have used cognitive engineering methods to inform the design process for a system itself (15, 41-43). It is this gap in knowledge - how cognitive engineering methods can be optimally applied to inform the system design process - that I addressed through this dissertation research. The results of this study will contribute to designing clinical systems that provide clinicians with better cognitive support during patient care. Such a system will contribute to enhancing the quality and safety of patient care, and potentially to reducing healthcare costs.

1.4 GUIDE FOR THE READER

Chapter 1 consists of the introduction and background for this research, a general description of the project and a statement of the overall significance of this research

Chapter 2 provides a description of the history of early HIT systems and discusses barriers to using HIT systems in clinical settings. Since this dissertation focuses on improving data presentation using cognitive task analysis methods, this chapter describes human factors barriers in detail and the impact of HIT on ambulatory settings specifically dentistry.

Chapter 3 discusses studies conducted on the adoption and use of electronic health records in dentistry. This chapter discusses specifically the survey results on the adoption and barriers to using dental electronic health records, results of usability evaluation of commercial dental electronic health records and finally adoption and users' perception on using dental electronic health records in dental schools.

Chapter 4 discusses the user-centered design and cognitive engineering methods employed during the design and evaluation phases of HIT. The chapter discusses specifically, two early projects that used user-centered design methods, their drawback and the subsequent human-computer interaction methods developed by Patel, Kushniruk, Zhang and colleagues. Finally, this chapter discusses the cognitive science studies conducted to develop anesthetic simulators and training systems in radiology and pathology that paved the way to its application to evaluate and redesign HIT.

Chapter 5 describes the studies that employed cognitive engineering methods to evaluate existing clinical systems to support the redesign phases of these systems.

Chapter 6 describes the significance of applying cognitive engineering methods to inform the design of clinical systems and includes an overview of the literature of empirical studies attempting to apply cognitive engineering methods that guide the design of clinical systems.

Chapter 7 describes the proposed dissertation research project including the research objectives and questions, research design and methods including the study participants, the study method, data collection methods, verbal protocol analysis and data analysis methods.

Chapter 8 describes the results of the four studies in this research.

Chapter 9 discusses the study results, the study limitations and finally the conclusion.

2.0 HISTORY OF HEALTH INFORMATION TECHNOLOGY AND BARRIERS TO ITS SUCCESS

2.1 THREE GENERATIONS OF CLINICAL SYSTEMS

Pioneers of biomedical informatics began thinking about how computers could support clinical care as early as 1958 (44-47). Their goal was to integrate information from different sources and thus enable clinicians to use information more efficiently and effectively in patient care (44-47). While this goal has not changed over the years, the approaches for achieving it have changed. William Stead described three distinct generations of work (48) in the evolution of clinical information systems over the last four decades. The first generation focused on the narrow issue of data capture and retrieval for specific purposes, the second addressed integrating information from multiple systems and the third extended that vision towards seamless interoperability.

While the primary motivation of this work was to improve clinical care through automation, first generation systems emphasized data and functions, rather than the cognitive needs of care providers. For instance, the automated history taker developed at Duke University in 1970 allowed patients complaining of headaches to enter their clinical history and provided physicians with potential diagnoses (49). However, physicians rejected the system because it provided help in differential diagnosis, an area in which they felt they did not need help (49). Second-generation systems began to interface different information silos, such as registration, admitting, discharge and transfer, and pharmacy and laboratory information systems (48, 50). While data began to be communicated among these systems using interoperability standards such as Health Level Seven International HL7, it was up to the end user to review data in different systems, and integrate them with the specific task and work context. *StatLan* is an example of a second generation project where a single user interface provides access to the information about a patient from each participating system (51). Third generation projects began to separate data representation from the associated information systems, mainly through standardization using controlled terminologies and ontologies. In this context, ontology refers to an explicit representation of the concepts that system builders define to exist in a particular domain (48). For instance, data and knowledge that reside outside a system are linked to the data and work processes that reside within the system. The *Unified Medical Language System* (UMLS) (52) is an example of a third-generation project. In these systems, however, end user concerns were still secondary (44).

2.2 IMPACT OF HIT ON CLINICAL CARE PROCESSES

The three generations of work described by Stead significantly improved the clinical care processes by introducing more efficient communication and automation than in the past. These projects resulted in speedier order completion and treatment delivery, as well as opportunities to inform or remind physicians about the benefits and costs of providing a specific treatment. The advanced features of electronic health records, such as disease management programs and other clinical decision support systems, improved guideline adherence and reduced the gap between the knowledge and practice of applying preventive management guidelines (10, 53).

Several early studies were successful in changing clinician behavior through clinical decision support systems and computerized reminders (54, 55). The studies reported statistically significant improvements in reducing adverse drug events by achieving therapeutic drug levels and effective titration of potentially toxic drugs. Clinical decision support systems and computerized reminders also enhanced preventive management by issuing timely reminders for vaccinations, breast cancer screening, colorectal cancer screening and cardio-vascular risk assessment. However, these capabilities were most effective in homegrown systems, which were developed over a long period and in institutions where there was a close relationship between computer scientists and physicians. These homegrown systems were primarily in four major institutions: 1) Computer-Stored Ambulatory Record (COSTAR) developed at the Laboratory of Computer Science of Massachusetts General Hospital; 2) The Medical Record (TMR) developed at Duke University; 3) Regenstrief Medical Information System (RMIS) at Indiana University and 4) HELP developed at LDS Hospital, Salt Lake City (45). In contrast, commercially developed systems when implemented in hospitals or academic centers either faced stiff resistance from clinicians or failed (54). Three factors contributed to these outcomes: the drastic change imposed on the workflow of clinicians, literal interpretation of rules by the computer and the lack of understanding of the long-term value of HIT within physician community (44). The new workflow bypassed unit clerks and nurses and forced physicians to enter all orders themselves. They were also forced to sign every verbal order before the system could accept an order. In addition, the quality and user friendliness of HIT became a huge concern because it required increased time to learn and use the system.

2.3 BARRIERS TO SUCCESS OF HEALTH INFORMATION TECHNOLOGY

Despite achievements in improving the clinical care processes, HIT implementations often failed to meet desired expectations when introduced and used in clinical settings (56). Reasons included the increased time needed to enter and review patient data and the altered workflow and work processes (9, 57) when HIT is introduced in clinical settings. The failure to provide effective HIT systems that match clinical needs and work processes resulted in increased clinician frustration and resistance to use HIT, which was first reported by Friedman and Gustafson in 1977 (58). Subsequently, a survey conducted by Teach and Shortliffe in 1981 demonstrated clinicians' negative attitudes towards using computers in clinical settings (59). In one case, physicians resisted to a degree that forced the management at Cedars-Sinai hospital in Los Angeles to turn off a computerized provider order entry within months of implementation. At the same time, a survey in the United Kingdom demonstrated that clinicians were enthusiastic users of other new technologies (60). This observation showed that clinicians are ready to use technologies that meet their needs and are useful to them. Based on these results, informatics researchers concluded that for an HIT application to be successful, "clinicians must perceive a need for some assistance, the system must fulfill that need, the system must parallel the clinicians' reasoning process and the system must provide an efficient and intuitive user interface" (58, 59).

2.3.1 Human Factors: A Major Challenge to Success

Human factors issues emerged as a major challenge to using HIT in practice and led to many system failures in clinical practice (61). Human factors issues fell into two basic categories: 1) technology-induced negative changes in workflow and processes and 2) lack of support for the cognitive requirements of clinicians and their staff (61). The first problem is related mainly to the organizational infrastructure and has been studied extensively during the last two decades (11-13, 62). These studies resulted in the realization that "changing systems means changing behaviors", thus making individual and organizational change an essential factor for successful health IT implementations (63). However, these changes referred more to changing health care providers' behavior in adopting HIT through training than on assessing work practices in the context of HIT and its users (61). The second problem involved cognitive issues because, in general, HIT interfaces performed a relatively poor job of supporting health care providers' needs for information review, analysis and decision-making.

A survey conducted by Teach and Shortliffe suggested that physicians preferred systems that 1) aided clinical practice to those that automated clinical activities, 2) paralleled the physician's reasoning processes when working through a problem, and 3) were easy to learn with natural interactive capabilities (59). In 1987, Ted Shortliffe identified human-computer interaction as an important issue for clinical systems and proposed that it is not just the content but also the presentation of information on the screen that is crucial for the success of a clinical system (64). Van Bemmel and other pioneers in medical informatics agreed that user interface was one of the most significant challenges in medical informatics (65-67). Two major problems that human factors issues cause for clinical care processes are 1) a steep learning curve, and 2) unintended adverse events during HIT implementations and use. These two problems are addressed next.

2.3.2 Steep Learning Curve for Health Information Technology

The increasing complexity and functional scope of clinical information systems require that users receive in depth training and accumulate significant experience working with the system. For many, this is not practical because clinicians are always running against time to complete their clinical work (68, 69). As a result, users are forced to learn the system "on the job," which causes delays and potential medical errors during patient care (39, 69). These findings were confirmed in a study that evaluated the information management strategies of providers in ten sites where a Computerized Provider Entry System (CPOE) to enter orders had been deployed for over four years (39). The authors observed various strategies that providers used to adapt to the computerized information environment. They concluded that the CPOE caused significant information overload for users, who, as a result, developed work-arounds to minimize cognitive overload, enhance accuracy, recall important information and to negotiate responsibility (39).

2.3.3 Unintended Adverse Consequences

Recent studies have demonstrated that HIT applications can cause unintended adverse consequences in clinical settings (70). These adverse events included unfavorable workflow issues, medication errors and even increased mortality rates. Causes for such events were traced mainly to human-computer interaction design problems. Overly cluttered screen designs and fragmentation of data across multiple screens made it difficult to obtain an overview of a patient record (4, 71-74). This design increased the cognitive load for clinicians' who often missed key information required to make decisions. Cumbersome interfaces forced nurses to delay medication charting until the end of their shifts, which caused inaccurate recording of medication times and dosage, inappropriate duplication of prescriptions, less efficient communication between physicians and nurses and reduced efficacy of software checks (7).

These results indicate that clinical systems are yet to be designed to represent medical information intuitively to clinicians (6, 74, 75). Significantly, the United States Joint Commission on Accreditation of Healthcare Organizations recognized these problems and issued a sentinel alert in December 2008, which warned of technology-related adverse events (76).

2.4 CAREFUL DESIGN TO ELIMINATE COGNITIVE OVERLOAD

In order to try to avoid user frustration and misuse, HIT applications need to be carefully designed to minimize cognitive overload. This can be done by automating routine tasks and displaying context-relevant information in formats that require minimal interpretation or mental manipulation for immediate, direct use (74, 77, 78). Empirical studies reported that clinical performance improved when information displays matched the users' mental models and their clinical work processes (78). Clinicians then are able to focus their attention completely on the patient's problem and are able to devote all cognitive resources toward clinical reasoning, strategy and treatment planning (26).

Researchers also have argued that user interface in health care should exploit the findings from the psychology literature that humans are much better at recognizing than at recalling information from memory (79). These insights into good design have been available at least since the 1970s and have led to the application of techniques and methodologies adapted from applied cognitive psychology to study human-computer interaction. However, they have yet to become widely accepted methods for the design of clinical systems.

2.5 HEALTH INFORMATION TECHNOLGY IN DENTISTRY AND OTHER AMBULATORY CARE SETTINGS

Despite several decades of research on decision support systems in medicine, little is known about how to create and implement effective systems in ambulatory settings, where most health care is delivered (54, 80). In these settings, effective use of the health information technology continues to be a challenge (81, 82). A systematic review of the effects of health information technology on the quality, efficiency and costs of care demonstrated that most studies were performed in four "benchmark" institutions – Regenstrief Institute, Brigham and Women's Hospital/Partners Health Care, the Department of Veterans Affairs, and LDS Hospital/Intermountain Health Care – and in other major institutions, where internally designed systems were evaluated over time (54). However, it is difficult to generalize the results of these studies to ambulatory care settings because HIT tools support the delivery of care and they do not change the states of disease or of health. Therefore, it is crucial to learn how HIT systems are used and the context in which they are used. As a result, more studies are needed that address organizational change, workflow redesign and human factors issues to realize benefits of HIT in ambulatory settings.

The scant literature on designing and implementing informatics interventions in ambulatory settings applies to dentistry as well, a primary care discipline with approximately 137,000 practicing dentists in the United States. Moreover, the adoption of health information technology to improve patient care continues to be slow and limited even though more than 95% of dental offices use HIT for administrative purposes. One critical reason is the poor usability of dental clinical systems (18-23), making it difficult for providers to navigate these systems and to obtain an integrated view of patient data during patient care and decision-making activities. Four studies conducted by the Center for Dental Informatics at the University of Pittsburgh School of Dental Medicine have yielded evidence that usability problems may be an important factor in retarding the adoption of EHR systems by dental practitioners.

2.6 CHAPTER SUMMARY

Attempts to design and develop HIT, and to implement them effectively in clinical settings, have had mixed success. Automation has enhanced the speed of administrative activities and can facilitate efforts to improve adherence to guidelines. However, research indicates that clinicians often find these information systems to be non-intuitive and intrusive, rather that helpful. Major system design barriers have been identified through studies on the adoption and rejection of early clinical systems. They point to the need for ensuring that a system integrates well with clinical processes, does not add significant cognitive load, and effectively addresses human factors requirements. History further suggests that the design of effective and efficient HIT systems for dentistry and other ambulatory medicine settings may be particularly challenging.

3.0 ADOPTION AND USE OF ELECTRONIC HEALTH RECORDS IN DENTISTRY

Until recently, little was known about the adoption, use and effectiveness of electronic health records (EHR) in dentistry. According to data from the American Dental Association, as of 2006, the majority of dentists in the U.S. used the computer in their offices for patient accounting and billing (93.6%), processing insurance forms (90.9%) and scheduling patients (82.9%). Thirty-seven percent reported that they used the computer to maintain patient records and 31% to download or print patient education information. With a telephone survey of a national, randomized sample of 102 general dentists in 2006, the Center for Dental Informatics (CDI) at University of Pittsburgh obtained a much more differentiated picture of the adoption, usage, attitudes and opinions regarding clinical computing (20). This study showed that 25% of all general dentists in the U.S. use computers in the clinical environment (i.e., in the dental operatory), and that approximately two percent maintain completely electronic patient records.

3.1 BARRIERS AND POTENTIAL IMPROVEMENTS

We also surveyed respondents on the features of the electronic health record systems they disliked, the perceived barriers to using them and potential improvements needed for making the systems more useful (20). While over one-fourth of the respondents (26%) could not identify any features they disliked, 15% each placed functionality and usability of their systems as significant features they disliked. Major barriers to clinical computing identified by respondents included insufficient operational reliability (such as crashes) (16%), functional limitations of the software (14%) and the learning curve (14%). Several of these findings are reported in other surveys as well (83, 84). When asked how clinical systems could be improved, the top three responses were “better input methods” (37%), “smaller computers in dentistry” (15%) and “better user interface design (10%).

3.2 HEURISTIC VIOLATIONS IN DENTAL ELECTRONIC HEALTH RECORDS

Based on the results of the survey study (20),investigators at the University of Pittsburgh Center for Dental Informatics decided to evaluate the human-computer interfaces of the four market-leading dental electronic health records (EHR) using heuristic evaluation and usability tests (21, 22, 85) (Heuristic evaluation refers to an evaluation method where expert reviewers judge the user interface and system functionality to determine whether they conform to established principles of usability and good design (86, 87). Usability testing refers to the "evaluation of information systems that involves testing of participants who are representative of the target user population as they perform representative tasks using an information technology in a particular clinical context" (86). The four systems were *Dentrix* [DX], Version 10.0.36.0 [Dentrix, America Fork, Utah]; *EagleSoft* [ES], Version 10.0 [Patterson Dental, St. Paul, Minn.]; *SoftDent* [SD], Version 10.0.2 [Kodak Dental Systems, Atlanta]; and *PracticeWorks* [PW], Version 5.0.2 [Kodak Dental Systems]. The heuristic evaluation of the four systems (22), revealed 229 heuristic violations, primarily in the categories of “consistency and standards” (ensuring that identical data and functions can be perceived as such), “match between system and the real world” (representing data and functions on the computer in words, concepts and representations familiar to users) and “error prevention” (reducing opportunities for users to make errors). Both “consistency and standards” and “match between system and the real world” are heuristics that have a significant influence on a novice user’s ability to understand a system (26, 27, 88), lending credibility to the survey participants’ assertion that dental Electronic Health Record (EHR) systems are hard to learn to use. The 41 violations related to the error prevention heuristic suggested that use of the systems might result in frequent errors.

3.3 USABILITY PROBLEMS IN DENTAL ELECTRONIC HEALTH RECORDS

In the third CDI study, a usability evaluation was conducted of the same four major dental EHRs by using a purposive sample of four groups of five novice users (21). The objective of this study was to determine the intuitiveness of clinical charting functions when used by novice users. We measured task outcomes (correctly completed, incorrectly completed and incomplete) in each EHR system when the participants performed nine clinical documentation tasks (see Table 1). We also identified the usability problems participants experienced in each system and their potential relationship to task outcomes. Finally, we determined the interface design aspects that were the most problematic in light of the observed usability problems.

Table 1. Clinical Documentation Tasks for Usability Evaluation

Task	Type of Task
1. Record Tooth 28 as missing.	General pathologic findings
2. Record mesio-occlusal-distal caries on Tooth 2.	
3. Record mesio-occlusal amalgam on Tooth 14.	Existing restorations
4. Record existing porcelain-fused-to-metal crown on Tooth 19.	
5. Record proposed root canal treatment on Tooth 18.	Planned procedures
6. Record a proposed porcelain-fused-to-high-noble bridge for the missing Tooth 21, with pontic on Tooth 21 and abutments on teeth 20 and 22.	
7. Record pocket depths of 2 mm for Teeth 1 through 8.	Periodontal findings
8. Record bleeding on the buccal surface of Tooth 12.	
9. Delete the existing entry for a mesio-occlusal amalgam on Tooth 14.	Delete the restorative finding

Table 2 shows the cumulative outcomes for the nine usability tasks in each of the four software applications. The percentage of correctly completed tasks ranged from 16 to 64 percent. The percentage of incorrectly completed tasks followed an inverse distribution, from 18 to 38 percent. Incomplete tasks made up the remaining percentage (9 to 47 percent). There were no statistically significant differences for task outcomes among the four systems except for two tasks ($p < 0.05$). The frequency of observed usability problems correlated positively with the frequency of task failures for all tasks except two ($p < 0.05$). The main types of usability problems identified (Figure 1) were users making three unsuccessful attempts, expressing negative affect and tasks incorrectly completed. The problematic interface and interaction designs that led to usability problems included the counterintuitive sequence of steps to record findings, poorly organized controls to enter findings and treatment, mismatch between the user's and the system's task model, separation of clinically related information and failure to leverage existing user knowledge and customary design affordances.

The results of this study yielded strong evidence for considerable usability problems in dental EHR systems that were suggested by our earlier studies (20-22) . A second significant finding was the high frequency of task failures in the usability study results. While it is difficult to infer error rates in daily practice from a laboratory study, these findings suggested a need to examine the incidence of documentation errors in practices that use dental EHR systems. Similar to study results in medicine, the strong correlation between the frequency of usability problems and the frequency of task failures indicated that usability problems could lead to errors that affect task outcomes (27, 89, 90).

Table 2. Cumulative Outcomes of Usability Tasks in Four Dental Software Applications

% of tasks / **Dental EHR**	**Correctly completed**	**Incorrectly completed**	**Incomplete**	**Total # of usability problems**
	Percentage			
EagleSoft	64	18	18	60
PracticeWorks	58	33	9	44
Dentrix	33	29	38	96
SoftDent	16	38	47	86
Average	**43**	**30**	**28**	**286**

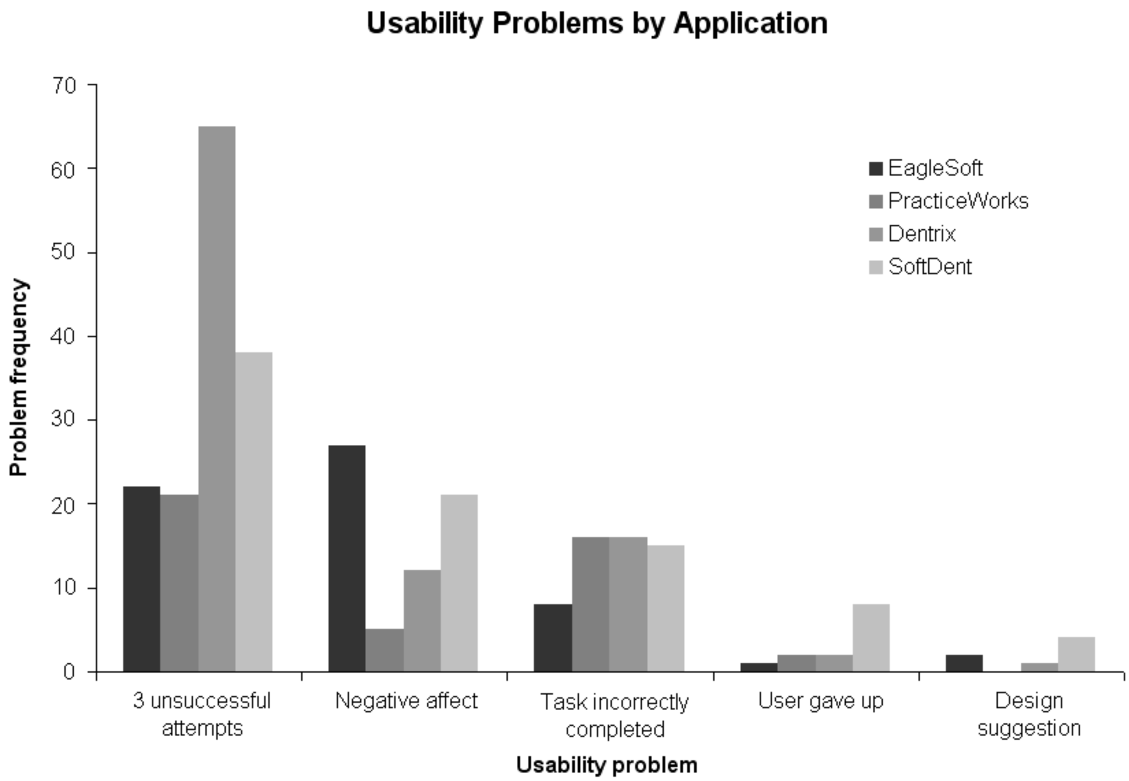


Figure 1. Usability Problems by Task and Application

3.4 WORKFLOW DURING DENTAL PATIENT VISITS

The objective of the fourth CDI study (91) was to formally describe the work process for charting and treatment planning in general dental practice and to use the results to inform the design of a new clinical computing environment. The investigators observed workflow processes in 12 dental practices, of which four used EHR systems for clinical purposes. The authors observed that dental personnel collaborate extensively during initial patient visits and the dental EHR systems' support for collaboration and communication were very limited. In paper-based offices, the paper records provided significant flexibility in information design and presentation. For example, dental personnel are able to hand-draw symbols and markings on the tooth chart and look at information on different forms side by side. The investigators also reported breakdowns related to technology which interrupted the workflow, caused rework and increased the number of steps in work processes. They concluded that current systems could be significantly improved to support better communication, collaboration, information design and presentation and data entry.

The four CDI studies (20-22, 91) collectively demonstrated that poor usability and a steep learning curve are major barriers for use of dental EHR systems in clinical settings and retard the adoption of EHR systems in dental practices. These results were comparable to results from physicians' studies where investigators found that usability problems and the resultant loss of time and productivity were significant barriers to adopting a CPR system (92-94). These results suggest that there is significant room for improvement for dental EHR systems in dentistry.

3.5 ELECTRONIC HEALTH RECORD ADOPTION IN DENTAL SCHOOLS

Recently, dental schools in US have been expanding the functionalities of their information systems and using them for patient care and education (19, 23). In the 1990s, these systems were primarily used for billing and insurance purposes, but since then, they have evolved to include the electronic health record, student assessments, oral disease risk assessments and qualitative assurance assessments. Now, nearly all dental schools use Health Information Technology (HIT) systems in some capacity and most use commercially developed systems such as *axiUm* (Exan, Port Coquitlam, Canada), *ICE Dental Systems* (Calgary, Canada), *Salud* (Dublin, Ireland), *Software of Excellence International* (Henry Schein, Auckland, New Zealand) and *Windent* (Richardson, TX, USA) (19). According to the President of *Exan* software (oral communication), who is the primary vendor for academic dental electronic health school systems, 45 out of the 54 dental schools have adopted *Exan* software, axiUm as their electronic health record system and 25 of them are completely paperless. However, very few studies report on how these systems are used in academic settings.

3.6 IMPACT OF HIT IN DENTAL SCHOOL SETTINGS

The factors that influence the success of HIT applications in dental school settings have just begun to be studied. A survey of end users of the *Exan* software, axiUm found that the faculty members, staff and students had mixed feelings about the its effect on their efficiency and only very few users believed axiUm improved productivity (23). Hardware settings such as system reliability and speed (54%) and usability (28%) were the most frequently disliked features of axiUm. When asked about potential improvements to use the EHR, the top three suggestions were usability (47%), hardware (31%), and digital imaging (28%). Similar results were reported in a qualitative case study conducted at a dental school located in the Northwest U.S. to determine the impact of HIT on dental school users (19). The authors reported that the users believed they spent longer time interacting with HIT than with paper records and this resulted in less time face-to-face time with their patients. The users reported usability problems such as separation of patient information across different screens and poor navigation for access to patient information. As a result, users have to shift their attention from patients to clinical system to navigate through the information and avoid making mistakes. The clinical workflow was disrupted and users were frustrated with the system's difficulty of use and its negative impact on workflow. The investigators suggested that incorporating user-centered design methods when developing systems and studying clinical workflow before implementation, would result in systems that make it easy for clinicians to interact with HIT during patient care.

3.7 CHAPTER SUMMARY

Chapter 3 summarizes the adoption and use of electronic health records in dental practices, as well as research on barriers to their adoption and use. Among earlier adopters, reliability, functionality and a steep learning curve were found to be barriers to use. Researchers at the University of Pittsburgh's CDI and others found usability problems related to the following: consistency and standards, match between the system and actual work processes, lack of error prevention functionality, problematic interface design (including navigational overload), and lack of tools for collaboration among dental personnel. Despite fairly widespread adoption of electronic health records at U.S. dental schools, investigators still find that many users are not convinced that they improve efficiency and effectiveness. Users want better design, shorter learning curves, reliable hardware and digital imaging capabilities. The challenge for dental informatics is to find better ways to overcome known barriers and meet user needs.

4.0 USER-CENTERED DESIGN AND COGNITIVE ENGINEERING METHODS

4.1 USER-CENTERED DESIGN METHODS

As described in previous chapters, clinicians were and continue to be resistant to using health information technology in clinical practice. A key reason is the difficulty of developing HIT applications that clinicians find useful and easy to use during patient care. Early researchers involved with developing and implementing HIT concluded that developers lacked a good understanding of the clinicians' work practices and their interactions with computers. As a result, designers implemented strategies to improve the match between the user's work practices and the system's work practices. Among these strategies was user-centered design, using methods adapted from the works of Monk, Mumford, Norman and Draper (95-97), where users participated in system design from the early stage onwards.

User-centered design methods include an iterative process of rapid prototyping and formative evaluation where user requirements are considered from the beginning and incorporated during the entire development cycle. These requirements are elicited and refined through methods such as ethnographic studies, contextual inquiry, prototype testing and usability testing. The importance of understanding user needs to design effective and efficient HIT systems led to the adoption of methods from cognitive psychology and usability engineering (74, 79, 98) and were collectively called cognitive engineering methods. These methods were used formatively, to iteratively evaluate systems during their development in order to guide the design of an effective system. Kushniruk and Patel (79) described methods that could be successfully used to determine users' needs when designing a health information system. The foremost methods include cognitive task analysis, usability testing and usability inspection.

4.1.1 Cognitive Task Analysis

Cognitive task analysis is "the extension of traditional (behavioral) task analysis techniques to yield information about the knowledge, thought processes and goal structures that underlie observable task performance" (39). It is used to identify the concepts, contextual cues, goals and strategies that contribute to the mental activities of an individual when solving a specific problem or a task. Methods used include observations of physical actions, semi-structured interviews to elicit cognitive activity, formal cognitive mapping and observations using think-aloud techniques wherein participants talk aloud while thinking and completing a task (99). Kushniruk and Patel (56, 79, 98) proposed using the think-aloud method originally described by Means and Gott (100) to develop intelligent tutoring systems. In this method, cognitive task analysis starts by describing and cataloguing individual work activities and activities that occur in an organization. This is followed by observations of individuals with varying levels of expertise. In a healthcare setting, for example, the individuals observed would be medical students, residents, and physicians. This approach helps in understanding how variations among users influence performing a task and the problems encountered by users while performing a task. Kushniruk and Patel (79, 98, 101, 102) enhanced this method with video and audio recordings of the think-aloud sessions when individuals performed a task. Cognitive task analysis also has been used to learn the users' information needs when designing a system (15, 103).

4.1.2 Usability Testing

Usability testing, the foremost usability engineering method employed to evaluate health information technology applications, refers to the "evaluation of information systems that involves testing of participants who are representative of the target user population as they perform representative tasks using an information technology in a particular clinical context" (86). Formal usability testing using a think-aloud protocol is the commonest method used for measuring usability. During usability testing, participants are asked to verbalize their thoughts as they perform a task and an observer records the participants' actions and verbalizations. In addition, screen capture software is used to capture user-computer interactions and utterances

(79, 101, 104). These think-aloud reports are then analyzed to identify problems experienced by users and the factors that caused them. In a usability test, the typical variables of interest are ease of use, efficiency and user satisfaction with the system. Usability testing is typically employed to address specific objectives: to assess system functionality and usability; to obtain feedback to refine emerging prototypes; to identify human-computer interaction problems; and to evaluate the impact of a system on physician's decision-making activities and clinical workflow. As a result, usability testing could be applied throughout the development cycle of a health information technology system.

4.1.3 Usability Inspection Methods

While usability testing helps to assess users' interactions with a system, usability inspection methods rely on expert evaluations of the interface to identify potential problems. The methods most commonly used for expert evaluation of health information systems are the heuristic evaluation and the cognitive walkthrough (79, 101, 104). In *heuristic evaluation*, expert reviewers judge the user interface and system functionality to determine whether they conform to established principles of usability and good design. An example of such a principle or heuristic is Error Prevention, meaning that the system should help the users avoid errors as much as possible. In the beginning, heuristic evaluation was developed by Nielsen (86, 87, 105) to evaluate websites and desktop software applications. Later, it also was used to evaluate the designs of paper and electronic prototypes and completely developed systems. The evaluation is typically performed by applying the ten heuristics developed by Nielsen that are essential for a good interface design (87). Later, Shneiderman (106) also developed eight golden rules essential for a good interface design. These rules were created to evaluate fully developed interactive systems.

While in heuristic evaluation an expert reviewer evaluates the interface design against a set of principles, in *cognitive walkthrough* (101) an expert reviewer evaluates how easy it is to complete a task using a system. This is, therefore, considered a form of task analysis. The reviewer identifies the sequences of actions and subgoals required to complete a task and the potential problems that might be encountered when completing it.

4.2 EARLY USER-CENTERED DESIGN PROJECTS

Two early projects that employed user-centered design techniques included the PEN & PAD clinical workstation developed by Nowlan and colleagues (107-111) and The Physicans' Workstation developed by Tang and colleagues (112-115).

4.2.1 The PEN & PAD Project

The goal of the PEN & PAD project was to design and develop a useful and usable workstation for day-to-day use in patient care with the active involvement of users in the development process (107-109). To achieve this goal, a user-centered design method was incorporated by including physicians in the development team – the group that provided input to the design and evaluation process and also in the formative and summative evaluation phases of product development. The investigators held workshops with physicians to determine initial user requirements and to outline proposed designs. During formative evaluation, a group of twelve physicians were divided into pairs and each pair of physicians interacted with the system prototype while enacting a clinical scenario. At the end of the session, each of the two physicians completed a questionnaire and a structured interview. This was followed by a brief discussion with the evaluation team. Following the completion of all sessions, the evaluation teams met with the development team to discuss the results and brain-storm new ideas (107-109).

4.2.1.1 Lessons Learned The user-centered design method helped developers understand the physicians' work practice and their needs (107, 109). They learned more by watching physicians interact with the prototype than by hearing/receiving physicians' comments on a system. The developers also observed variability in how the physicians interacted with the system and the different medical situations they encountered in their practice. Developers also discovered that physicians are good at recognizing patterns if the information is clearly presented. They concluded that simple clear presentations are more effective than sophisticated presentations that provide intelligent summaries. These observations were in contrast to what developers and design team previously believed about medical practice: that it is a "clear-cut deterministic activity" and all health care professionals performed their work in the same manner (107, 109).

4.2.1.2 What Didn't Work? Nowlan and colleagues also discovered limitations of using this method in healthcare settings (107). While users identified what was wrong with the system, they were unable to provide solutions and to express their needs. They were also usually wrong in their suggestions on how best to meet their needs or remedy a problem. The researchers also experienced difficulty in extending the methodology to other sites due to the absence of a close relationship between the developers and the users.

4.2.2 The Physician's Workstation Project

The objective for developing The Physician's Workstation was to provide physicians with context sensitive patient tools to retrieve, display and manage patient information within a clinical information system (112). Tang, Fafchamps and colleagues pursued this goal because previous studies demonstrated physicians' difficulty in accessing patient information during patient care. To determine the physicians' information needs, the investigators conducted ethnographic studies and used patients' visits as the context of physicians' work. They recorded 168 clinical sessions where internal medicine residents presented cases to attending physicians and analyzed the transcripts to identify the information physicians had difficulty in obtaining from the medical record (112).

The investigators reported that, in 81% of the cases, the physicians could not obtain all the information they needed and spent more time searching for information than they were willing to spend. They experienced difficulty finding laboratory tests and procedure results (36%), medication and treatment history (23%), medical history (31%) and other (10%) types of information. As a result, physicians searched alternate sources of information, like checking results on the computer terminal or test reports bins, or asking patients or family members for missing information. Sometimes, they simply made clinical decisions without the required information.

4.2.2.1 Lessons Learned Based on these findings, The Physician's Workstation was built to meet the following functional needs of the physicians: easy access to distributed patient information; effective presentation of information; clinical decision support tools and integrated access to information resources. Innovative features included a graphical user interface, a graph displaying laboratory data chronologically and point of care decision support systems.

4.2.2.2 What Didn't Work? Despite the innovative features built into The Physician's Workstation, a subsequent randomized controlled trial that evaluated the system showed decreased user satisfaction and no statistically significant changes in health outcomes and costs (116). The researchers reported that insufficient network infrastructure, poor understanding of what worked and did not work in the existing workflow and inadequate time for training users on the new system contributed to its failure.

4.3 STUDYING CLINICIANS' COGNITIVE PROCESSES

The results from the above two projects and other studies demonstrated that user-centered design methods improved the usefulness and usability of clinical systems. However, developers also recognized the value of adopting cognitive science methods to assess users' needs and thought processes and to model actual work practices to augment the developers' understanding of users' needs (74, 117). Patel and colleagues (79, 98, 101, 102, 104) recognized that cognitive science methods historically used to study medical expertise, such as think-aloud protocols and cognitive task analysis, could be applied to learn more about user needs and human-computer interaction problems. They argued that, although conducting such analyses could be time consuming and labor intensive, it is necessary because of the complex nature of the health care domain. In many health care domains, providers are often not conscious about how they use evidence and make complex decisions and therefore, unable to articulate their needs. Patel and Groen (118) used formal methods such as propositional and semantic representation of information to study physician explanations, reasoning and decision making during patient care. They were successful in identifying the reasoning strategies and the knowledge used by physicians during decision-making activities. They suggested that these methods could successfully be applied to design clinical systems interfaces that support users' needs and their levels of expertise and understanding.

4.3.1 Cognitive Assessment of Users' Needs

Several methods exist from fields such as software engineering and cognitive psychology that help in assessing user needs within the clinical context (74). They include semi-structured interviews, observations of users performing work, think-aloud studies of users interacting with clinical systems and cognitive task analysis studies of user workflow. Previous research indicated that protocol analysis, analysis of a verbal description of mental activity while performing a task, offered a promising methodology for studying the information needs and information processing tasks of the user (74). When combined with ethnographic studies that involve noninvasive, naturalistic observation, protocol analysis was even more useful for assessing users' needs and work practices because introduction of health information technology actually changes the work practices of healthcare professionals. In addition, observations of group interactions and communication patterns have important implications for the design of user interfaces as well as for the evaluation of their effects on work practices and communication. As a result, field study observations that characterized users' needs along with the context of work increased in value and came to be known as 'contextual design or contextual inquiry' (119, 120).

In the early 1990's, experts in human-computer interaction (HCI) decided that individual models of human-computer interaction were not enough to provide usable frameworks for improving system design in natural work settings. Such a decision was made based on work done in HCI for more than a decade and was based on four main reasons (102). First, both HCI researchers and experts realized that studying the interaction between an individual computer user and the computer system did not provide a sufficiently broad understanding of interactions within real world settings. Second, they envisioned that studying the social and organizational context of the users' work settings would supplement individual models of human-computer interaction. Third, the growing technical prominence of HCI made it imperative to characterize how people interact with social and technological environments to resolve problems and learn. Fourth, the advent of World Wide Web and other technologies opened new ways of communicating and collaborating, thus changing how people worked in groups. All these factors raised new challenges and opportunities to HCI and as a result, more research was directed at understanding situated and distributed cognition (102). There was a shift from studying individuals out of their work context to studying them in their work context and learning the social environment of those work settings.

In 1998, Patel and Kushniruk (98, 102) proposed two sets of human-computer interaction methods to better understand the cognitive processes observed in health care settings: 1) methods to study individual interactions of users with HIT and 2) methods to understand group processes and interactions among health care professionals and HIT using a distributed cognitive framework. Subsequently, Zhang, Patel and colleagues developed a human-centered distributed information design (HCDID) method to generate design specifications and requirements for systems to support distributed collaborative work environments. In the sections below, the two sets of methods proposed by Patel and Kushniruk are briefly described, followed by a description of the study conducted by Zhang and colleagues to design a web-based knowledge management system using HCDID method.

4.3.2 Individual Human-Computer Interactions

To study individual human-computer interactions, Patel and Kushniruk (101, 102, 104) advised employing usability testing methods with think-aloud protocols and emphasized understanding the cognitive processes of users as they interacted with user interfaces. *Usability testing* refers to evaluation of HIT with the involvement of participants who are representative users of the system. By combining think-aloud methods with usability testing, clinicians are asked to verbalize their thoughts as they interact with the systems. The entire session is audio and/or video recorded and analyzed to identify problems in the human-computer interaction and to recommend changes to improve the interface. Kushniruk and Patel (101) refined this method by including descriptions of clinical cases that would act as stimulus materials for participants when interacting with the system. For instance, subjects would be asked to enter or summarize the essential findings of a patient into the HIT system. This approach allowed for experimental control in the development and presentation of information to participants. The researchers also extended usability testing to study physicians-patient interactions by audio and/or video recording of physicians interacting with patients in real world clinical settings.

4.3.3 Distributed Cognition

Studies showed that individual models of human-computer interaction are not enough to provide usable frameworks for improving system design in natural work settings. Patel and Kushniruk proposed adopting the concept of distributed cognition developed by Salomen (121) to resolve this problem. This concept emphasized understanding the use of computers and technology in the context of work places and real tasks that involve collaboration. In a study that employed this method, video and audio recordings were made of groups of physicians and nurses as they discussed ordering blood gases in an intensive unit (102). Investigators coded the transcripts to identify use of evidence by the group during discussion. Results indicated the importance of personal work experience in joint decision-making activities even in the presence of external evidence obtained from a decision support system. The study demonstrated the importance of evaluating clinical systems within the context of the natural settings where the system is used.

The authors recommended conducting laboratory based usability testing to evaluate how individual users interacted with computer-based clinical systems and then moving to real world settings to evaluate how health care providers interact with computer-based clinical systems as a group during patient care (102). The authors commented that usability testing might iterate from laboratory setting to real world settings and back depending on the questions being asked and the type of analysis being performed.

4.3.4 Human-Centered Distributed Information Design Method

Zhang, Patel and colleagues described that human-computer interaction methods and user-centered engineering methods are primarily concerned with improving the interfaces of systems and not with structures that are essential for designing human-centered systems (122). They postulated that human-centered design should take into account the dynamic interactions in a distributed system of humans, artificial agents and the context in which the system is situated. Human-centered computing, grounded on the theory of distributed cognition, has three key aspects: 1) the system comprising humans and artificial agents constitutes the unit of analysis; 2) the pattern of information distribution among human and artificial agents, which can greatly impact the behavior of the distributed system; and 3) the behavior of the distributed system, which can adequately be described by the information flow dynamics.

Zhang and colleagues successfully applied their newly developed human-centered distributed information design (HCDID) to generate systems requirements and specifications for a web-based knowledge management system for biomedical engineers (BMEs) in the Mission Control Center at the NASA Johnson Space Center (34, 35). The HCDID methodology provided a framework that addressed the distributed social, cultural and organizational interactions and the cognitive issues involved in designing information technologies within a complex, distributed, collaborative environment. The researchers conducted observations and interviews with biomedical engineers, as well as document reviews, to understand the communication flow and the information exchange in that environment (34, 35). The data analysis uncovered many complex, interdependent, social, cultural, organizational and cognitive characteristics of the BMEs' environment. Examples included:

- BMEs often thought they had a similar problem previously when faced with a problem, but could not recall with certainty;
- BMEs spent minimal time searching documents for information;
- searching hard copy manuals did not produce desired results and information retrieval was labor intensive;
- problem solving depended on seamless communication between BMEs, Flight Surgeons and people in other related domains;
- request for routine information resulted in numerous phone calls/voice loop interactions which caused additional burden to BMEs.

Based on these findings, the investigators suggested that the proposed knowledge management system support collaborative communication, capture informal knowledge, organize knowledge as searchable data, increase information sharing across groups and minimize repeated problem solving for repeated tasks. This study demonstrated how the HCDID method, when integrated with the project design lifecycle, helped with designing a human-centered information system (34, 35).

4.3.5 Effects of Information Technology on Medical Reasoning

Patel and Kushniruk also emphasized the importance of studying the effects of information technologies on clinical reasoning (14). They assessed the effects of computer-based patient records on new users' decision-making strategies over time. They performed a baseline evaluation of how users' interviewed patients, followed by how users interacted with the system when in training and how users interacted with the system while interviewing a simulated patient. The authors discovered that the users became comfortable with technology over time as they interviewed and started interacting with their patients based on the sequence and organization of information displayed on the system. Eventually, users started to utilize an exclusive screen driven strategy, wherein the questions they asked the patient matched the sequence of information displayed on the screen. The authors concluded that, since reasoning is intimately related to the organization of knowledge structures, the consistent use of computer-based patient records could have a direct effect on the organization of knowledge and on users' reasoning strategies during decision-making. These results showed the significance of studying the effects of information technology on the decision-making processes of clinicians when HIT is introduced into their workflow (14).

4.3.6 Studying Cognitive Processes as a Basis to Design Expert Systems

Studies also demonstrated the importance of understanding cognitive processes to develop expert decision-making systems in a complex workspace such as health care. Early systems developed based on cognitive studies were training systems in anesthesiology (123, 124), radiology and pathology (125-127) for medical students and residents. These systems were developed based on cognitive studies of diagnostic reasoning and expertise development and how it differed among novices, intermediates and experts.

4.3.7 Task Analysis Studies to Assess Anesthesiologists' Performance

Anesthesia-related deaths have been extensively studied ever since 1848 when they were first reported. Many reasons were reported, such as faulty procedures, coexistent diseases, failure of postoperative care and drug overdose (128). In the late 1970's and early 1980's, human errors and human-equipment interface interaction errors gained attention as major reasons for anesthesia-related deaths (128, 129). In the classic study by Cooper et al., "An analysis of major errors and equipment failures in anesthesia management: considerations for prevention and detection" (128), the authors reported human errors and equipment failures as crucial reasons for critical incidents in anesthesia. They also reported that 75% of these errors occurred due to inadequate experience of the anesthetist, unfamiliarity with technique or equipment, and conflicting equipments designs. Based on these findings, they recommended increased training and supervisions of anesthesia residents, human factors improvements and improved monitoring to prevent anesthesia-related critical events. These recommendations led to the application of cognitive science methods to study anesthesiologists' task patterns and their workflow in real world settings. Researchers also hoped that a comprehensive description of anesthesiologists' tasks requirements and workload would provide a basis to improve the design of their equipment and training.

One of the early studies on understanding the anesthesiologist's work processes was conducted by Weinger and colleagues (124). They used time-motion analysis, secondary task probing and subjective workload assessment to understand the anesthesiologist's work processes in the operating room. A trained observer recorded all the activities of the primary anesthesia provider. The results revealed significant differences in task behavior among experts and novices. Expert providers spent significant amounts of time observing the monitors and surgical fields, whereas novice providers spent more time conversing with the supervising attending. The experts were more efficient in performing different tasks when compared to novices and novices experienced increased workload than the experienced providers. In summary, the results of the study provided objective confirmation of a number of intuitive beliefs about anesthesia personnel in actual work practice (124) and demonstrated that these methods could be used to understand the factors that affect anesthesiologists' performance and to assess their progress in training.

4.3.8 Intelligent Tutoring Systems in Radiology and Pathology

The successful development and use of simulators to improve the training of anesthesiologists led to the application of cognitive studies in other medical domains to develop intelligent tutoring systems, such as *RadTutor*, an intelligent tutor for mammography interpretation (130, 131) and *SlideTutor* (125, 126, 132, 133), a model tracing intelligent tutoring systems for teaching microscopic diagnosis. These intelligent tutoring systems were developed based on cognitive studies of expertise development and incorporated timely tutoring interventions and dialogues based on analyses of human interactions.

4.3.8.1 *RadTutor* Project to Improve Training in Mammography Interpretation In the *RadTutor* project (130, 131), Azevedo and Lajoie developed an intelligent tutoring system to improve consistency and standardization of training for mammography interpretation. They developed the system based on cognitive studies of diagnostic reasoning in mammography interpretation and effects of perceptual scaffolding on the diagnosis of difficult mammograms. The researchers studied the problem solving strategies used by staff radiologists and residents during the interpretation of difficult mammograms. The study participants diagnosed ten cases under two different experimental settings: authentic and augmented. In the authentic setting, the participants read a type-written clinical scenario and a set of corresponding mammograms. In the augmented setting, the critical mammogram features were highlighted to test the hypotheses that highlighted findings would facilitate developing the diagnostic schema and thus enhance diagnostic accuracy. The think aloud protocol was used where participants talked aloud while working through the cases. The verbal protocols were subsequently analyzed to develop a cognitive model of the diagnostic reasoning process of radiologists. Preliminary results demonstrated that radiology staff and radiology residents used both forward reasoning (data-driven) and backward reasoning (hypothesis-driven) strategies when diagnosing cases. Residents had the most difficulty eliciting critical findings and diagnosing accuracy. The study findings confirmed the hypothesis that highlighting critical findings will enhance residents' diagnostic schema and accuracy.

4.3.8.2 Observation of Teaching Methods in Radiology Azevedo and Lajoie also studied the teaching methods employed by a staff radiologist with six radiology residents during two one-hour mammography rounds (130, 131). The staff radiologist assigned a case to a resident and asked him/her to diagnose the case. The residents placed the mammograms on the 'viewbox' and "talked aloud" when diagnosing the case. The diagnostic reasoning process was characterized by the residents reading the clinical history, identifying the technical positioning of the mammograms, identifying and describing film findings, relating surrounding anatomic structures to the finding, providing diagnosis or differential diagnosis and discussing patient management. The observation also illustrated how the radiologist externalized her own reasoning process by first assigning the probabilities to pathological features, followed by elimination of each differential diagnosis and finally arriving at a diagnosis. Based on these findings, the *RadTutor* was designed to support cognitive flexibility by providing multiple knowledge representations, support active learning through problem solving activities, facilitate adaptability by considering the learners' knowledge level and correct misconceptions by providing real-world context.

4.3.8.3 Intelligent Tutoring System to Improve Microscopic Diagnosis In the *SlideTutor* project (125, 133), Crowley et al. first performed a cognitive task analysis study of microscopic diagnosis to learn differences in the visual diagnostic processes between novice, intermediate and expert pathologists (126, 132, 133). The findings from this study were then used to design a knowledge-based tutoring system called the *SlideTutor*. In the cognitive task analysis study, participants were asked to examine and interpret a set of slides and to think aloud during the entire session. The investigators recorded the participants' think aloud verbal data and digitally captured the visual data they examined with the microscope. They then coded the video/verbal protocols for cognitive processes and errors. Following data analysis, the investigators concluded that novices made frequent errors when searching the slide; could not identify diagnostically relevant areas of the slide and made errors when identifying visual evidence. Intermediates demonstrated an explicit strategy of visual cues and reasoning from these cues to reach a diagnosis. They accurately detected the lesion but frequently made diagnostic reasoning mistakes that resulted in diagnostic errors.

Based on these findings, the investigators designed the *SlideTutor* (a knowledge-based tutoring system with the following features to enhance the training of pathology residents and students: monitor and provide feedback on searching skills; assist students in learning to assign the correct term to the specific visual feature; and help students learn and apply the steps of reasoning through a case. A subsequent comparative evaluation of the intelligent tutoring system demonstrated that students exhibited significant metacognitive gains when they used the knowledge-based tutoring system (125). Students also rated the knowledge-based interface significantly higher than the case-focused interface. The results of this study suggested that knowledge-focused external representations may provide a metacognitive advantage and might be the reason for increased student acceptance. The results also demonstrated that use of cognitive tutoring system is associated with improved diagnostic performance in a complex medical domain.

4.4 CHAPTER SUMMARY

Chapter 4 has introduced and described common user-centered design methods and reviewed lessons learned from some of the early user-centered design projects. The importance and potential of studying the cognitive processes of clinicians was explained, as was the need to examine human-computer interactions from both the individual and group perspective. The chapter described the emergent view of a system as comprising technologies and human clinicians, as well as their interactions in a real world environment, and emphasized the need to incorporate this complexity into user-centered design. This view of complex systems supported the development of simulators to better reflect the real world in training and practice situations. Examples were provided of the use of cognitive analysis and user-centered design to plan, create and evaluate simulators and other intelligent tutoring systems.

5.0 APPLYING COGNITIVE METHODS TO EVALUATE CLINICAL SYSTEMS

As mentioned before, human factors design is a major challenge to using HIT effectively and efficiently in clinical settings. The encouraging results from applying cognitive engineering methods to develop intelligent tutoring systems led to its application to evaluate and redesign clinical systems. Cognitive engineering methods and human-computer interaction methods were employed to evaluate the effectiveness of the current system design, efficiency of using the system and user satisfaction (134). *Effectiveness* refers to the usefulness of a tool to complete a task or a set of tasks and the safety of the tool and *efficiency* refers to the time taken to complete a specific task (134). For instance, efficiency is measured by counting the number of clicks to perform tasks, by determining the cost of tools and/or the amount of time needed for users to learn a software application. *Satisfaction* refers to the perception of users about workload or the effectiveness of the specific design (134). The human-computer interaction methods commonly used were heuristic evaluation, cognitive walkthrough, formal usability testing using think-aloud methods and observations in natural clinical settings. Researchers also used surveys, semi-structured interviews and focus groups to gather user's needs and opinions during the design phase and development phase of the system.

5.1 STUDIES OF HIT USING COGNITIVE ENGINEERING METHODS

Table 3 summarizes 23 evaluative studies of clinical applications conducted over the past decade or so that utilized cognitive engineering methods. The purpose of each study is delineated, along with the methods used and the main outcomes, to illustrate the scope and nature of these investigations of human-computer interaction.

Table 3. Evaluation Studies of Clinical Systems Using Cognitive Engineering Methods

			Think aloud: TA; Interviews with users: I; Ethnographic Observations: EO; Cognitive Task Analysis: CTA; Cognitive Walkthrough: CW; Questionnaire: Q; Focus Groups: FG; Usability testing: UT								
	Reference	**Purpose of the study**	**Cognitive engineering method used**								**Outcome**
			TA	I	EO	CTA	C W	Q	FG	UT	
1	Sittig et al. 1999 (37)	To measure user interaction satisfaction with an EMR in routine clinical use						X			Overall user satisfaction was correlated with screen design and layout and not with system response time.
2	Wang et al. 2002 (38)	Examine the QUI's ability to allow users to easily and intuitively express their information needs.				X	X			X	QUI imposes significant cognitive load on the user. The study suggested several ways in which the QUI can be improved.
3	Horsky et al. 2003 (26)	Characterization of cognitive demands of a medical information system			X	X	X				The system placed unnecessarily heavy cognitive demands on the user.
4	Rinkus et al. 2003, 2005 (34, 35)	Analyze complex distributed human-computer system of Mission control center at NASA Johnson Space Center, Houston, Texas and generate designs		X	X						Identified the complex interdependencies between human and artificial agents that occur within a distributed collaborative environment. Developed design reqs.
5	Graham et al. 2004 (25)	Uncover design and interface deficiencies of infusion pumps								X	Evaluators identified 231 heuristic violations. commonly violated heuristic consistency and standards
6	Patterson et al. 2004 (32)	Identify human factors barriers to the use of clinical reminders		X	X						Six human factors barriers identified. Reducing these barriers will increase use of CR and increase quality of HIV care
7	Baxter et al. 2005 (135)	Identify contextual factors that would affect FLORENCE's success		X	X				X		Recommendations for the redesign of FLORENCE so that it fits with the ICU workflow
8	Horsky et al. (1) 2005 (28)	Analyze a dosing error related to a computerized order entry system		X						X	The error occurred due to confusing-screen laboratory results review, system usability difficulties, user training problems and suboptimal clinical safeguards

Table 3 (continued)

9	Horsky et al. 2005 (136)	Characterize the available information resources in the system interface and in the users' memory and determine how effectively the system supported the decision-making process	X			X					Analysis showed that efficiency was contingent upon high level of procedural and conceptual systems knowledge. Therefore the CPOE design should support the decision-making and workflow processes to become an effective tool.
10	Peute & Jaspers 2005 (33)	Usability evaluation of working prototype computerized provider order entry system	X				X				Identified 33 usability problems that led to inefficiency, omissions in ordering and even to cancelled orders. Most of the suability problems were due to lack of understanding of steps required to complete actions and due to inability to understand the text used in the system.
11	Rose et al. 2005 (137)	To improve usability of a results management module of a widely adopted web-based electronic medical record			X				X		Identified areas to be improved: 1) amount and organization of information displayed; 2) interference with workflow patterns of PCPs
12	Johnson et al. 2006 (30)	How traditional mnemonic-based ordering systems may conflict with physicians' mental model used in planning patient care	X	X							Suggested improvements to traditional CPOE
13	Sharda et al. 2006 (138)	Conversion of medical texts to a more structured, user-customized presentation in the electronic medical record	X	X							Developed conceptual representation of the patient record based on how healthcare providers use patient data using cognitive science methodology
14	Chen & Zhang 2007 (139)	Compared test user interface and GUI of a dental system				X					GUI was not better than TUI. Usability of interface depend based on mapping between user interface and tasks
15	Despont-Gros et al. 2007 (140)	Usability evaluation and user acceptance of digital pen and paper technology			X			X			Digital pen induced unexpected cognitive burden. The proposed technology appeared to not as natural as presented.
16	Saleem et al. 2007 (36)	Compare the redesigned interface to the current CR system on learnability, efficiency, usability and workload		X				X			The redesigned interface increased learnability, efficiency, usability, reduced mental workload and frustration

Table 3 (continued)

17	Weir et al. 2007 (39)	Explore information management strategies that clinicians use with CPOE		X	X						Identified tasks that were not fully supported by available technology
18	Guappone et al. 2008 (141)	How users interact with CPOE in real time in hospital setting	X		X						Identified ten themes of usability issues with the CPOE interface
19	Beuscart-Zéphir et al. 2009 (24)	Redesign a hospital medication CPOE project to improve safety and efficiency of medication process		X	X					X	Identified currently unsafe and uncomfortable work situations and recommended design suggestions to improve safety and efficiency of CPOE.
20	Nies & Pelayo 2009 (31)	To understand users' needs and to properly formalize design needs while redesigning a CPOE system.		X	X					X	Set of recommendations illustrated in schematic mock-ups. Did not do an evaluation of the new design with users
21	Shachak et al. 2009 (142)	To reveal underlying cognitive elements involved in EMR use, possible resulting errors and influences on patient-doctor communication		X	X						There is a fine balance between the benefits and risk of EMRs.Automaticity, especially in combination with interruptions, emerged as the main cognitive factor contributing to errors.
22	Wright et al. 2009 (40)	Evaluate clinical decision support capabilities of commercially available clinical systems		X							Five of the nine systems had access to patient specific data Six of the nine systems tailored interventions based on the severity of clinical situation and user's workflow. One system offered choices to allow physicians to take action directly within the alert.
23	Hysong et al. 2010 (29)	Evaluate how PCPs manage alerts related to critical diagnostic results on their EMR screens	X								Almost half of providers did not use any of the alerts and none used more than two. Considerable heterogeneity exists in how providers manage alerts. 46% of providers used work around strategies to manage alerts.

5.2 HUMAN-COMPUTER INTERACTION DESIGN FOR CRITICAL SYSTEMS

5.2.1 Sources for Error in IV Infusion Pumps

Several studies demonstrated the significance of optimal interface design for health care applications to prevent life threatening events. For instance, Zhang et al. and Graham et al. revealed several usability problems with IV pumps due to limited information visibility and faulty data synchronization that could potentially cause medical errors (25, 143). Human computer interaction methods such as heuristic evaluation and usability testing were performed to redesign a family history tracking program from family history data and a digital emergency medical record system for paramedics

Zhang and his colleagues conducted heuristic evaluation of two 1-channel volumetric infusion pumps (143) to identify usability problems that potentially could cause medical errors. To achieve this objective, they adapted the heuristics developed by Nielsen (86, 87, 105) and Shneiderman (106) to suit the needs to evaluate medical devices and identify trouble spots in these devices. Subsequently, four trained evaluators evaluated assessed the two medical devices against the modified set of heuristic principles. The evaluators discovered that "consistency and standards" and "visibility of system status" were the two most frequently violated heuristics in pump 1 and "visibility of systems status" was the most frequently violated heuristic in pump 2. The authors described an instance of violating visibility of system status as follows: "When the "enter" button is not pressed, after entering part or all of the value for 'Rate' and 'VTBI' (volume to be infused), a message that appears that reads 'complete entry.' It is not clear what this means. A better phrasing would be Press 'enter' to confirm value." The authors found that Pump 1 had more usability problems, than Pump 2 and therefore may be more error prone, than Pump 2. They concluded that the modified heuristic evaluation is a useful and efficient method to discover usability problems in the patient safety features designed for medical devices.

5.2.2 Improving a Family History Tracking Program for Genetic Studies

The family history tracking program is a program designed in 1997 at the University of Texas MD Anderson Cancer Center (UTMDACC) for conducting cancer genetics studies as a part of an academic program (144, 145). Its primary function was to enable practitioners with the tools to create readable and consistent pedigrees or family trees. The system consisted of data entry interfaces, predefined reports, data editing screens and a link to a pedigree drawing program. Although the system had many advanced functionalities, an initial user survey and usability evaluation revealed that the system had many missing functions and usability problems. Subsequently a group of cognitive psychologists conducted user and task analyses to determine its usability and functional problems. The users were analyzed both on horizontal and vertical dimensions. At the horizontal dimension level, users were categorized according to their different types of tasks and at the vertical dimension level, users were categorized according to their different levels of experience for specific types of tasks.

Task analysis was performed to identify the system functions and features that matched with the users' needs to complete a task. Any functions and features that do not match with the users' needs will only generate additional work for the user and thus make the system harder to use. The investigators conducted a heuristic evaluation of the system and also analyzed the differences in the conceptualization of task between a first time user's and the designer's' conceptualization of the task. The users' and designers' conceptualization of tasks were studied by employing verbal protocol analysis and Keystroke Level Model method. Subsequently, the results were compared with the results of a cognitive walkthrough for specific tasks. A total of four tasks were first analyzed to determine the designers' conceptualization of the task and the first time users' conceptualization of the task using the verbal protocol analysis. The tasks were then analyzed using The Key Stroke Model to detected differences in the execution times by summing up the time taken for each keystroke, pointing, clicking, thinking, waiting and deciding. The cognitive walkthrough was conducted to determine the steps a new user would take to complete a task and to identify potential usability problems and ease of learning the system. Finally, recommendations for change were determined and the Key-stroke Level Model (refer 7.5.2) was used to show the predicted execution times of the suggested redesign.

The results showed that the redesigned interface would considerably reduce the time taken to complete a task and the users would also find it easy to learn and easy to use. The results of this study showed a significant difference in user performance and satisfaction between the original and redesigned versions of this program. The authors concluded that this study demonstrated how a system designed without regard to user-centered design guidelines could be redesigned using this framework to create a system that models the characteristics and tasks of the users, thus increasing user satisfaction.

5.2.3 Improving Time-Critical Patient Records

In a project on digital emergency medical patient records for telemedicine, a group consisting of human-computer interaction researchers, cognitive scientists and clinicians worked together, to develop a system that is easy to learn and use in a time-critical situation (146). During the early stages of system development, Tang and colleagues recognized usability as having a critical role on the clinical outcomes of the program. Medical emergency services are time-critical situations where human lives are at stake and any delay or error in users' task performance could have severe consequences. The investigators integrated user-centered design methods into the iterative design process, which resulted in an increasingly refined user interface with increased usability. Tang and colleagues conducted heuristic evaluation during the early development phases of the system and made changes accordingly. They also conducted ethnographic studies where the users interacted with a simulated version of the system and used the findings to validate the heuristic evaluation results from the last prototype. The investigators found that the heuristic evaluation results from early versions of the prototype significantly improved the interface design. The study also provided evidence that heuristic evaluation results predict, to a certain extent, how users would perform when interacting with the system.

5.2.4 Limitations of Heuristic Evaluation

The predictive power of heuristic evaluation demonstrated the validity of usability experts' judgments about a user interface design. However, the investigators also saw its limitations when compared to other usability engineering methods. Heuristic evaluation relies heavily on the expertise of the usability experts and even though they are familiar with the usability principles, they may not necessarily possess sufficient domain knowledge. As a result, there is a possibility that the usability these experts may overlook usability problems concerned with domain expertise. In the ethnographic phase of the study (146), Tang and colleagues discovered a number of usability problems that went unnoticed during heuristic evaluation. They believed this shortcoming is was due to the evaluators' lack of domain knowledge and recommended to have using double experts who are experienced in both usability and domain knowledge to conduct heuristic evaluation.

Another limitation of heuristic evaluation is that this method is primarily concerned with information presentation on the interface and does not consider other usability issues. To overcome this obstacle, Tang and colleagues (146) suggested three levels of system usability analyses: functional, task and representational analyses. Functional analysis is concerned with top-level domain structures and ideal task space independent of implementation. Task analysis is concerned with specific structures and procedures and representational analysis is concerned with specific implementation issues given the constraints of system functionality and task structure. According to Tang and colleagues, representational analysis is primarily concerned with designing the most appropriate information flow structure and the most appropriate information display to achieve direct user-system interaction. The authors concluded that while heuristic evaluation uncovered several usability problems, it is also important to pay close attention to users and the issues involved during the development phases of a system.

6.0 COGNITIVE ENGINEERING METHODS: A GUIDE TO SYSTEM DESIGN

The previous chapter described how cognitive engineering methods have been adapted and applied to evaluate and redesign existing health information technologies to enhance their use and prevent errors. These studies illustrated the success of cognitive engineering methods in identifying user interface problems that could potentially lead to errors and in recommending design solutions that would better support the clinicians' work and workflow. While these studies focused primarily on studying the impact of existing clinical systems, a few studies have explored how cognitive science methods would inform the design of a future clinical system. Studies done in this field include works done by Nygren (41-43) and Jaspers (15, 103) who first examined how clinicians performed their work and interacted in their work settings and used that as a model to design clinical systems. These studies collectively demonstrated how cognitive analysis methods can be used to inform the design of clinical systems to support clinicians' work and their workflow. The following sections describe the methods in these studies, their findings and how they inform the design of clinical systems designed for health care settings.

6.1 EXAMINING PHYSICIAN USE OF RECORDS

In the first study, Nygren et al. observed and interviewed physicians to learn how they searched data, used them in paper-based patient records and subsequently developed recommendations to design the interface of electronic medical records (41). One major criticism of paper-based patient records is the inability to gain an overview of the patient and the time spent searching for relevant information (43) . In an observational study of how clinicians used paper-based patient records, the investigators found that the search method varied based on the clinicians' reason to review the record (41, 42). Clinicians typically review patient records for three major reasons: to gain an overview of a new or an existing patient, to search for specific details, and to prompt or explore hypotheses.

To obtain an overview of the patient, the clinician relies on cues triggering recognition such as an unusual last name or the letterhead of the referring hospital or physician. They also use features like time-lines and case summaries to gain an overview of the patient.

Once the clinician is familiar with the patient, he or she searches for specific details of the patient’s problem or explore hypotheses. The clinician uses his knowledge of the record structure, the ordering of documents and the layout of text and data to navigate and locate the data. This strategy limits the search space and therefore speeds the search provided the record structure matches the readers’ expectations (147). Studies on physicians searching data also showed that physicians skimmed rapidly over pages of text while continuously assessing the relevance of the information. A paragraph judged irrelevant is immediately skipped whereas a paragraph judged relevant prompts the reader to switch from skimming to reading word by word. This finding showed that clinicians acquire useful information from the overall pattern and it helps in defining the context and in deciding when to stop skimming and start reading (41-43, 147). Physicians also read the medical record to search for facts such as the drugs prescribed previously, previous actions taken to treat the patient and so on.

The medical record is used as a problem solving instrument in situations where decision-making is not straightforward. In these situations, the record is read in a special way to test the hypotheses and to evaluate strategies of action based on the facts in the record. In such situations, the information is read more than once and a great deal of navigation of the record. In this type of reading, it is not possible to say what is relevant or not. The authors observed that the text is processed in three different ways regardless of the purpose of the reading: by reading every word, skimming the text, and by skipping the text.

The authors also found that disordered records severely delay searching (41). They commented that it is easy to navigate through patient information when it is presented in a logical and consistent manner and when all information is available on the same page instead on several pages. Easy access to information makes decision-making faster and less error prone

(148). The authors concluded that these effects are observed both in paper- and computer-based patient records even when the reader is familiar with the data layout. They also concluded that reading from the computer screen is slower than reading from the paper (41, 149, 150). However no difference in time was observed when the computerized medical record was read from paper printouts and not from the screen (151). This observation suggests that it is not the computerized screen but the human-computer interaction that accounts for the slow reading (41).

6.2 EXPERIMENTAL READING IS NOT ENOUGH

The results of this study demonstrated studies involving experimental reading (research related to reading comprehension) cannot be applied to understand how physicians read patient records. This is because physicians read the text in different ways depending on the situation and therefore navigation is an integral part of the reading task. Experimental reading concentrate mostly on proof-reading and reading for comprehension where the text material is unfamiliar to the reader. Nygren et al. commented that the current guidelines for human-computer interfaces are based on experimental reading studies and therefore cannot be applied to design an interface for reading a medical record. The authors advised exposing a lot of information to the user and providing better orientation and navigation of information as essential aspects when designing the user interface for reading a medical record. The interview participants also complained that a disordered record severely slowed searching and reading the text.

6.3 THINK-ALOUD TO EXAMINE PHYSICIANS USE OF RECORDS

In the second study, Jaspers (15) used the think-aloud method to learn how pediatric oncologists searched through the paper-based patient records when preparing a patient visit. The resulting verbal protocols and video recordings were analyzed to develop a cognitive task model that represented the clinicians' model of performing their work. This model was then used to design the interface of an electronic medical record, which was found to have improved the efficiency and information needs of the clinicians. The results of the cognitive tasks analysis study revealed nine categories of information needs for the pediatric oncologists: patient identification, history of cancer, history of cancer treatment, patients' current medical conditions, complaints, symptoms and findings, medication, smoking and drinking history, family members' medical history and laboratory or additional test results. The authors also found that the information needs were identical across all participants and they reviewed the information in the same sequence when reviewing patient demographics, history of cancer and its treatment, medical history, patients' complaints and symptoms and findings. Some variation was observed when pediatric oncologists reviewed medication history, smoking and drinking history, family history and laboratory/additional test results.

Based on these results, the investigators structured information on the screen to correspond to the order in which pediatric oncologists reviewed patient information. They also presented as much as information as possible on the first screen to avoid the need for users to scroll down or click on additional screens. Related information elements were also clustered on the computer screen to make the navigation easy for clinicians. Subsequent evaluation of the prototype demonstrated that pediatric oncologists liked using the system to review information, did not miss any relevant information and took less time reviewing information than when using paper-based patient record.

6.4 CHAPTER SUMMARY

Chapters Four and Five reviewed some of the most significant research on user-centered design and cognitive engineering methods employed during the evaluation and redesign phases of HIT, as well as the studies leading to development of some early simulators and training systems. This chapter has extended the review of research to include a few key studies that applied cognitive engineering methods to inform the design of new clinical systems. It is these studies that are most closely related to the research proposed in this document by this researcher

7.0 RESEARCH STATEMENT

Cognitive science methods have shown significant promise to meaningfully inform and formulate the design, development and assessment of clinical information systems. The last two decades saw extensive research in applying cognitive engineering methods during the design and developmental phases of clinical systems (101, 102, 152-155). Most of these methods were applied to evaluate the design of systems after they had been developed. Very few studies, on the other hand, have used cognitive engineering methods to inform the design process for a system itself. These studies employed methods such as think-aloud protocols and semi-structured interviews to understand the cognitive processes, and information strategies used by clinicians during patient care (15, 43). The resulting cognitive models were then used as the basis to design clinical systems. Preliminary results demonstrated its effectiveness for the design of systems that provide cognitive support during patient care and thus raised the potential to improve the quality and safety of patient care. However, research is still nascent as many methods have been proposed with little empirical evaluation. It is this gap in knowledge – how cognitive engineering methods can be optimally applied to inform the system design process – that was addressed through this project proposal.

In my research, I addressed this gap by comparing a novel dental record system designed based on two cognitive engineering methods (Cognitive Task Analysis and Contextual Inquiry) to one that was not. First, I conducted a seminal study of the cognitive processes and information management strategies used by dentists during a typical patient exam. I then used these results to display clinical information that offer cognitive support to dentists during patient-centered decision-making activities. The resulting 'proof of concept' was then evaluated to determine its effectiveness for the support of clinicians' review, diagnosis and treatment planning of a patient case. The results of this study contributed to designing clinical systems that provide clinicians with better cognitive support during patient care. Such systems will contribute to enhancing the quality and safety of patient care, and potentially to reducing healthcare costs.

7.1 RESEARCH OBJECTIVES

The objective of this project was to evaluate empirically whether performing cognitive engineering methods prior to design can help improve the interface of an electronic dental record. The overall research question was, "Will a prototype designed on the basis of the cognitive engineering methods support the clinicians' review, diagnosis and treatment planning of a patient case better than a system that is not designed using such methods?" I subsequently comparatively evaluated the users' perception of information organization, navigation and usability of the prototype against a commercial electronic dental record system used in academic institutions (henceforth referred as cEDR).

To answer this question, I completed the following four steps:

1. Conduct a cognitive task analysis (CTA) study to gain a detailed understanding of dentists' information review and decision-making activities during diagnosis and treatment planning. From here on, 'patient exam' will be used instead of 'diagnosis and treatment planning'.
2. Conduct a contextual inquiry (CI) to gain a detailed understanding of the workflow, sequences roles for data acquisition, data entry and retrieval in a dental practice.
3. Develop a proof-of-concept electronic dental record interface named DMD Prototype for retrieving and reviewing patient information using the results of the CTA and CI.
4. Compare the DMD Prototype with cEDR in a laboratory experiment with 10 dental clinicians regarding its capability to support review, diagnosis and treatment planning of a patient case.

7.2 RESEARCH QUESTIONS

1. What is the pattern of information review, processing and decision-making when dentists examine new patient cases?
    a. What information sources do dentists retrieve and in what sequence when examining patient cases of varying complexities?
    b. What information do dentists use to make clinical decisions and how do they use it?
    c. What cognitive processes characterize a dentists' information management and decision-making activities when examining patients?
2. What is the sequence of activities and roles of the dental team members during data acquisition, data entry and retrieval?
3. How does the DMD Prototype differ from cEDR in supporting clinicians' review, diagnosis and treatment planning of a patient case with regard to information organization, navigation and usability?

7.3 RESEARCH METHODS: COGNITIVE TASK ANALYSIS

7.3.1 Study Objective

The objective of this study was to document the information review and decision-making activities of general dentists during diagnosis and treatment planning. To accomplish this goal, 10 general dentists were observed examining three patient cases using the think-aloud protocol.

7.3.2 Patient Cases

The patient case documentation for the three patient cases (one each of low, medium and high complexity included the chief complaint, dental history, medical history, extraoral examination, complete intraoral status (soft tissue, hard tissue and periodontal status), extraoral images, intraoral images, radiographs and plaster models (if available). Each category of patient information was clearly labeled (e.g., “medical history,” dental history,” etc.). The three cases were selected from the pool of approximately 80 patient cases that senior dental students at the School of Dental Medicine develop each year as part of the course DENT 5412 (Senior Case Presentation). The clinical cases were selected by a three dental faculty to ensure the cases represented the patient cases typically seen in a general dental practice. Complete documentation of the three clinical cases is included in Appendix A.

7.3.3 Study Participants

Ten general dentists with more than two years of practicing experience were recruited, five from the American Dental Association’s list of dentists in Pittsburgh area and five from the list of general dental faculty members at the University of Pittsburgh School of Dental Medicine.

7.3.4 Participant Recruitment

General dentists in the Pittsburgh area were contacted via telephone and dental faculty via email. On the phone, we briefly described the study to the dentists and invited them to participate. Upon agreeing to participate or upon request for additional information, the study description was faxed to the dentist. A similar approach was used to recruit the dental faculty via email. A brief description of the study was emailed to the faculty. Once a faculty member agreed to participate, an appointment was scheduled for the study.

7.3.5 Study Participant Payment

Research participants who participated in the study received a moderate financial incentive in appreciation for the time spent for the study.

7.3.6 Study Design

We conducted a cognitive task analysis study in which each participating dentist conducted a dental diagnosis and developed a treatment plan using the think-aloud protocol for three documented patient cases. Think-aloud protocols are standard techniques in cognitive psychology where participants are asked to verbalize their thoughts without filtering them while performing a task. The entire session was video and audio-recorded to capture participants' interactions with the patient record and other documentation. Participants were provided with table space for documents and records, as well as writing supplies to record observations and planned procedures. Before starting the session, the process of conducting the experiment was reviewed with the participant. The goal of the experiment was explained: to conduct a diagnosis and develop a treatment plan for each given case. It was also explained that participants would be provided first with patient information and the chief complaint for each case. All the participants were trained through practice with the think-aloud process, using one or two tasks that were not used in the study.

After practice, the patient cases were presented to the participants one by one in random order to prevent sequential bias. The observer began by handing out the patient information for the first case, along with the chief complaint, to the participant. The participant was encouraged to request more information as needed to examine the patient case and to develop a treatment plan. They were instructed to verbalize both the type of information desired and what he/she was thinking while reviewing and assessing patient information. The observer reminded participants to keep thinking aloud if they fell silent for more than 15 seconds. As stated before, all sessions were video and audio recorded.

7.3.7 Think-Aloud Protocol Coding

After each session, experimental data were transcribed and divided into data segments, each segment representing a single sentence or single patient information item. If the participant referred to a patient documentation artifact, its identification was included in the transcript. Each data segment was coded to determine the information used and the cognitive processes (as derived from the verbal, think-aloud data) that contributed to developing treatment plans for the three cases. In addition to verbal data, the video recorded sessions were reviewed to identify and record which information was used by dentists at which particular points in the process, instances when dentists reviewed more than one patient documentation artifact, and instances when they wrote something.

Data coding followed the process described in the research studies published by Jaspers and Crowley (15, 133). Each segment of the verbal data was coded for process type, specific process value and information source. *Process type* refers to "information processes that produce new states of knowledge by acting on existing states of knowledge" (133). *Specific process* indicates the content of the process or new knowledge acquired through the process. Table 2 lists and provides examples for the 28 specific processes identified in the data from this study. *Information source* refers to the different patient documentation artifacts a dentist reviews during a patient exam. In this study, information sources included chief complaint, dental history and medical history, intraoral exam findings recorded on hard tissue and periodontal charts, and intraoral images and radiographs.

Instances when dentists reviewed more than one information source simultaneously were coded and the specific section and data element reviewed in each information source also were identified through video record analysis and coded. Since the time taken may not be the same for each case, an additional *time_percent* variable was created by converting time into percentage and using ten percent intervals. This helped in plotting data from all 30 cases on the same graph in ten percent time intervals. Table 4 shows a draft of the proposed coding scheme and Figure 2 shows an example of the coded verbal protocol.

Table 4. Example of a Draft Coding Scheme

Variables	Values	Example(s)
Independent variables		
Dentist	ID of the dentist	n/a
Case Complexity (CASE)	Case 1 (low complexity), Case 2 (medium complexity), Case 3 (high complexity)	n/a
Time (time_percent)	Time taken to complete each case converted to percentage	
Dependent variables		
Process type (PROCESS)	Information retrieval/review	"Looking at that, the next thing that I would like to know is a medical history."
	Processing	" But the patient, in my clinical charting, I would note that tooth No. 16 has retained root tips."
	Deciding	"I can already tell that she has a lot of cavities or caries."
	Other	"That's basically it. I think she's in good shape. I would just do those things I recommended. That would be it."
Information source (INFO)	Identification of form or artifact (e.g., radiograph); section on form (if applicable); data element (if applicable)	Medical history form → cardiovascular system → stroke in 2000
Segment order (ORDER)	Sequential number assigned to each successive segment	n/a

B	C	D	E	F	G	H	I	J	K	L	M	N	O
Dentist	**Case Order**	**Complexity**	**ORDER**	**Segment**	**PROCESS**	**Values**	**INFO**	**2nd INFO**	**3rd INFO**	**Section**	**Data Element**	**Video Time**	**Actual Sec**
p1	1st	medium	1	Okay, so the first piece of information that I'm getting is that the gender of the patient is an African-American female.	reviewing	female, AA	Patient Information	n/a	n/a	Demographic Info	Gender	5:23	1
p1	1st	medium	2	She is 43 years old	reviewing	43 years old	Patient Information	n/a	n/a	Demographic Info	Age	5:25	3
p1	1st	medium	3	and her chief complaint is that the patient is interested in getting her teeth fixed.	reviewing	getting teeth fixed	Patient Information	n/a	n/a	Chief Complaint	Chief Complaint	5:31	9
p1	1st	medium	4	Now, with that general information the information I'd like to know is a little bit more about medical history.	information request		(Medical History)	n/a	n/a	n/a	n/a	5:41	19
p1	1st	medium	5	Is there something you can tell me about her medical history? Yes.	information request		(Medical History)	n/a	n/a	n/a	n/a	5:46	24
p1	1st	medium	6	So, the medical history is stated as PS2 or physical status two.	reviewing	medical history - PS 2	Medical History	n/a	n/a	n/a	Physical Status	5:53	31
p1	1st	medium	7	She has an allergy to erythromycin and penicillin.	reviewing	allergies - erythromycin, penicilling	Medical History	n/a	n/a	n/a	Allergies	5:58	36
p1	1st	medium	8	So she has allergies to antibiotics	deciding/finding	patient has allergies	Medical History	n/a	n/a	n/a	Allergies	6:00	38
p1	1st	medium	9	and her vitals are 123/82,	reviewing	vital signs	Medical History	n/a	n/a	Vital Signs	Blood Pressure	6:04	42
p1	1st	medium	10	which is within normal limits	deciding/finding	vital signs are in normal range	Medical History	n/a	n/a	Vital Signs	Blood Pressure	6:07	45

Figure 2. Example of Think-Aloud Protocol Coding

7.3.8 Design of the Coding Scheme

Initially, two researchers reviewed the verbal reports from two sessions and developed a draft coding scheme. An incremental and iterative process was followed to develop and refine the coding scheme. Once the coding scheme was finalized, the two researchers coded two sessions independently to refine and validate the coding scheme. Inter-rater variability was then calculated for each variable using the κ-statistic for a randomly selected patient case. The initial coding scheme developed by two researchers consisted of 29 process codes, including an "uncoded" option that covered four major types: information review or retrieval, information processing, deciding and other (see Table 5). *Information review or retrieval* included actions or processes involved with retrieving and reviewing patient information; for example, requesting information, asking a follow-up question, scanning records and reviewing images. *Information Processing* included actions or processes involved with processing the information reviewed, such as setting goal, hypothesizing, contextualizing and comparing/cross checking. *Deciding* included decision-making actions such as deciding on a finding, diagnosis or a treatment and making recommendations for a treatment or on a diagnostic procedure. Process type 'other' included actions that led to the conclusion or evaluation of one's own reasoning such as summarizing, wrapping up, and expressing ignorance. Table 5 shows the complete list of process types covered under these four major process types. Information artifacts consisted of patient information participants requested and reviewed in the three cases.

The 14 types of patient information sources used for the three cases were classified into three major categories: images, patient meta information and chart information. *Images* included all images such as intraoral images and radiographs. *Patient meta information* included information related to the general status and attitudes of the patient such as patient information, medical history, medications, medical consult, dental history and social history. *Chart information* included information typically documented in a patient chart during a dental exam such as hard tissue chart, periodontal chart and periodontal indices, extraoral and intraoral exam findings, study models, notes, pathology consult.

Table 5. Coding Scheme Developed by Two Researchers

Process types	Process codes	Definitions	Example statement
Information retrieval or review	reviewing	reading the findings	Chief complaint: "I have some cavities. Need teeth extracted. And my front teeth need fillings."
	information request	looking for specific additional patient information from experimenter or the patient (e.g. through questioning or clinical exam), making specific request	Looking at that, the next thing that I would like to know is a medical history
	follow-up question	seeking additional information as a follow-up to reviewing clinical information	So, she doesn't have anything such as diabetes, hypertension, heart disease, anything like that that we are aware of?
	scanning	look through or read through quickly	Basically, looking at these teeth, don't get me wrong, but if this were – if this patient were in my office,
Processing	focusing	concentrating attention on a fact, situation or question currently under review	I notice that patient is HIV positive; I'm looking at tooth No. 7
	setting goal	making a decision on what needs to be the next step. Something that has not been done and will be done in the future	I can now go, given this much time, I can now go and do my clinical exam and do a charting
	sequencing	ordering the different treatment or ordering the way to exam	I will give a quick look at the X--ray, the radiographic information that I have, and then I would check clinically.
	hypothesizing	a tentative explanation for a phenomenon used as a basis for further investigation or expressing uncertainty that needs further investigation to be confirmed	that also looks like it will have endodontic involvement
	contextualizing	assessing a finding in the context of another patient specific information	definitely, and it concurs with the patient's medical history,
	going back	directly (physically) referring back to information that was reviewed already (especially on paper)	Looking back at the panorex, at the apex,
	confirming	to prove something to be true; the coder needs to be there already once	But the patient, in my clinical charting, I would note that tooth No. 16 has retained root tips
	justifying	giving a reason or explaining why something is the case or was done. Look for words such as 'because'.	because of deep caries.
	recall	remembering something or bringing something back to mind; recalling from memory	Does she say? Was that in her history? She has had ortho?

Table 5 (continued)

	comparing/cross-checking	examining two different types of information for similarity	comparing - examining two different types of information for similarity
	prioritizing	ranking things according to importance	First I will do extract all teeth. I will then complete all restorations
Deciding	deciding/general	deciding on the general condition of the patient	So she seems to be a semi-client patient where she would go in for some dental work
	deciding/finding	deciding on a finding	From the mandible I can see again that she has some restorations.
	deciding/diagnostic	deciding on a diagnosis	I can already tell that she has a lot of cavities or caries
	deciding/treatment	deciding on a treatment	So most likely for that tooth I would diagnose removal of that tooth
	deciding/conditional treatment	a statement that states a treatment based on some conditions	If I was determining with the patient that we would be able to pursue endodontic treatment, then I would have to have a periapical film in order to perform that.
	ruling out	to exclude something	I don't see anything from this x-ray showing me any major lesions, any neoplasms.I don't see any foreign bodies here.
	recommending/general	make suggestions	and should be, if we have the option, in the ideal sense, we would want to preserve that tooth with endodontic treatment.
	recommending/non-treatment action	recommending an non-treatment action. Such as testing vitality, taking Xray	Every time that you see them, make sure that these lesions aren't necessarily getting bigger, not complaining of anything hurting, and things like that.
	recommending/treatment	recommending treatment	I would recommend for the patient to be placed on a night guard
Other Reflection	summarizing	stating the main points	I would take the wisdom teeth out. She'd have her teeth cleaned. And we'd just – and do those small pinhole cavities and, like I said, I would possibly even do sealants on her teeth if they're not caries
	wrapping up	coming to an end of the case	That's basically it. I think she's in good shape. I would just do those things I recommended. That would be it.
	expressing ignorance	expressing lack of knowledge about something	
	prognosis	a future oriented statement about the condition, disease or treatment of the patient	So for this patient actually most likely the pockets of fives and sixes are not going to resolve on their own.
	Not coded	any statement that does not relate to the patient at hand	if the sentence included the word 'always'

7.3.9 Data Analysis

Upon completing the coding of all 30 verbal protocols, the coded protocols were then analyzed to answer research question 1: "What is the pattern of information review, processing and decision-making when dentists examine new patient cases?" Ten dentists evaluated the same three patient cases of different levels of complexity, so cases are crossed within dentist. As shown in Table 4, there are three independent variables: dentist, case complexity (low, medium and high) and time_percent. Dependent variables include process type (PROCESS), which includes four possible values and information source (INFO).

The working hypothesis was that each dentist will exhibit a pattern of information review, processing, hypothesis generation and decision-making that is relatively constant regardless of case complexity. In addition, the process type frequencies were expected to differ depending on case complexity level. For instance, the low complexity case was expected to yield a relatively straight progression from information review to decision-making, while in the high-complexity case a participant might engage in several iterations of the review-processing-decision cycle before reaching a sufficiently refined treatment plan. For the medium and high complexity cases, participants also may develop alternative treatment plans. The analysis across dentists would identify whether there were any generalizable patterns in the dependent variables. The analyzed data were expected to yield much needed information about these patterns.

7.3.10 Analyzing Use of Information Sources Over Time

Examining the sources of information used was expected to provide important insights on which information is typically reviewed and in what order to make decisions regarding diagnosis and treatment planning. The information in the dental patient record is typically organized in the sequence and categories it is collected in, such as medical history, dental history and intraoral status. However, many clinical decisions are made using information from several categories. Our experiments were expected to reveal those patterns, and allow us to support them in the new EDR design. The average frequency of different information sources used over time was graphed against time percent in ten percent increments. This showed when the various information sources were used and in what sequence. Uses of information sources also were graphed over time to observe how a participant reviewed those sources and what patterns they used when retrieving and reviewing information for a case. The verbal protocols and video-recorded sessions also were analyzed to determine instances when participants reviewed more than one information source simultaneously and when and what kind of additional information was needed.

7.3.11 Analyzing Process Types Over Time

Analyzing the types of cognitive processing exhibited by dentists over time was expected to provide information about the relative distribution and frequency of information review, processing and decision-making activities. This knowledge would help in designing the user interface to support appropriate data review and entry workflows. The frequency of different processes such as information retrieval, processing, and decision-making and the information recording was graphed against the ten percent time increments. This analysis showed when certain information processing activities occurred, and in what sequence.

7.3.12 Statistical Analysis

Statistical analysis was performed using STATA software. Three independent variables were: dentist, case complexity (low, medium and high), and time_percent (see Table 4). Since the time taken for case completion were not the same for each case, an *time_percent* variable was created by converting time into percentage and using ten percent intervals. This helped in plotting data from all 30 cases on the same graph in ten percent time intervals. Dependent variables included process type and information source (see Table 4).

Mixed model analysis such as Poisson mixed model with a random intercept and negative binomial mixed model were performed to determine 1) whether the distribution of information sources was same or different; 2) whether the average number of dental history usage was different than the average number of radiographs usage; 3) whether the mean number of each information source used varied by complexity of the case; and 4) whether the distribution of information source used varied across dentists. *Process* types were also analyzed to determine 1) whether the distribution of process types were same; 2) whether the average number of information retrieval/review events were different than the average number of deciding events; 3) whether the mean number of occurrences of each process type varies by case; and 4) whether the distribution of process types varied across dentists.

For statistical analysis, the number of segment occurrences over time was considered the main outcome. Case time was expressed as the percentage of total case duration and was categorized in intervals of 10%. This gave 10 outcome measurements per case. Since each dentist reviewed three cases with varying levels of complexity, we expected the outcome measurements within a dentist to be correlated. In addition, there may be dentist-to-dentist heterogeneity. Poisson mixed models with a random intercept term were fitted to account for the potential within-dentist correlation. The covariates in the main effects model included complexity, process type, and time: linear (time), quadratic (time^2), and cubic (time^3). To derive an initial working model, a main-effects model, a model with all two-way interactions, and a model with all three-way interactions were considered. In addition, analogous negative-binomial mixed models were fitted to correct for the possibility of over dispersion in the data. The best initial model was selected based on the Akaike information criterion (AIC). Backward selection via likelihood ratio tests and Wald tests was then applied to develop the final model.

7.4 RESEARCH METHODS: CONTEXTUAL INQUIRY

7.4.1 Study Objective

As described in Section 4.3.1, it is important to observe how users perform their work and interact with clinical systems in the context of their work. To obtain this understanding, we conducted contextual inquiry in five dental offices. The research foci for the contextual inquiry were data acquisition, data entry and retrieval during initial examination and treatment planning during dental patient care.

7.4.2 Contextual Inquiry

Contextual inquiry (CI) as described by Beyer and Holtzblatt (119, 120) is a user-centered design method that is used to examine and understand how users perform their work within the context of their workplace and to understand their issues and preferences they experience when performing their work. It is typically used to develop an understanding of the users of an existing or a proposed system. A contextual inquiry (CI) (119, 120) usually consists of observing several users carry out their work in their work settings, documenting the observed data and analyzing it. Two research students observed the users and record data. The observers asked questions to the users during instances when they were not sure of users' actions or when they want to confirm their observations. At the end of each visit, observers entered their notes electronically and held a briefing session to confirm each others' findings. The notes were then used to create five models that capture the data in a usable format and help the research team understand and interpret the data. The concepts and themes that emerge from the data and the 'breakdowns' shown in the models when there is a problem formed the basis for design ideas. The five models typically created are flow models, sequence model, artifacts model, cultural model and physical model (119, 120). Briefly, the five models are described below:

The flow model displays individual's roles and their responsibilities and the information flow between the individuals involved in the work process. It also helps in obtaining a broad understanding of the work processes and the breakdowns that occur while performing work such as interruptions in communication and coordination.

A sequence model documents the steps involved in completing a work in sequence, the trigger that kicked off the steps and the intent or goal for completing a work. Any interruptions or problems encountered are marked as lightning bolts in red. The sequence model thus provides step-by-step instructions to designs on how work is actually done which helps them in designing the system.

An artifact model is a collection of artifacts used by individuals to perform their work. They could be a drawing or a photocopy of the things they used to get their work done. An artifact refers to the tangible things used and developed by people to complete their work. The model would also include information on the intent, strategies and structure of the artifacts used.

The physical model represents the physical environment where people work and how they interact with it. It includes information on how people move about, how the space supports or prevents communication and the location of tools used by people to do their work. The physical model helps in understanding the constraints in which individuals perform their work and how it influences their work.

The cultural model refers to the influence of emotion, standards, policies and preferences on work environment and people who perform work. This is because people and organizations often act as influences on one another.

7.4.3 Study Participant Recruitment

Convenience samples of five dental offices in Pittsburgh area that have a working relationship with CDI were recruited for the study. A sample of five dental offices was considered sufficient because this study built on a previous study that developed a preliminary model of work during initial examination and treatment planning appointments in dental offices (91).

7.4.4 Study Design

As described above, two research students performed all observations. Signed informed consents were obtained from the dentists and the dentists explained the study to the patient and obtained their verbal consent. Once verbal consent was obtained, the two research students started their observation of the patient visit. During observations, they recorded salient findings and observations and occasionally asked questions about what they observed. Once the patient visit was completed, the observers debriefed the dentist and dental staff and asked any remaining questions on the observation.

7.4.5 Developing Models

After the conclusion of each CI sessions, the two observers met for an interpretation session to review the observation notes and to develop the five CI work models. The research team developed the consolidated summative models for each model type after all sessions were completed. Once the models are developed, the research team held an interpretation session to obtain a shared understanding of the data to draw conclusions and design ideas from the data.

7.5 RESEARCH METHODS: PROOF OF CONCEPT DEVELOPMENT

7.5.1 Study Objective

We developed a paper prototype of the interface, based on the task model developed from the cognitive task analysis study and the user model and workflow models developed from the contextual inquiry study. This prototype was iteratively refined and evaluated through formal usability tests. (We have used the latter methodology in our preliminary study (21)). Based on these early usability tests, the paper prototype was further refined until it was translated into a wireframe prototype.

In this study phase of developing prototype, a group of Masters in Human Computer Interaction (MHCI) students from the Carnegie Mellon University developed the prototypes and conducted formative evaluation under my supervision. The student group included students with bachelors' degrees in computer science, cognitive psychology or in human-computer interaction. The wireframe prototype is a set of screen designs that include labels, controls and sample data, and allow basic navigation by the user. Its visual design is not highly refined, because the emphasis is on the design of screen layout and functionality. The student with programming experience developed the wireframe prototype in Adobe Air (Adobe Systems, San Jose, CA). A user interface designer and a Human-Computer Interaction consultant assisted in the process. We used Adobe Air because it is a convenient programming language for prototyping, allows for full control of the look and feel of the user interface, and requires comparatively less coding effort than, for instance, Java.

The wireframe prototype was evaluated iteratively through formal usability tests, heuristic evaluation and other user-centered evaluation methodologies. Once the wireframe prototype was sufficiently mature, we began constructing a high-fidelity prototype. The final, high-fidelity prototype has a polished visual design and fully working screen navigation and was named DMD Prototype. It displayed sample data and provide capabilities for data retrieval. The user was able to interact with the application as if it were a production application, with the exception that it did not have any database-based storage and entry of data.

7.5.2 Formative Evaluation

A formative evaluation of the high fidelity prototype was conducted through formal usability testing, keystroke level model and administration of questionnaire for user interaction satisfaction (QUIS) (156). Usability testing identified usability problems when users interacted with the prototype, the Keystroke-Level Model (KLM) predicted task execution time for a specific design and specific task and QUIS measured user satisfaction.

The *KLM* is a method developed by Card and Moran (157, 158) to predict user performance. It essentially answers the following question: "How long will it take for an expert user of an interface design to complete a given task?" The KLM lists the sequence of keystroke-level actions a user must perform to complete a task and then adds up the times required for the actions. There is no representation of users' higher level goals and cognitive processes; it includes only low-level actions needed to complete a task such as pressing a key or pointing with mouse. These keystroke actions are called operators and KLM consists of a standard set of operators with execution times estimated using experimental data. The KLM attempts to accurately represent the times for the users' cognitive, perceptual and motor processes necessary to perform actions and can also consider system wait times.

The *Questionnaire for User Interaction Satisfaction* (QUIS) is a validated tool developed by the Human-Computer Interaction laboratory at the University of Maryland to measure user satisfaction (156). The QUIS measures the overall subjective reaction of a user to a computer system, and assesses satisfaction with the display of graphics, readability, reliability, understandability and other features.

7.5.2.1 Study Objective The objective of formative evaluation was to identify usability problems in the high-fidelity prototype, estimate expert user performance with DMD Prototype and measure user satisfaction.

7.5.2.2 Study Participants and Recruitment A convenience sample of eight general dentists in Pittsburgh area and dental faculty at the University of Pittsburgh School of Dental Medicine who have a working relationship with CDI were recruited for this study.

7.5.2.3 Patient Case A patient case with moderate complexity was selected from the pool of 80 patient cases available from the senior presentation class at the University of Pittsburgh School of Dental Medicine. A group of three dental faculty selected this case and ensured that complete documentation was available. The selected patient case was then entered into the DMD Prototype.

7.5.2.4 Study Design The usability testing was conducted using the think-aloud protocol. First, a student researcher briefly described the study and allowed the participants to practice think aloud using one or two tasks that were not part of the study. Once the participant was comfortable with thinking aloud, the student briefly introduced the prototype and described the functionalities and navigational features of prototype to familiarize participants with the prototype. The student researcher then asked the participant to review the patient findings using the DMD Prototype and develop a treatment plan. They talked aloud while they interacted with the DMD Prototype. The student researcher took notes of instances when participants experienced difficulty in finding information, was frustrated or expressed a design idea. Once the session completed, the participant were requested to complete the QUIS for user satisfaction. Each usability testing session was completed in 15-20 minutes.

7.5.2.5 Data Analysis The identified usability problems were summarized from the observer notes. The QUIS answers were summarized using descriptive statistics for the eight participants.

7.5.2.6 Key-stroke Level Model (KLM) A set of representative tasks (see Table 6) were developed by two dental faculty and a senior dental student (TPT, TKS, AM). The dental faculty ensured the tasks were selected based on the features available in the DMD Prototype and in a commercial system called EagleSoft version 14. One student researcher used the software called CogTool that calculates the time taken to complete a task in each system. It is a tool developed at the Carnegie Mellon University that calculates KLM accurately and quickly (159).

The time taken to complete a task in both systems were recorded and compared to determine which system took less time to perform the selected tasks.

Table 6. Representative Tasks to Perform Keystroke-Level Model

Tasks	**Time in seconds**	
	EagleSoft	**DMD Prototype**
View patient's picture		
View the hard tissue chart		
View all radiographs for tooth 6		
Open one of these radiographs		
Change the brightness/contrast		
Invert		
Undo/reset radiograph		
View the periodontal chart		
Look for patient's birthday, insurance		
View R Bitewing, change brightness/contrast and reset		
Compare bitewing to last visit's bitewing		
View today's bitewing in full screen		
Total		

7.6 RESEARCH METHODS: COMPARATIVE EVALUATION

7.6.1 Study Objective

The high-fidelity prototype, named the DMD Prototype, will be comparatively evaluated against a major commercial electronic dental record system, cEDR to determine the users' perception on information organization, navigation flow and usability. Our working hypothesis is that the users will perceive the DMD Prototype to have an improved 1) information organization 2) navigation flow and 3) usability than a system not designed based on cognitive engineering methods. A 'within subject design' will be employed and participants will be randomized to work first with the DMD Prototype or cEDR.

7.6.2 Study Participants and Recruitment

A convenience sample of five dental faculty and five senior dental students with in-depth experience of using cEDR (> two years) were recruited for the study.

7.6.3 Video-recordings of the process of reviewing a simulated patient case

Videos will be created that demonstrate how to perform the following tasks in the DMD Prototype and cEDR:

1. obtaining a general overview of the patient's status and the reason for the dental visit;
2. reviewing all information pertaining to tooth #30 to arrive at a diagnosis and develop a treatment plan; and
3. reviewing the radiographs for the patient and identifying missing teeth.

The tasks were developed with the assistance of two practicing general dentists. These tasks were also created to correspond to the typical information review and management activities performed by dentists during a patient visit. During a new patient exam, dentists first review the information to assess the general status of the patient and then proceed to examining each tooth individually after a quick assessment of the oral cavity. For the first two tasks, the information presentation and the sequence in which they are reviewed are different in the DMD Prototype and cEDR. The third task of reviewing radiographs is similar in both the DMD Prototype and cEDR.

7.6.4 Study Design

On the day of the study, a study researcher 1) described the study goals to the participant; 2) explained the experiment that includes watching video recordings of reviewing information in both the DMD Prototype and cEDR; and 3) subsequently answered questions on the information organization, navigation and usability in both systems. The study researcher then played the videos to the participants to demonstrate how they could perform the above three tasks of information review in the DMD Prototype and in the cEDR. The participants were randomized so that half of the participants watched the video from the DMD Prototype first and the other half watches the video from the cEDR first. Once the participants completed watching the videos, the study researcher interviewed them to explore their views regarding information organization, navigation flow and usability of the DMD Prototype and cEDR. The participants were asked to answer in the order in which they reviewed the two systems. At this time, the participants were allowed to interact with the DMD Prototype or with cEDR, if they wanted, to help them answer the questions. Finally, the study researcher l also elicited participant suggestions on improving the DMD Prototype and also administered a slimmed down version of the Questionnaire for User Interface Satisfaction (QUIS). The researcher recorded the answers and subsequently transcribed them electronically.

7.6.5 Data Analysis

The transcripts were reviewed and analyzed using thematic analysis to summarize results on the users' perception of information organization, navigation flow and usability in the DMD Prototype and cEDR. Descriptive statistics were used to describe the results from the QUIS and paired t- tests were performed to detect statistically significant differences in the participants' responses to QUIS for cEDR and the DMD Prototype.

Table 7. Interview Questions to the Study Participants

Navigation flow
1. Was it is easy to get from one view of information to the next? Please explain.
2. Were program controls, such as buttons and menu items, labeled so you could understand what they did?
3. Was it clear what information you would see when pushing a button or choosing a menu item? If not, please explain.
4. Did the way of navigating through the information follow a logical order that facilitated the performance of the task? Please explain.
Information organization
5. Did you see all the information items that you were expecting for the task? If no, please explain.
6. Were any information items displayed in places where you did not expect them? If yes, please explain. Were the information items about the patient grouped in a way that facilitated the performance of the task? Please explain
System usability
7. How, in general, does the DMD Prototype compare to cEDR in supporting the tasks shown in the videos?
Final question
8. How could the DMD Prototype be improved to review information during patient care?

Table 8. Questionnaire for User Interface Satisfaction Used for the Comparative Evaluation

			0	1	2	3	4	5	6	7	8	9		NA
	OVERALL REACTION TO THE SOFTWARE													
1		terrible	□	□	□	□	□	□	□	□	□	□	wonderful	
2		difficult	□	□	□	□	□	□	□	□	□	□	easy	
3		frustrating	□	□	□	□	□	□	□	□	□	□	satisfying	
4		inadequate power	□	□	□	□	□	□	□	□	□	□	adequate power	
5		dull	□	□	□	□	□	□	□	□	□	□	stimulating	
6		rigid	□	□	□	□	□	□	□	□	□	□	flexible	
	SCREEN		0	1	2	3	4	5	6	7	8	9		NA
7	Reading characters on the screen	hard	□	□	□	□	□	□	□	□	□	□	easy	
8	Highlighting simplifies task	not at all	□	□	□	□	□	□	□	□	□	□	very much	
9	Organization of information	confusing	□	□	□	□	□	□	□	□	□	□	very clear	
10	Sequence of screens	confusing	□	□	□	□	□	□	□	□	□	□	very clear	
	LEARNING		0	1	2	3	4	5	6	7	8	9		NA
11	Learning to operate the system	difficult	□	□	□	□	□	□	□	□	□	□	easy	
12	Exploring new features by trial and error	difficult	□	□	□	□	□	□	□	□	□	□	easy	
13	Remembering names and use of commands	difficult	□	□	□	□	□	□	□	□	□	□	easy	
14	Performing tasks is straightforward	never	□	□	□	□	□	□	□	□	□	□	always	

8.0 STUDY RESULTS

8.1 CHAPTER OVERVIEW

Chapter 8.0 summarizes the results of the research study reported in this document. The chapter's four major sections address the results of the cognitive task analysis, the contextual inquiry, the proof of concept development and the comparative evaluation. Results of the cognitive task analysis describe how participant clinicians used case information to examine, diagnose and design treatment for the assigned clinical cases. The sequence in which they accessed and used various records is explained, as well as how that sequence changed for cases of differing complexity. Section 8.3 reports findings related to the analysis of dental context in five sample dental offices. It describes types of physical spaces within the offices, including examples of technology integration, documents various roles and tasks common in these offices, and emphasizes the importance of collaboration and time. The proof of concept section of this chapter summarizes the process and results of concept validation, the iterative design of paper prototypes, and the design of the high fidelity prototype. It includes findings from usability and keystroke level modeling analyses. Finally, the chapter reports findings from comparison testing of specific functions within the DMD Prototype with those functions in other commonly used programs.

8.2 COGNITIVE TASK ANALYSIS STUDY RESULTS

Five dental faculty and five practicing dentists in Pittsburgh area participated in the study. Six of the ten participants were male and five participants were graduates of the University of Pittsburgh School of Dental Medicine. All participants completed the development of diagnosis and treatment plans for three standardized patient cases. The average time spent by participants reviewing and developing a treatment plan for the three patient cases was 73 minutes (standard deviation 22 minutes). Table 9 shows the average time spent by each participant for each type of case. Table 9 also shows the average number of segments in the verbal protocols by case complexity. The ten transcribed verbal protocols consisted of a total of 6631 segments, an average of 664 segments (per participant). Each segment represented a single sentence or a single patient item. Overall, the number of segments appeared to be constant over time regardless of case complexity. However, the rate of segments per second was higher for the low complexity case than for the medium and the high complexity case. This suggests that dentists are able to process information more quickly with a low complexity case than with a medium or a high complexity case.

Table 9. Average Time Spent by Participants and Average Number of Segments

Patient case by complexity	Average time spent by each participant (minutes)	Standard deviation (minutes)	Average number of segments (rounded)	Standard deviation for number of segment
Low	17	7	158	65
Medium	25	7	240	89
High	31	14	266	106

8.2.1 Information Source Usage over Time

In the sections below, I first describe examples of how two participants worked through two cases, one a low complexity case and the other a high complexity case. Subsequently, I describe which information sources the ten participants requested and reviewed while working with the three patient cases.

8.2.2 Information Use for Low Complexity Cases

When working with the low complexity case, participants typically reviewed patient information in a linear sequence. Figure 3 shows how participant 3 reviewed the information sources for a low complexity case. Following the figure is a description of the sequence in which participant 3 reviewed information sources for the low complexity case.

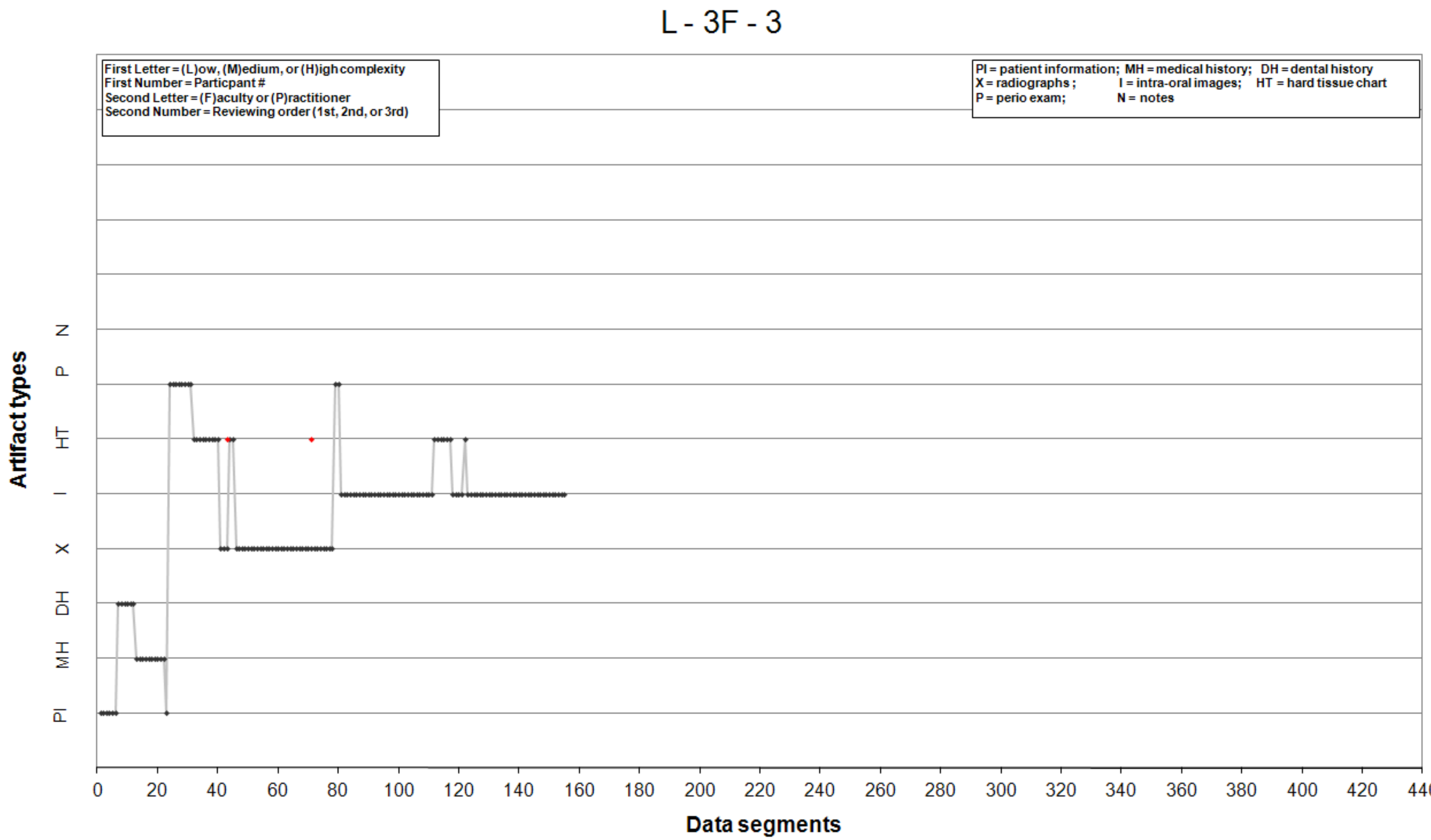


Figure 3. Graph Showing How a Participant Reviewed Different Information Sources in Sequence for a Low Complexity Case

Participant 3 started by reviewing the patient information followed by the dental history and the medical history. At this point, the participant decided that the patient was healthy and confirmed it by going back and reviewing the patient information. Next, the participant reviewed the periodontal chart for probing depths since the chief complaint of the patient was to clean teeth. When deep pocket depths were observed around certain teeth, participant reviewed the hard tissue chart to obtain additional information about these teeth such as the presence/absence of caries or stains. Participant 3 also reviewed information documented for all teeth on the hard tissue chart to determine the presence of any caries, stains, existing restorations and root canal treated teeth. Upon noticing the presence of impacted wisdom teeth recorded on the hard tissue chart, he/she reviewed radiographs to confirm their presence.

The participant also examined each tooth individually on the radiographs starting with upper right third molar, progressing to upper left third molar and then moving down to lower left third molar and ending with lower right third molar, a standard upper right to lower right sequence UR→LR sequence. He/she decided the patient was a routine patient who needed teeth cleaning especially in the lower anterior region and that no other major conditions existed. Participant 3 then asked to see the clinical photos to confirm findings from the radiographs. He/she first looked at the upper arch and lower arch photos to assess the presence of caries and then examined each tooth individually following the UR→LR sequence.

During this time, the participant finalized the findings and diagnoses and also made recommendations to maintain patient's oral health. At one point, the participant went back to the hard tissue chart briefly to confirm that the impacted lower wisdom teeth were documented accurately on the hard tissue chart. Finally, he/she confirmed patient's chief complaint to be consistent with clinical findings, which marked the end of the session.

8.2.3 Information Use for High Complexity Cases

Figure 4 shows how participant 2 reviewed the information sources for the high complexity case. In this section, we describe in detail the sequence in which participant 2 reviewed information sources for the high complexity case.

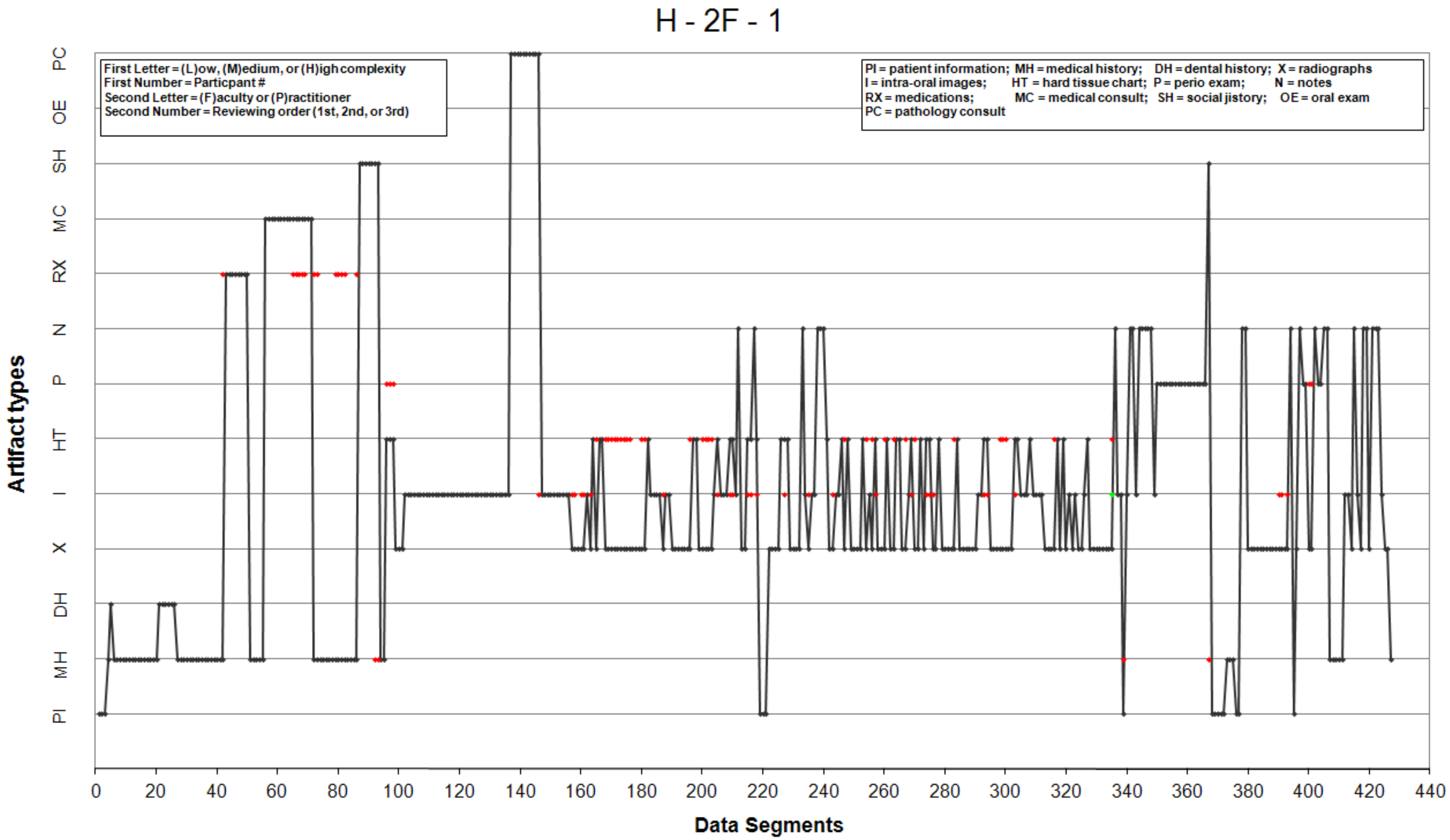


Figure 4. Graph Showing a Participant Rapidly Switching Between Different Information Sources for a High Complexity Case

As described in the previous example, participant 2 also started with patient information, dental history and medical history of the high complexity case. Since, the patient had a history of HIV, participant 2 spent some time reviewing medical history and requested medication lists and any referral letter from the primary care physician. Participant 2 reviewed the medication list and the medical consult from the PCP along with the patient's medical history to determine whether he/she was fit to undergo dental treatment. This participant also reviewed the patient's social history, to learn about his/her background, smoking status, occupation and financial status such as dental insurance to pay for dental expenses. He/she also was triggered to view social history due to the nature of the patient's chief complaint, "I have some cavities, need teeth extracted, and my front teeth need fillings," which indicated significant dental issues and treatment needs. These activities occurred mostly within the first 20% of the session's duration (see Figure 7 on page 84). Once the participant decided that the patient was eligible to undergo a dental exam with antibiotic prophylaxis, he/she moved on to review the patient's oral status. Participant 2 started by briefly reviewing the hard tissue chart, radiographs and then proceeding to do an oral exam by reviewing extraoral and intraoral images. He/she reviewed the images to examine the soft tissues status and, upon noticing an intraoral soft tissue lesion, requested a biopsy and a pathology consult. The participant then read the pathology consult that diagnosed the lesion as 'Condyloma acuminatum' and recommended surgical excision. He/she decided it was a benign lesion and proceeded to examine the patient's palatal tissues, the buccal mucosa, the tongue and the floor of the mouth. He also established a goal of performing an oral cancer screening considering the patient's high risk due to his underlying systemic condition.

Next, participant 2 examined the teeth on the radiographs following the UR→LR sequence. The participant examined each tooth individually for the presence of caries, extent of caries, existing restorations, root canal treated teeth and missing teeth. He/she diagnosed and confirmed his/her findings by also reviewing the hard tissue chart and intraoral images in addition to the radiographs. The presence of many teeth with caries and existing restorations in this high complexity case necessitated the participant to switch between radiographs, intraoral images, and the hard tissue chart. Sometimes the participant also reviewed these information sources simultaneously. The red dots in Figure 4 indicate instances when participants reviewed information simultaneously with another information source. Figure 4 also shows how participant 2 made notes on a finding or a treatment plan when reviewing radiographs and images. In between, he/she also went back to patient information to confirm that the patient was not in pain. Subsequent to examining the teeth, the participant decided to examine the patient's periodontal status by reviewing the periodontal chart. He/she reviewed the probing depths and identified areas with deep pockets and planned for root planing and scaling. At this point, the participant went back again to the patient information and social history to determine the patient's financial status. He/she then returned to radiographs and started finalizing and recording the patient's treatment plan. While finalizing the treatment plan at the end of the session, the participant went back to medical history and patient information to decide on counseling for smoking cessation and reduced sugar diet.

8.2.4 Use of Specific Information by Participants

Protocol analysis revealed that participants spent approximately 80 percent of their time interacting with patient information during diagnosis and treatment planning of the three cases. As expected, they reviewed patient information more for the high complexity case followed by the medium complexity and the low complexity case (see Table 10). Radiographs and intraoral images were the most often used information (see Table 10) when they reviewed the three patient cases. Together they made up 72% of the information sources used. As described before, all dentists started by reviewing patient demographics and chief complaint, medical history and/ or dental history and then progressed to oral specific information included in the radiographs, the intraoral images, the hard tissue and the periodontal charts. Figures 5, 6 and 7 clearly illustrate how the ten participants reviewed the information sources for the three cases. As expected, the frequency of using information sources was less for the low complexity case when compared with the medium and the high complexity case. In the following sections, we describe what information participants reviewed while working their way through the three patient cases.

As stated above, all participants started by reviewing the patient demographics and the chief complaint, the medical history and the dental history. Although no participants followed the same order, five participants reviewed the patient demographics followed by the medical history, the dental history and the other four participants reviewed the patient demographics followed by the dental history, the medical history. One participant asked for neither the medical history nor the dental history for any patient case. Participants reviewed patient information to learn the patient's age, sex and ethnicity and to understand the patient's chief complaint and expectations for dental treatment. Some also wanted to confirm whether the patients were in pain based on the nature of their chief complaint (see Table 11). For instance, the patient's chief complaint for the high complexity case was to have decayed teeth filled and seven participants asked whether the patient had experienced any pain. However, only three participants asked about pain when they learned that the patient in the low complexity case only want her teeth cleaned. Several participants also asked for additional information such as patient expectations on getting treated and any symptoms related to the patient's wisdom teeth. Financial information was important to the seven participants who requested it because it influenced the final treatment plan for all the three cases (see Table 11).

Table 10. Total Frequency of Information Source Usage and Average Time Spent for Each Case

Patient information artifacts	Total Frequency (freq)	Frequency Percent (%)	High complexity case (freq)	Average Time (minutes.secs)	Medium complexity case (freq)	Average Time (minutes.secs)	Low complexity case (freq)	Average Time (minutes.secs)
Intraoral images	1958	37.3	574	6.20	758	8.8	626	7.2
Radiographs	1810	34.5	723	8.40	747	7.52	340	3.39
Medical history	336	6.4	184	1.53	88	0.46	64	0.24
Notes	157	3.0	104	1.16	45	0.38	8	0.6
Periodontal chart	251	4.8	91	1.4	97	1.37	63	0.45
Hard tissue chart	211	4.0	88	0.52	84	0.44	39	0.23
Patient information	152	2.9	60	0.34	52	0.19	40	0.9
Medical consult	56	1.1	56	0.34	n/a	n/a	n/a	n/a
Dental history	121	2.3	54	0.35	29	0.16	38	0.19
Medications	46	0.9	46	0.32	n/a	n/a	n/a	n/a
Study models	44	0.8	n/a	n/a	44	0.24	n/a	n/a
Social history	43	0.8	43	0.27	n/a	n/a	n/a	n/a
Extra-oral and intraoral exam	33	0.6	33	0.30	n/a	n/a	n/a	n/a
Pathology consult	31	0.6	31	0.20	n/a	n/a	n/a	n/a
Total	5249	100.00	2087	24.22	1944	20.11	1218	12.44

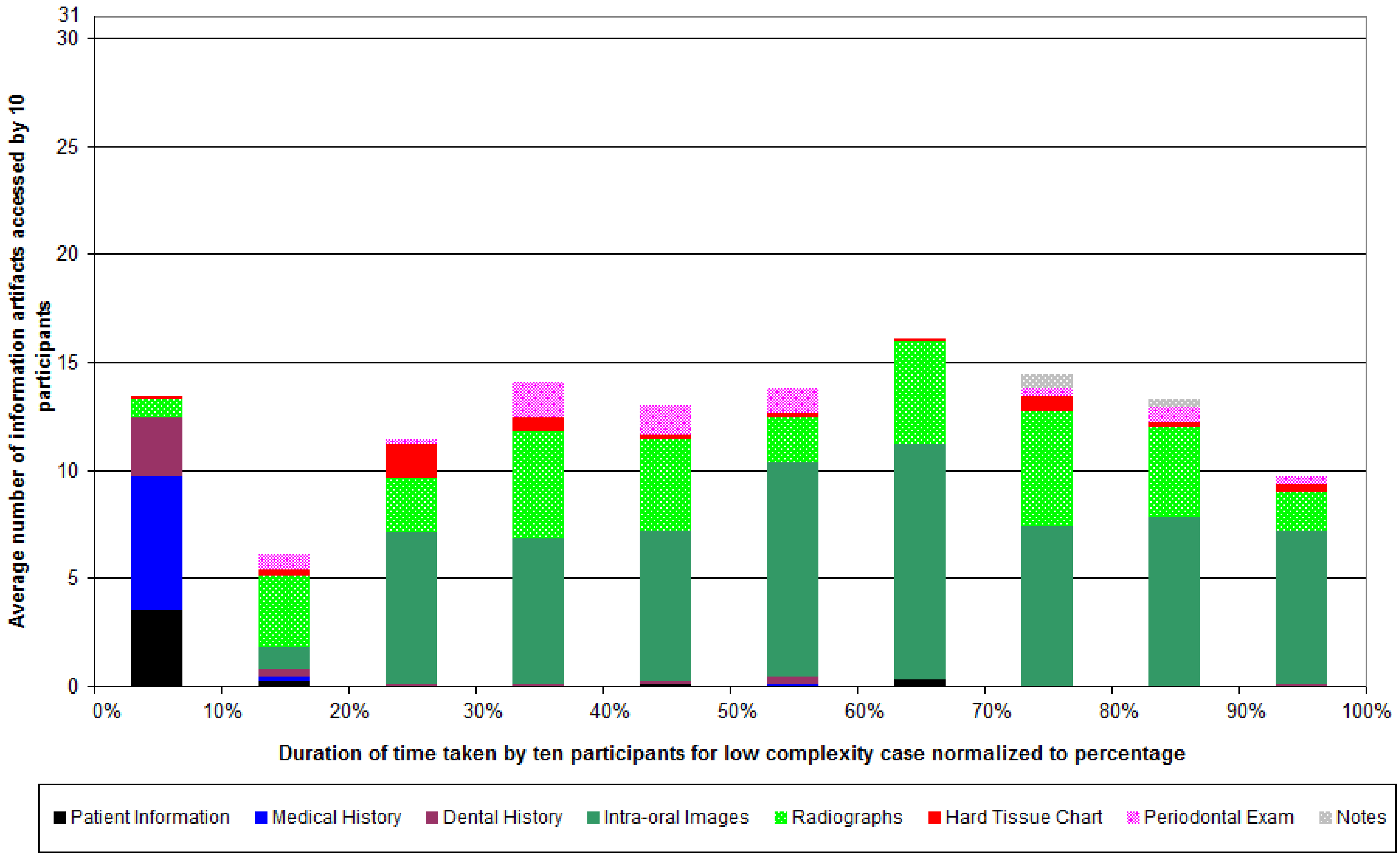


Figure 5. Average Number of Information Artifacts Accessed for a Low Complexity Case by 10 Participants

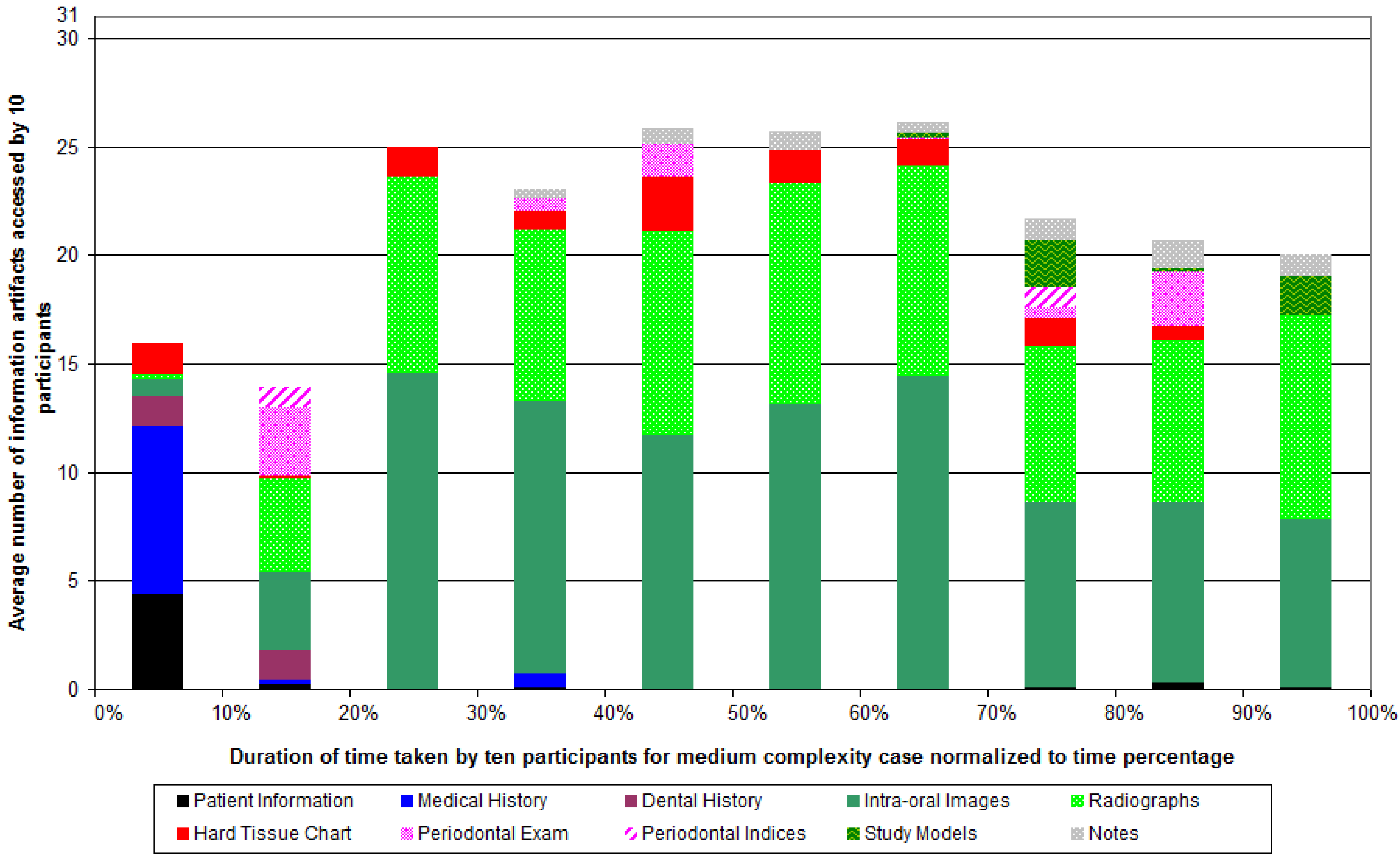


Figure 6. Average Number of Information Artifacts Accessed for a Medium Complexity Case by 10 Participants

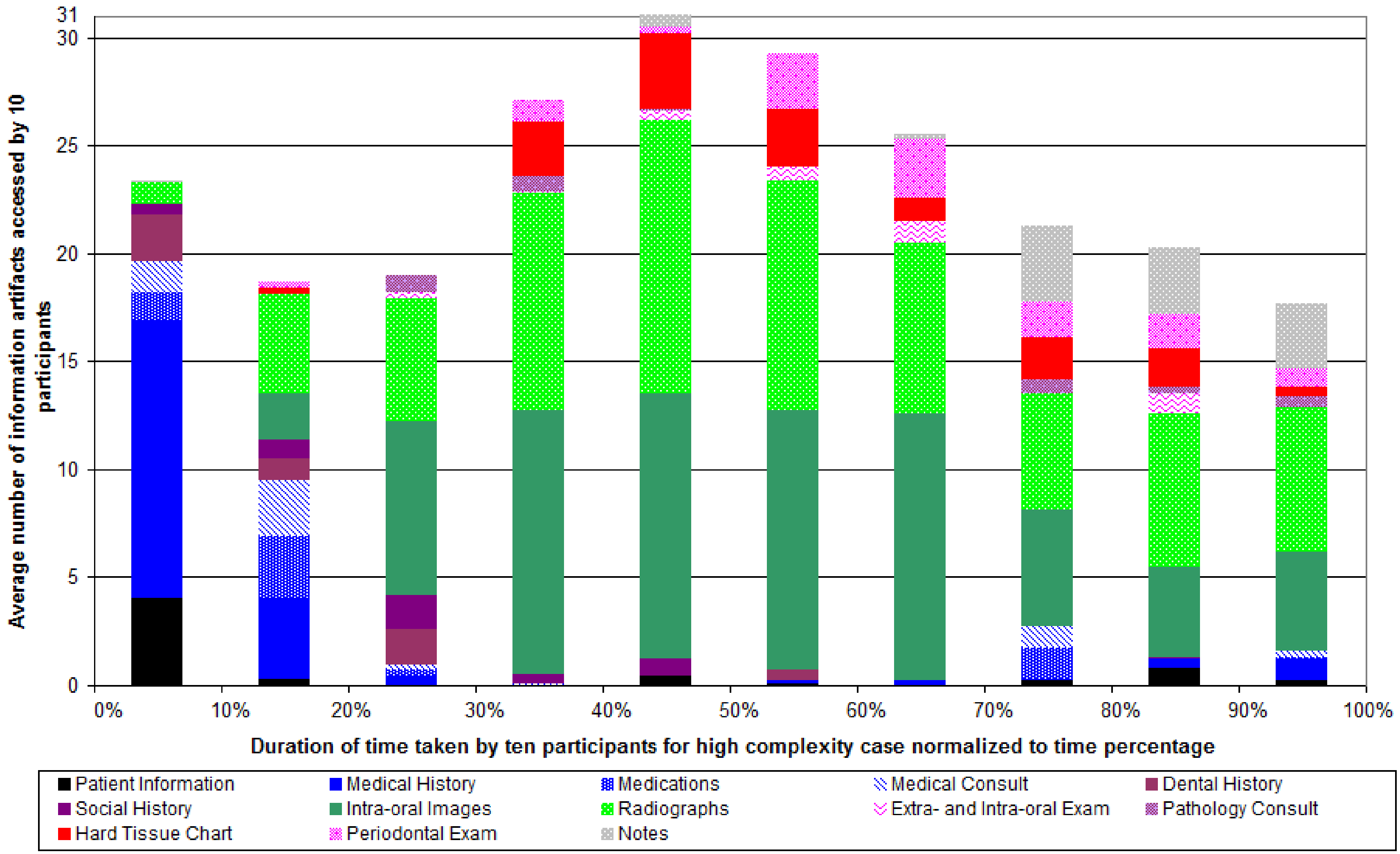


Figure 7. Average Number of Information Artifacts Accessed for a High Complexity Case by 10 Participants

Table 11. Additional Information Requested by Participants (Frequency in Parentheses)

History of pain (7) Symptoms related to wisdom teeth (2) Patient's expectations in getting teeth fixed: aesthetics or functional smile? (4) Patient's preference for treatment (4)
Date of last X-rays, previous X-rays (3) Radiographs taken before and after tooth cleaning (1)
Current physician name, Reason for being PS II (4) Allergic reaction type (2) Is patient pregnant? (1) Treatment history for pneumonia and hypertension (2) Hospitalization reason (4)
Reason for patient on antibiotics (3) Medication needs for nervousness during dental treatment
Patient's current lab values and viral load (6) Medical clearance for dental treatment (1) Patient's pre-medicated status (4) Current treatment for HIV and patient status (5)
Date of last cleaning, last dental visit (4) Date and details of orthodontic treatment (5) Reasons for not visiting a dentist (3)
Tooth mobility, PSR scores, Plaque index (5)
Date treatment of anterior teeth, crown material (5) Missing teeth, pulp testing results, occlusion and bite (4) Previous root canal treatments (1)
Patient's smile (2) Overall condition of patient's mouth (1) History of trauma to anterior teeth (1) History of parafunctional habits such as bruxism (3) History of any headaches (2)
Patient occupation (3) Patient diet, smoking, alcohol and drug use, brushing habits, patient's ability to understand English (3)
Financial information (7)

8.2.5 Medical History Information Usage

The primary reason participants asked about medical history was to determine whether the patients had any medical conditions that contraindicated dental treatment or needed additional precautions/pre-medications to receive the dental treatment. All participants sought information on the presence or absence of any drug or food allergies, allergic reaction type and the presence of any systemic diseases. They also wanted information on blood pressure and pulse rate recorded that day to confirm the patient's fitness for dental exam and treatment. If a patient had any underlying medical condition (HIV as in high complexity case), participants additionally asked for medications, medical consults with the primary care physician and the patient's social history such as occupation, drinking and smoking habits. Participants also wanted to know the reasons for taking the listed medications and any additional lab results and values based on patient's medical status. They also needed additional information, such as the patient's primary care physician's contact information, the reason for classifying the patient in the medium complexity case as physical status II patient and a description of the allergic reaction types (see Table 11). When reviewing the high complexity case, at least five participants wanted more information on the patient's current laboratory values for viral load, current status of HIV treatment and medical clearance to treat the patients' dental needs.

8.2.6 Dental History Information Usage

Participants next reviewed dental history to obtain information on past dental treatments received by patients. This information helped the participants in understanding the patient's preferences to dental treatment, previous experiences and their anxiety level to dental treatment. A patient's level of dental anxiety is important information for dentists when planning dental treatment because about 5-10% of US adults are estimated to have dental anxiety or fear. In general, more than half of the study participants asked for dental history when reviewing the three cases. In addition, participants also sought information on the last teeth cleaning and details of the orthodontic treatment with respect to the low complexity case.

8.2.7 Transition to Oral Exam

Once the participants obtained an in-depth understanding of the patients' general status and their past dental experiences, they proceeded to examine patients' oral status. The information sources they primarily used included intraoral images, radiographs, hard tissue chart and periodontal chart. Some participants asked for additional information such as study models to check the patient's teeth bite or occlusion, pulp testing results to determine vitality of the tooth pulp and the patient's smile or front profile photo to determine the teeth's influence on the patient's facial aesthetics (see Table 11). Overall, participants first reviewed the intraoral images and the radiographs to gather information and to make decisions for all three cases and later integrated information from hard tissue and periodontal charts to diagnose and develop a treatment plan for the three cases.

8.2.8 Intraoral Images and Radiograph Usage

Typically, all participants started with the intraoral images and first looked at the patient's oral condition, e.g., the oral hygiene of the patient, any obvious inflammation or swelling and color changes of the oral soft tissue. Finally, they also looked for missing teeth and carious teeth that may be present. They then proceeded to examine each tooth individually following the UR→LR sequence. During this time, they checked for any discontinuity or cracks on tooth structures that indicated tooth decay or fracture. They also checked for tooth mobility, which plays an important role in deciding whether to save or extract the tooth. They looked at radiographs for more information (such as extent of tooth decay or bone loss) or for confirmation of what they saw in the images. If participants started by reviewing the radiographs, they essentially followed the same order and integrated information from the images to confirm their observations.

This process of reviewing patient information was similar to that described in textbooks used to teach oral examination, diagnosis and treatment planning in dental schools. Participants also reviewed the charted documentation (hard tissue charts and mostly periodontal charts) either to confirm their findings or to obtain more information. However, radiographs and images were the primary information resources they used to diagnose and develop a treatment plan for the three cases. In addition, while the five dental faculty participants requested and reviewed the hard tissue chart, the five practicing dentists did not ask for the hard tissue chart. Instead, they said they would document all findings in the hard tissue chart while they performed the oral exam.

8.2.9 Variations among Participants and across Cases

Although participants used almost the same information sources for all three cases, there were some differences in how they used the information based on case complexity. For example, as seen in Figures 5, 6 and 7, all participants started with patient demographics, medical history and dental history. No significant differences were observed across the three cases on retrieving images, patient meta-information and chart information. However, it was found that participants reviewed patient meta-information (patient demographics, medical history, dental history, social history, medication list, medical consult) at significantly higher frequencies (p value < 0.01) for the high complexity case in the beginning of the session (20th time_percent) than for the low and the medium complexity case. This difference was most likely because the high complexity case had additional information on medications, medical consult and social history due to the patients' underlying systemic condition. Another interesting finding was that, while participants rarely went back to patient demographics, medical history, medical consult and medications at the end of the low or medium complexity case sessions, participants did go back and review this information for the high complexity case. Five of the 10 participants reviewed patients' medical history, medications and medical consult again when finalizing treatment at the end of the session.

Few participants recorded notes as they reviewed the three cases. However, those who did made fewer notes when reviewing the low complexity case and more for the medium and the high complexity cases. Participants also started writing halfway through the session for the medium and the high complexity cases and only towards the end of the session for the low complexity case.

8.2.10 Patterns of Information Retrieval and Review

It is important to learn the patterns of the participants' use of various information sources when diagnosing and planning treatment for the three cases. Video recorded sessions and verbal protocols were analyzed to graph the sequence in which the participants retrieved and reviewed information sources over time, how they switched back and forth between information sources when examining a patient case and instances when they viewed information sources simultaneously. Analysis revealed that participants exhibited three common patterns of reviewing information sources: 1) reviewing information in a linear sequence, which was mostly observed when they reviewed the low complexity case; 2) rapid switching between different information sources when they needed additional information or confirmation to make a decision on a finding, diagnosis or treatment; and 3) reviewing more than one information source simultaneously. The sections below describe the different patterns of reviewing and retrieving information by the participants for the three cases.

8.2.10.1 Reviewing Information in a Linear Sequence When working with the low complexity case, participants mostly reviewed patient information in a linear sequence. Figure 3 is the graph showing how a representative participant reviewed the information sources for a low complexity case. As discussed before, the participant started by reviewing patient information followed by dental history and medical history. Almost all participants reviewed these three information sources in a linear sequence both for the low complexity case and for the high complexity case. At this point, most participants made decisions on the patient's general health and then moved on to review the patient's oral status. In general, they reviewed the radiographs and the intraoral images, and these information sources were reviewed mostly in a linear sequence when they reviewed the low complexity case and to some extent when they reviewed the medium complexity case.

8.2.10.2 Rapid Switching Between and Among Information Sources Rapid switching between information sources was seen mostly when participants reviewed medium and high complexity cases. They mostly switched between radiographs and images to confirm their findings and to seek additional information on a finding. A few participants also switched between the radiographs and the hard tissue chart as seen in Figure 4, when participant 2 was reviewing high complexity case. Figure 4 also shows that participant 2 started switching between the radiographs and the hard tissue charts to review and confirm each tooth individually for caries and recurrent caries underlying existing restorations.

8.2.10.3 Reviewing Multiple Information Sources Simultaneously Participants reviewed at least two information sources simultaneously, especially when confirming their findings or finalizing their diagnoses and treatments. This pattern of information retrieval was observed mostly when they reviewed the medium and the high complexity cases that had multiple treatment needs. Participants most often reviewed the radiographs along with the intraoral images. Table 12 shows the number of times the participants reviewed these pairs of information sources and the time they spent reviewing multiple sources of information.

Table 12. Frequency and Time Participants Spent Reviewing at Least Two Information Sources

Information reviewed simultaneously		**High complexity case**		**Medium complexity case**		**Low complexity case**	
		Frequency	**Time (minutes, seconds)**	**Frequency**	**Time (minutes, seconds)**	**Frequency**	**Time (minutes, seconds)**
radiographs	intraoral images	115	14.33	163	20.53	19	2.4
radiographs	hard tissue chart	53	5.0	23	2.27	5	1.41
radiographs	periodontal chart	17	2.0	3	0.29	5	0.17
hard tissue chart	intraoral images	18	2.17	26	2.36	1	0.14
periodontal chart	intraoral images	19	1.58	3	0.35	1	0.8

8.2.11 Analyzing Process Types Over Time

Out of the 6631 coded segments, 13.8% were coded as the process type *information retrieval or review*, 26% as *processing*, 40.5% as *decision making* and 4.25% as the process type *other*. Process type 'other' comprised of segments coded as expressing ignorance, prognosis, summarizing and wrapping up. Of the total segments, 15.4% were not coded as they did not describe any patient case related information. In all 30 sessions, *information retrieval* occurred more in the first quarter and plateaued halfway through the case process (see Figure 8). At that point, *deciding* started to peak. Participants made more decisions in the middle phase and few at the end of the sessions. *Processing* was observed to be constant throughout all the sessions. As described before, participant 3 (as shown in Figure 3 in page 75) when reviewing the low complexity case, first reviewed the patient's chief complaint and demographics, the medical history and the dental history. Once the participant assessed the general status of the patient, which happened quickly, he/she went on to review the hard tissue and the periodontal chart, making many decisions on the presence or absence of caries on each tooth and on the gingival health of the patient. He/she also diagnosed and planned treatment while reviewing the two charts and then reviewed radiographs and intraoral images to finalize all findings and treatments. During this process, participants generally ruled out other potential findings or diagnoses, compared and cross-checked findings using more than one information sources and justified the treatment they recommended.

The pattern of process types, i.e. information retrieval, processing, deciding and other appeared to be the same over time in the three cases. However, case complexity had an effect on the process types (see Figures 8, 9, 10, 11 in pages 92-95). The frequencies of process types, especially information retrieval, processing and deciding, were higher for the high complexity case (see Figure 10). This is not surprising. As seen in Figure 4, the high complexity case had an underlying systemic disease that required participants to review additional information such as medical history, medication list, medical consult, lab values and social history. The incidence rates of process types were highest for the low complexity case. This may be because dentists processed information more quickly with the low complexity case than with the medium and the high complexity cases. The incidence rate for information retrieval was significantly higher at p value < 0.01 in the low complexity case. While the incidence rates for processing, deciding and other were higher in the low complexity case, it was not significantly high at p value = 0.05.

In the final model, the interaction of process types with case complexity and time were significant. For instance, in the case of medium complexity, the rate of *processing* is similar to *information retrieval* in the early phase and becomes more frequent in the later phases of the session. The rate of *deciding* is significantly higher when compared to other process types except in the initial time phase at 10%. The rate of process type *other* is low in all phases.

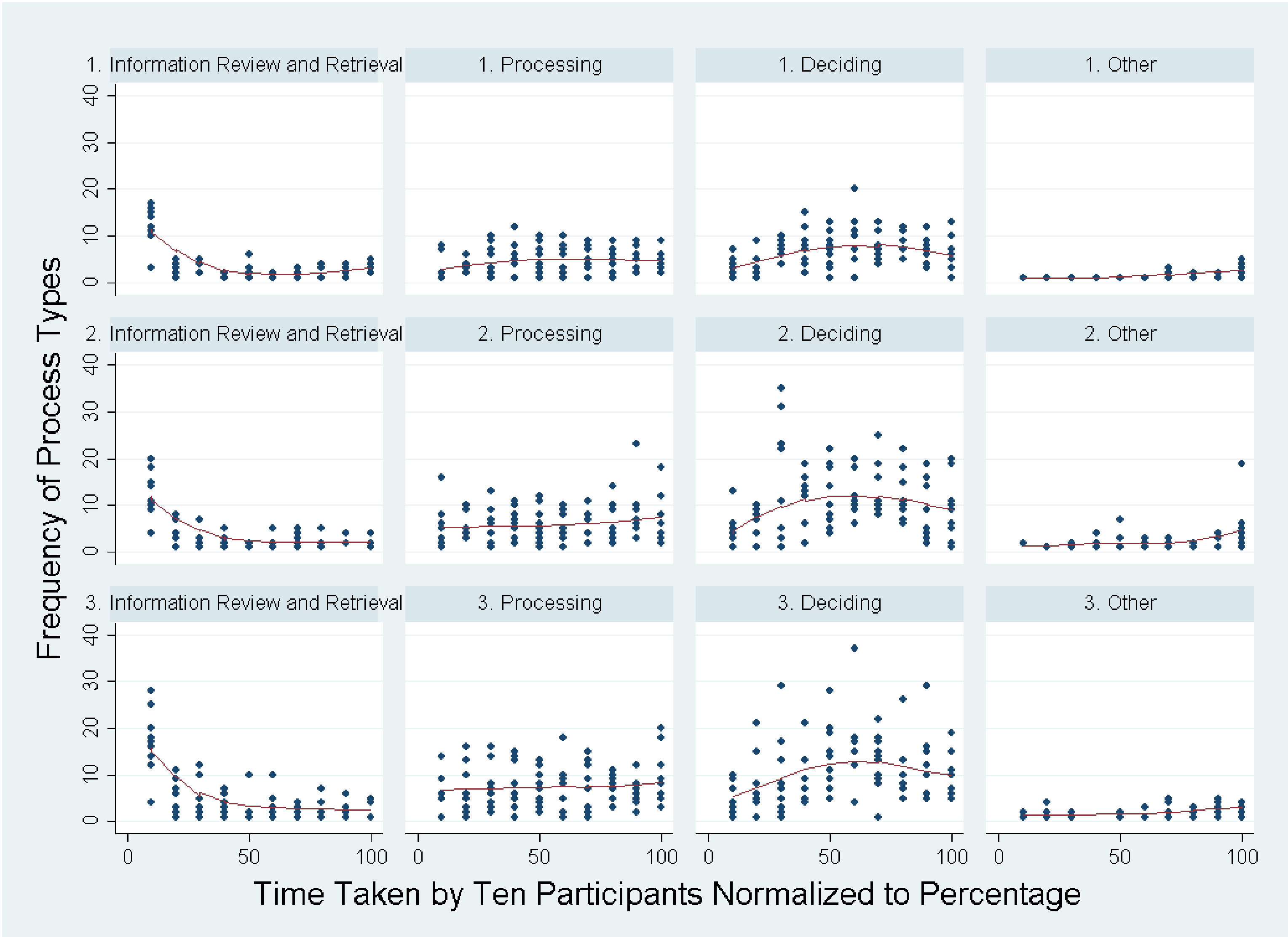


Figure 8. Patterns of the Four Process Types for the Three Patient Cases

Low Complexity Case (1), Medium Complexity Case (2), and High Complexity Case (3).

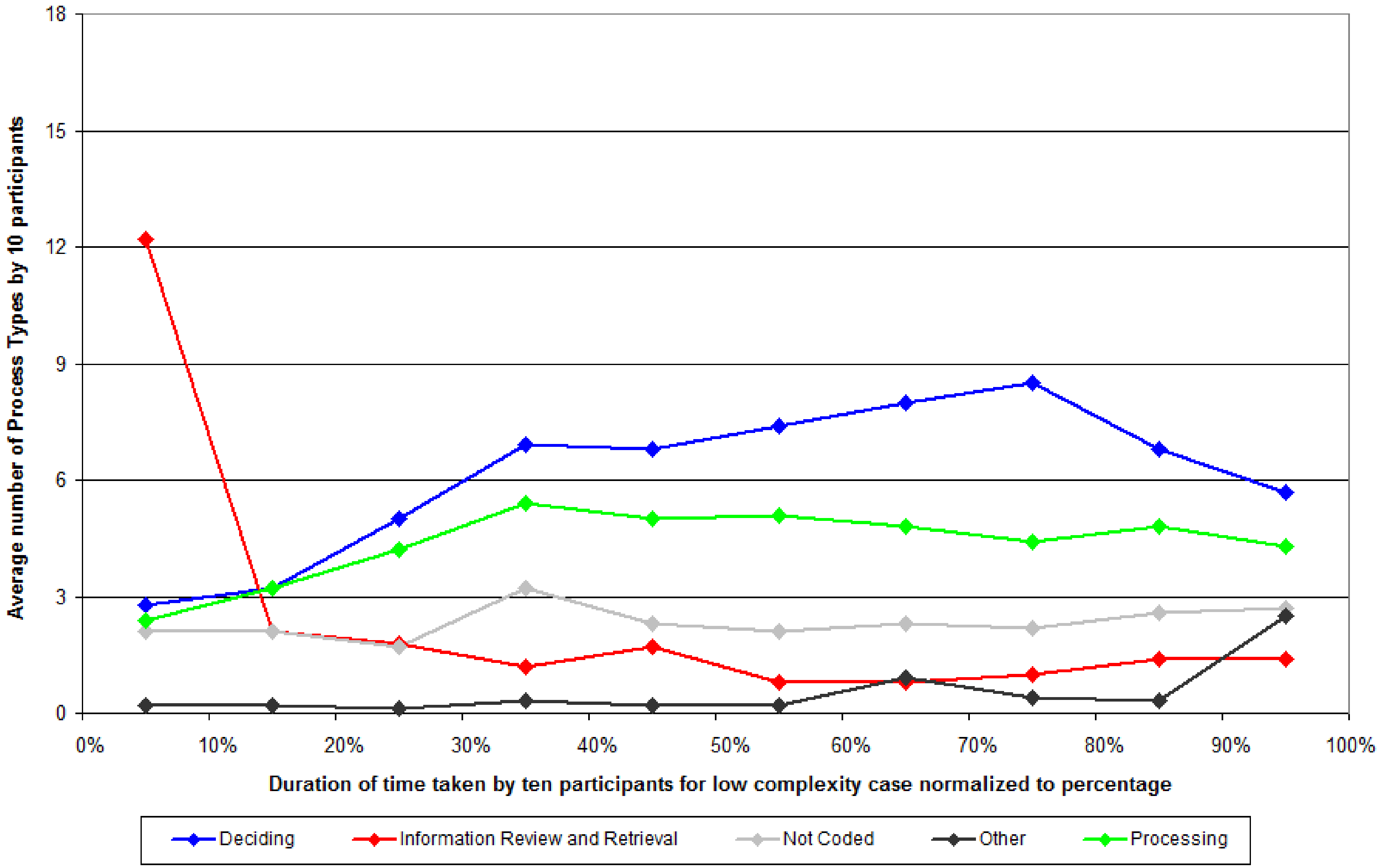


Figure 9. Graph Showing Average Number of Process Types for a Low Complexity Case by 10 Participants

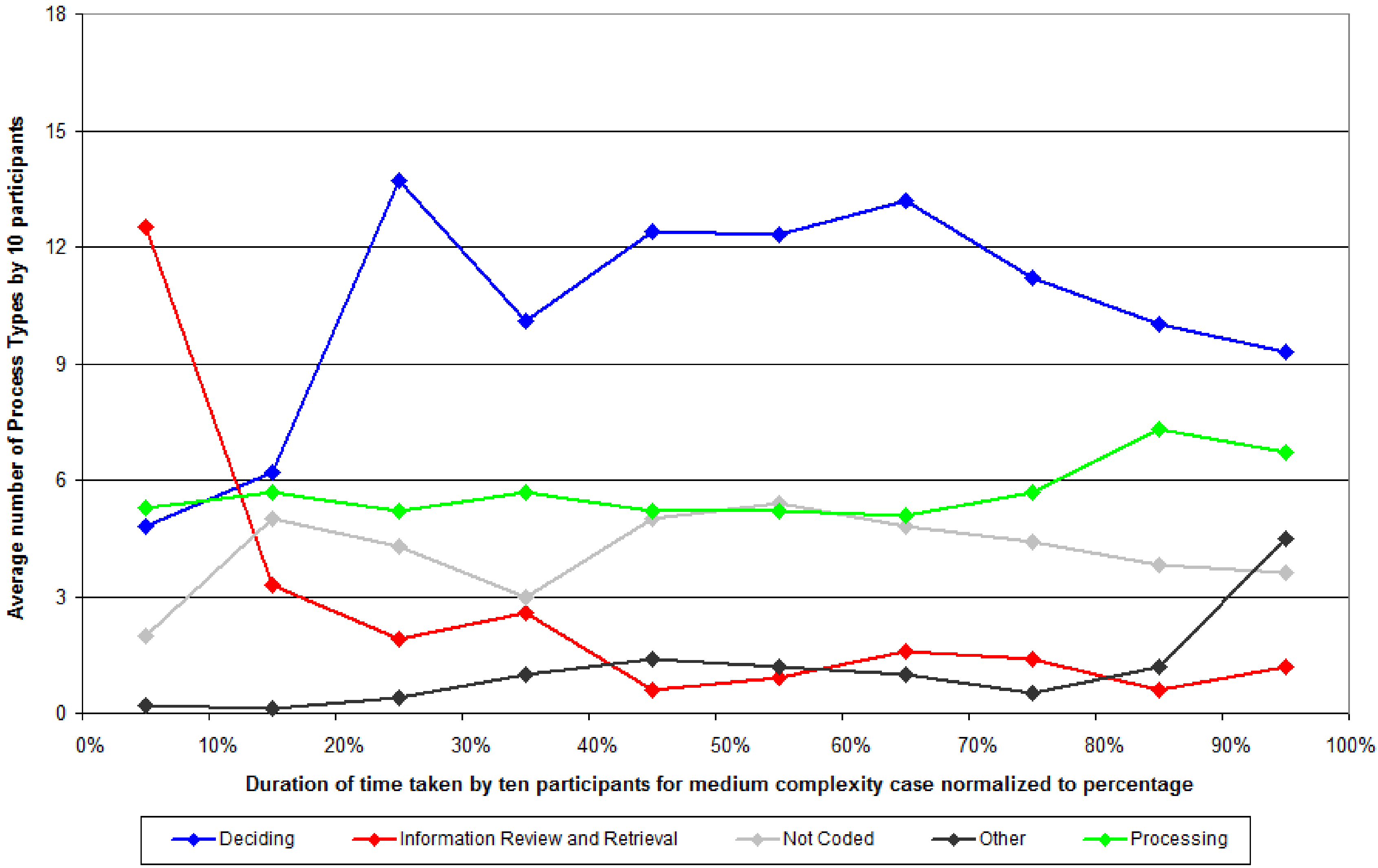


Figure 10. Graph Showing Average Number of Process Types for a Medium Complexity Case by 10 participants

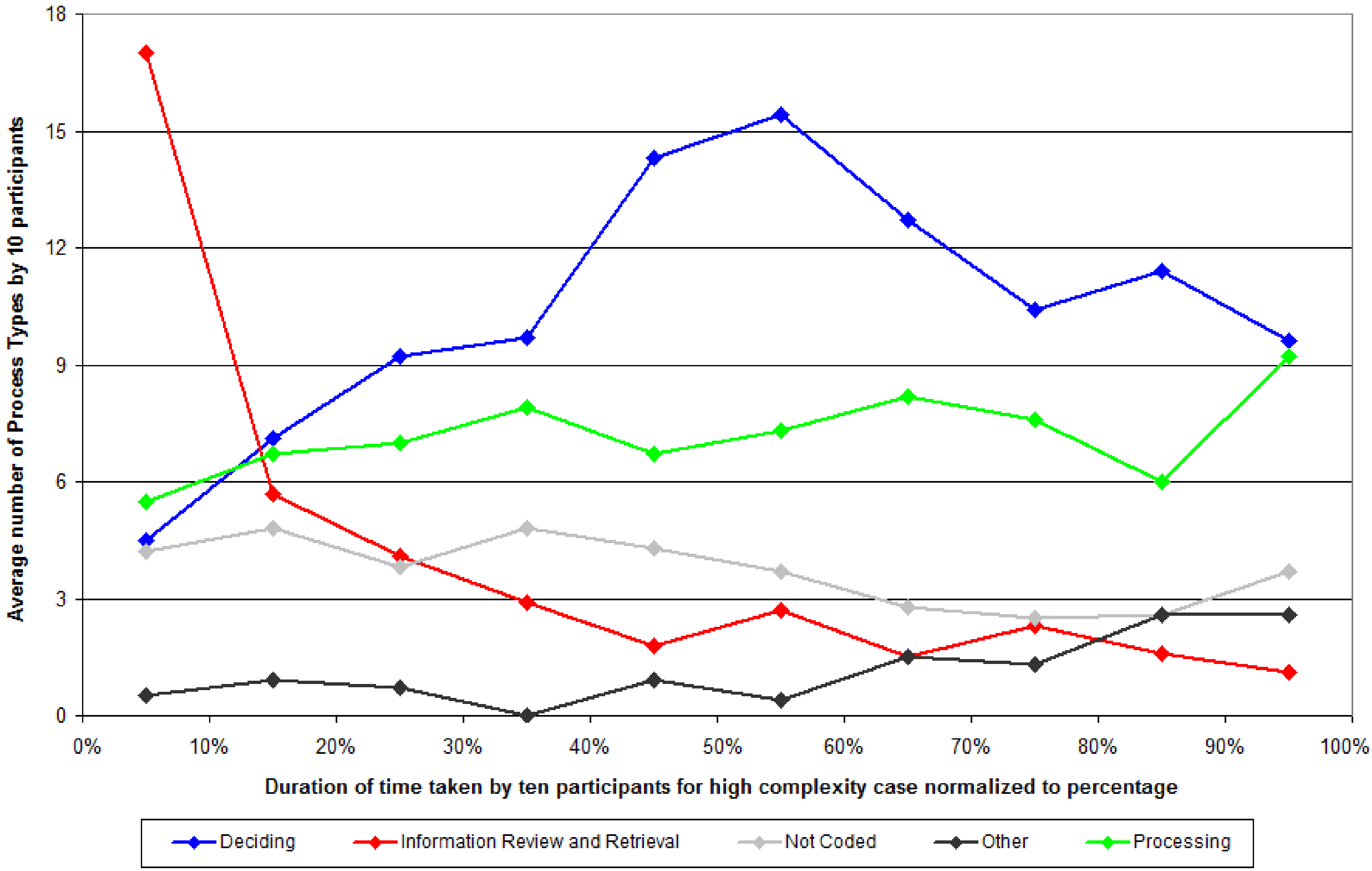


Figure 11. Graph Showing Average Number of Process Types for a High Complexity Case by 10 participants

The cognitive task analysis results provided a rich understanding of the dentists' information management and decision-making activities during a patient exam. The results offered valuable insights into what information dentists use, how they processed the information and what decisions they made. The detailed results helped with identifying the sequences in which the participants reviewed the different information sources, the different patterns of information retrieval and review and the information sources they accessed when they made decisions. These results were subsequently used as the basis to develop design ideas on how patient information should be presented to support clinician behavior. Tables 13 and 14 below shows the list of design ideas that were developed based on the cognitive task analysis results. While the sequences of information review and the patterns of navigation through the information helped us with designing flexible navigations, the patterns of process types such as information retrieval and review, processing and deciding helped with understanding what information sources need to be shown together or next to each other.

Table 13. Cognitive Task Analysis Results That Translated Into Design Ideas

	Design Idea	**Information sources used**	**Decisions**
1	Design an overview page that offers easy access to these information	Patient information, medical history or dental history, social history, medications, medical consult	General status of the patient
		Allergies and reaction type	
		Reasons for taking medications	
		Patient's profile or frontal photo	Facial aesthetics
		Financial information	Plan and finalize treatments
		Details of last dental treatment	Determine patient's dental status
2	Make the user aware of what photos and radiographs are available in the early phases of reviewing patient information. Show the presence, type and date of radiographs and photos taken.	Radiographs and Intraoral photos: most commonly used and the information sources that are accessed first to examine the patient's oral status	Decisions on the findings, diagnoses and treatment
3	Make the related transitions such as radiographs, intraoral photos, hard tissue and periodontal chart as easy as possible.	Hard tissue and periodontal chart used mainly for documentation and communication purposes Used as supplemental information in addition to radiographs and photos	Confirm findings and diagnoses
4	Enable data entry while reviewing data or examining a patient Use voice recognition or touch screen	Doing charting during exam	Abstracting and processing information
5	Have three dimensional models of patient's jaws and teeth	Check patient's bite and occlusion Use radiographs and photos to determine the extent of decay.	Determine problems with patient's bite or malocclusion, extent of decay

Table 14. Patterns of Navigation through Information That Translated into Design Ideas

Pattern of information retrieval	Design idea
Reviewing in a linear sequence	Support retrieving information sources in a linear sequence
Reviewing clinically relevant information in sequence or in a logical manner to make interim decisions such as the general status of the patient to undergo dental procedures,	Present related information about the same class of decisions together Ex: general status of the patient Entire dentition and oral cavity Single tooth decisions Sextants
Reviewing each tooth in a sequence on radiographs and photos	Enable users to move from one tooth to the other: starting with upper third right molar and ending with lower right third molar Make the layout of the photos and radiographs consistent to how they are navigated by clinicians
Rapid transition between radiographs and intraoral photos when examining the entire dentition and subsequently each tooth	Enable rapid switching between different information sources Support showing information from radiographs and photos on the same screen
Reviewing information from two information sources	Support showing information from radiographs and photos on the same screen
First scanning for relevant information and subsequently reading information in detail	Enable drill-down/bubble up capability

8.3 CONTEXTUAL INQUIRY

We conducted five contextual inquiries in five dental offices in the Pittsburgh area. We observed several patient appointments in each, viewing mainly patients new to the office. The foci of these sessions were to understand how data documentation and reviewing occurred in the context of patient care activities. Because of the HIPAA privacy regulations, we were unable to video record these sessions. As a compensation strategy, we used screen capture software to keep track of what users did on the dental software screen, making sure to censor out any sensitive information. Two observers trained in HCI typically observed a session and took notes. Per the standard contextual inquiry method, all sessions were modeled and consolidated to provide a cohesive view of the dental world.

8.3.1 Physical Models of Dental Offices

Physical setups were the most consistent across the five dental offices. As Figure 12 illustrates, a dental operatory consisted of a patient chair, one or two stools for the dental staff, and many supporting tools. A number of key insights could be obtained from the physical setup.

The most significant finding is that space is very limited in the dental operatories. Generally, all the tools a dentist needs cannot fit in the room itself, and overflow containers of tools are kept on shelves just outside the room or in another room altogether. This lack of space resulted in cramped computer setups. These cramped setups led to a number of flow issues, discussed below.

Another aspect of the physical setup was that important parts of examinations occurred in different rooms. The panoramic x-ray was always in a different room than the operatory, and the patient had to be led there and back during an examination. Computers were often split across rooms as well, with supporting computers for scanning X-rays or importing photographs in a different room.

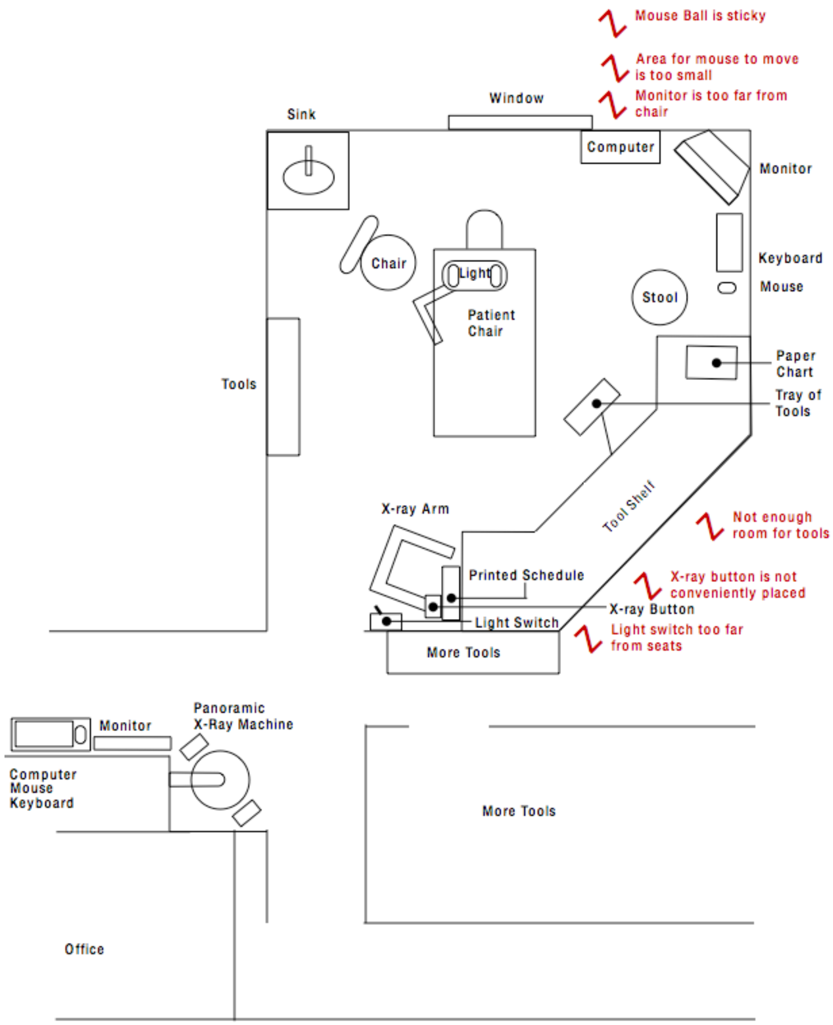


Figure 12. The Physical Setup of Dental Offices

As Figures 13 and 14 show, dentists took elaborate steps to integrate the hardware with their environments. Wall mounted keyboards and mice, although clever, were ergonomic disasters. Similarly, space constraints caused dentists to place keyboards in inconvenient places. This offered a clear and simple design implication: we need to integrate our system with the operatory space. At first glance, this most likely meant getting rid of the keyboard and the mouse and exploring other types of interactions. However, another possibility may be looking at innovative keyboards and mouse designs intended for space-limited environments. A trackball, for example, might be a big boon for large mouse movements.

Figure 13. Wall Mounted Keyboard in a Dental Office

Figure 14. Example of Poor Hardware Integration

Another important issue from our observations related to the patient' privacy concerns when planning physical setups. While a large screen might be good for displaying more information, there could be confidentiality concerns, especially if the screen is observable from the hallway. Due to lighting problems, several dentists struggled to view the monitor from where they were, which was often across the room. Sometimes they had to ask an assistant to turn off the lights so that they could see the screen. Therefore, the charts need to be designed so that they are viewable in many lighting situations.

This physical set up for reviewing records saw another constraint placed on it by standard medical procedures: everything needed to be disinfected. The Occupational Safety and Health Administration (OSHA) sets stringent requirements that must be met for equipment used in a medical setting (25), and these apply to computers as well. However, we consistently observed instances where these requirements were ignored. In one location, an assistant was observed working (with gloves on) in the patient's mouth, turning around and using the computer's mouse (still with gloves on), and returning to the patient's mouth, still with the same gloves on. When questioned, the assistant said they did not worry about infection issues with regards to the computer equipment because ‘the patient doesn’t go anywhere near the computer.’ Other offices tried their best to avoid spreading any disease, but practically speaking this meant putting on and removing gloves every minute. One possible constraint on our design direction may be looking at medical grade equipment to avoid this type of breakdown.

A final observation, and one reconfirmed by our cognitive task analysis study analysis, was that reviewing records literally meant the plural records. A single source of information was almost never enough to come to any meaningful conclusion. Instead, the users often needed to review the radiographs, the hard tissue charts, the soft tissue charts, and any other information available.

8.3.2 The Roles In Dental Offices

A naive view of dentistry might assign dentists the job of analyzing and treating teeth, and assistants the job of finding tools and dictating findings. However, our observations led to a much more complex view of the dental environment.

A quick view of Figures 15 and 16 reveal that across offices, there is a large overlap in what a dentist or assistant might do. This is in large part due to variance between offices. For example, in the first office the dentist dictated to the assistant. In the second office, the dentist and the assistant worked together on the patient. And in the third, the dentist was never in the room at the same time as the assistant or hygienist. These variations indicated that it is difficult to define the title ‘assistant’ in any single office. More specifically, it brought up a key design implication: we need to design for a role or roles, not for any official title like ‘dentist’.

Each of the roles had a number of interesting issues behind them, and here we describe the most critical observations. *The Create & Maintain Records* role was one of the most problematic. As observed in previous studies (20, 91), no office had a single set of records; instead, information was duplicated between the paper records and the computer-based records. This problem was compounded by the fact that records were not identical between the two mediums. Often, assistants or dentists would transcribe what they described as “the most important information” from the paper to the computer. Our glimpses were limited by the amount of time we were there, but one could imagine that this would present an issue when a certain piece of information needs to be reviewed. Does someone refer to the paper record or the electronic record?

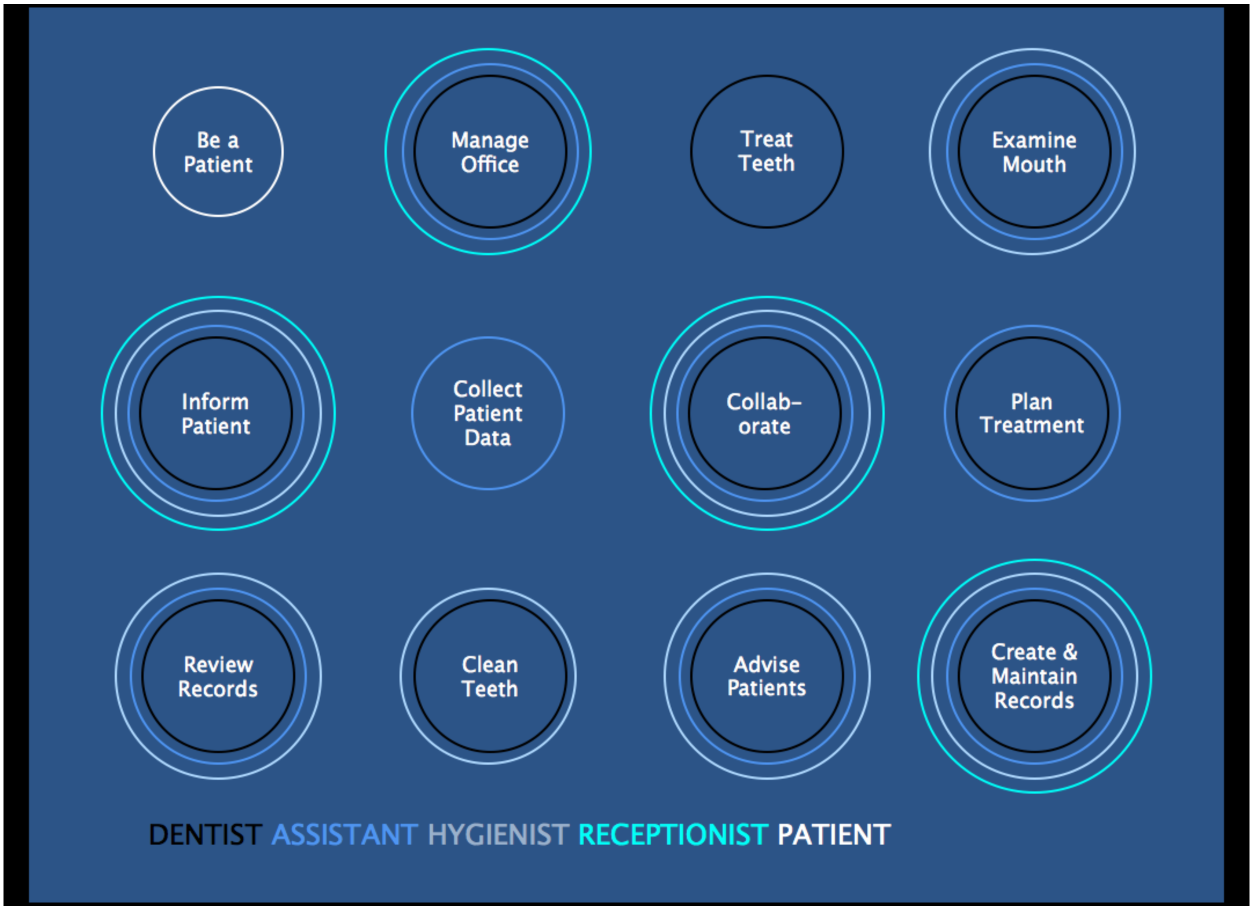


Figure 15. The Consolidated Roles from the Flow Model

Another problem inherent to the role was the poor design of the electronic charts. Inputting information into them was time consuming, and often all of the initial recording happened on the paper. Even paper was sometimes too slow – in one case, we observed the dentist dictating his findings to the assistant only to find the assistant had fallen behind. Permission problems also appeared multiple times. In one situation, an assistant spent well over 15 minutes and hundreds of clicks looking for a specific condition to add to a chart. When this failed, the dentist tried to find it only to come across the same problem. The insight into this breakdown was that, for insurance reasons, only the front desk had proper permissions to add the condition to the chart. While this may make sense from the perspective of the insurers, it makes little sense to the users. Paper overcomes this issue by avoiding permission problems altogether – anyone can write on a piece of paper.

Collect Patient Data was another role we examined in detail. Here, surprisingly, we found that digital integration had done small wonders. For example, digital X-rays were used in all the offices observed. The process went smoothly in all cases, in contrast to the findings by Irwin et al. (91), who found that digital X-rays caused breakdowns in workflow several times, and were quite complicated. The software in the offices we observed was connected to the X-ray machine in some way such that the assistant or hygienist could set the software to take the X-rays, position the patient and X-ray machine, take the X-ray, and it would appear on the screen. The dentist would later examine the X-rays. In all cases, the staff seemed pleased with the digital X-ray process. This is clearly one area where digitizing made a huge improvement. There is no longer any need to process and produce the physical X-rays, which also then would require a light box with which to be examined. Now, the X-rays can be seen on the monitor, and the dentist can adjust the X-ray if needed. One dentist we observed changed the contrast and brightness, for example, to better examine the X-ray.

Even this role of collecting data had a number of small issues, however. Often assistants collected information from a variety of sources – cameras, diagnodents, etc. – and found that they could not enter the information into electronic charts. This relates back somewhat to the *Create & Maintain Records role,* but assistants had to write this information on the margins of paper charts or use a separate program to manage excess data.

A final role we examined in detail was *Review Records*. The purpose of collecting and recording data is to be able to review it at a later date, but few paper or electronic charts seemed to support that notion. Problems were especially found with electronic charts. For instance, the users could not quickly switch between different types of information, although that is essential when reviewing records.

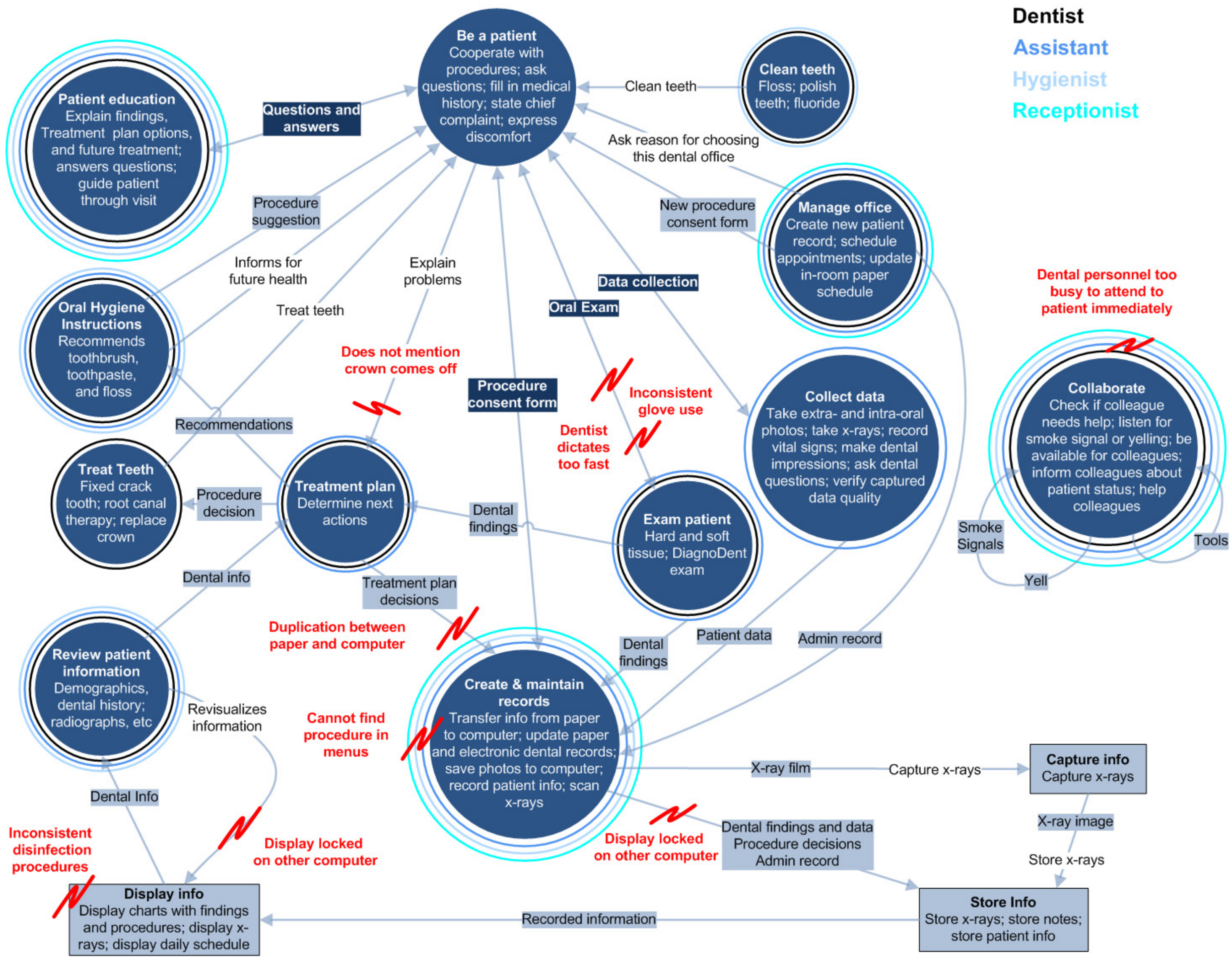


Figure 16. Consolidated Flow Model from the Five Dental Offices

8.3.3 The Cultural Model

The cultures of the dental offices observed were complex and offered a number of insights into the design process. As the consolidated cultural model in Figure 17 demonstrates, there were many influencers (or people) exerting influence on others. Describing every aspect of the culture would be an exhaustive process, and therefore this description focuses on the most influential interactions.

The most significant and consistent aspect of the dental office culture is that collaboration is not only expected, but also vital to the whole process. Staff consistently asked one another for help, generally physical help for obtaining tools or diagnostic help with understanding problems. Usually, this manifested itself by yelling over to the next operatory asking for assistance. In one of the larger offices, however, this meant a formal 'smoke signal' system. In this system, staff could trigger certain sounds – waterfalls, lion roars, etc. – to play across the entire dental office. Each sound corresponded to a person and upon hearing that sound they knew they were needed. A bit complex, but it certainly illustrated the importance placed on collaboration.

Another cultural aspect consistently observed was the staff's varied levels of experience with the dental software they used. Vendors came in yearly to train the staff, but this was obviously insufficient. Assistants were often new, meaning they had received no training and needed to ask for assistance when they got stuck. On the other end of the spectrum, some dentists had used the same software for years and had become intimately familiar with its use. In one extreme example, a dentist moved the cursor and began clicking for the next step before the screen had finished loading. The design implication from this observation is that any system we build needs to support both novices and experienced users.

One last cultural observation, but still an important one, was that time was extremely valuable to dentists. They were easily the largest bottleneck in the office, and assistants were constantly telling them a patient was ready. Dentists would have to push back, saying they were busy and would get there as soon as possible. In one extreme case, this resulted in a patient waiting over 30 minutes for the dentist to come and complete the exam. This could have been a large cultural breakdown, but assistants and hygienists compensated by talking with patients during this downtime.

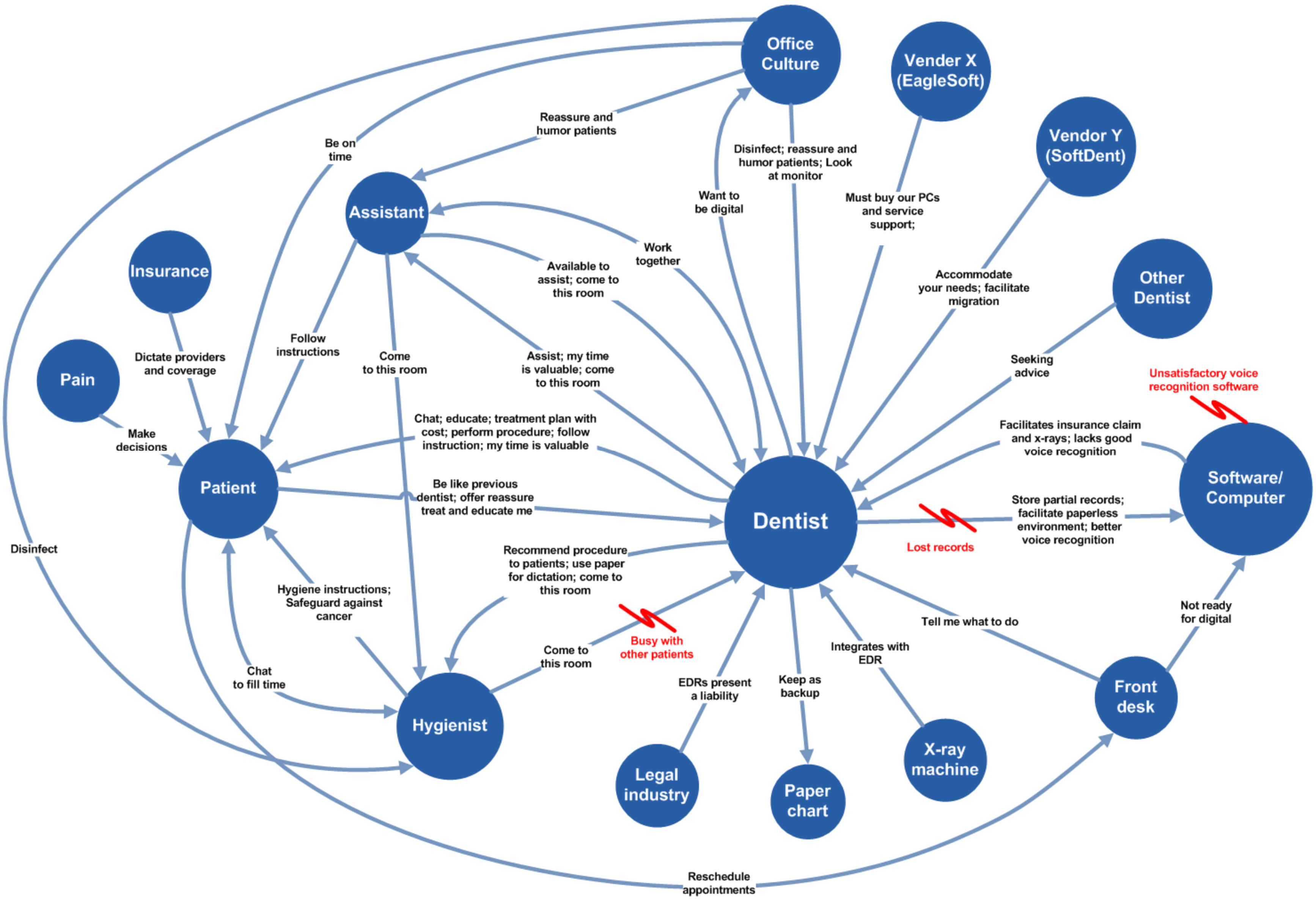


Figure 17. The Consolidated Cultural Model: Each Bubble Represents an Influencer: The Arrows Indicate Who They Are Influencing

8.3.4 The Artifacts of Dental Offices

As previously noted, both print and digital forms of records were kept in all of these offices. Figure 18 shows a consolidated model of all the forms used in the five dental offices. The information on a paper copy of a record and its corresponding digital record may contain different information. This could be due to errors during the process of entering the information in the computer, but it is mostly because of the difference in structure between the two forms of record keeping. On paper, informal notes were frequently used; on the computer, while that function was available in some software systems, it seemed to be used less often. Sometimes the digital version did not have all of the necessary fields. Other times, it was difficult, or even impossible, for the user to find the procedure for which they were looking.

Figure 18. Consolidated Artifact Model from the Five Dental Offices

One related technological breakdown we saw in multiple offices was that only one person could be viewing a given patient's digital record at a time. Generally, a patient's record was open in the operatory they were in, as well as on the computer by the panoramic x-ray machine when they were having those types of X-rays taken. Whenever one person tried to open a record that someone else had open, they had to figure out who else had the record open and get that person to close it (generally interrupting someone else's workflow, as well as their own). Obviously, this should not happen in the proposed system.

Generalized Conclusions from Contextual Inquiries

- The device(s) we choose for our system must be able to be disinfected.
- Digital X-rays are currently well-integrated into dental software packages.
- Multiple people should be allowed to view the same record at the same time.
- Work flows and roles are flexible, and must be allowed to remain so in our system.
- Our system should be designed for both novice and expert users.
- Time is key – efficiency is a must.
- The device(s) must be small and easily integrated into the operatory.
- The screen must be visible even in poor lighting conditions.

8.4 PROOF OF CONCEPT DEVELOPMENT

The proof of concept development included concept validation with three dentists, paper prototyping, and finally developing the high fidelity prototype. Usability testing was conducted to iteratively refine the prototypes. Subsequently, the final prototype was formatively evaluated with eight dentists using the questionnaire for user satisfaction (QUIS) and finally conducted the Keystroke Level Model (KLM) with the prototype and EagleSoft version 14.

8.4.1 Concept Validation

Concept validation is a process whereby the designers take storyboards with potential scenarios to the users and observe how they react. Seven scenarios were developed to demonstrate the various technologies and the design concepts that could be applied to translate the cognitive task analysis and contextual inquiry findings. The concepts included showing patient's oral findings on a timeline, 3Dimensional (3D) teeth models, the zoom function and the single tooth view. The technologies included touch screen, hand gestures, heads-up display and voice. These concepts and technologies were validated with three practicing dentists in the Pittsburgh area.

When reviewing the scenarios, all three dentists focused more heavily on the feasibility of the concepts and the technologies than on their usefulness. They commented, for example, that 3D is not very common and they don't take intra-oral photos at every visit. Even though it was pointed out that these technologies may become the norm in 5-10 years, they continued to wonder about their feasibility. In the end, they were asked to rate the concepts and the technologies, in the order of their preferences. Table 15 shows how the three dentists rated the concepts and technologies.

The participants identified four additional important concepts and technologies during the concept validation. The foremost concept was the need to use drawing for education. Even though this concept was not part of the scenarios presented, all the three dentists stressed the need to mark up, draw or at least point to relevant findings to educate the patients. The second was the need to see the patient's oral cavity changes over time. Several dentists already compare radiographs from different time-periods but experience great difficulty performing this task with current tools. The third concept that the dentists verified was the usefulness in viewing the periodontal chart alongside the radiographs. They typically go back and forth between the radiographs and the periodontal chart when diagnosing periodontitis, which could be made easier if they were able to view both side-by-side. They also agreed that it would be useful to change from one radiograph to the next and to have the ability to zoom in. Regarding the technologies, all the three participants preferred voice, followed by hand gestures and then touch screen. Overall, they liked all the concepts we showed them; although two dentists were not enthusiastic about the single tooth view. Interestingly, once the iterative usability testing started, many dentists became excited with the 'view by tooth' tab.

Table 15. The Dentists' Order of Preferences of Concepts and Technologies

	Dentist #1	Dentist #2	Dentist #3
Concepts	3D view	Timeline	3 D view
	Historical information on the teeth (timeline) /zooming in for details	3D view	Zooming I for details
	Single tooth view (didn't think it was useful)	Zooming in for details	Single tooth view
		Single tooth view	Timeline
Technologies	Voice	Voice	Voice
	Hand gestures	Hand gestures (if perfect)	Hand gestures
	Touch screen	Touch screen	Touch screens
	In-glasses	(didn't test in-glasses and wrist control)	Wrist control
	Wrist control (hated this idea)		In-glasses

8.4.2 Paper Prototyping and Usability Test Results

The next phase was the prototyping phase. In this phase, three sketches were created, with one for each technology: the touch screen, voice recognition and gesture-based. Each of these sketches also focused on one of the concepts: the 3D model, single tooth view, zoom, and the timeline. While developing the prototypes, we realized the difficulty of implementing the gesture-based system and therefore, decided to go forward only with the voice and touch screen interactions. In the early prototyping phase, we conducted three rounds of usability testing, with each round consisting of two to four participants (practicing dentists and senior dental students). We had a total of twelve participants in this phase. Figure 19 shows the screenshots of the paper prototype that was developed. The complete screenshots of the paper prototype and the usability testing tasks are available in Appendix B. Once the prototype was converted to the high-fidelity prototype, the formative evaluation was performed by conducting usability testing with eight dentists who were dental faculty and practicing dentists in Pittsburgh area.

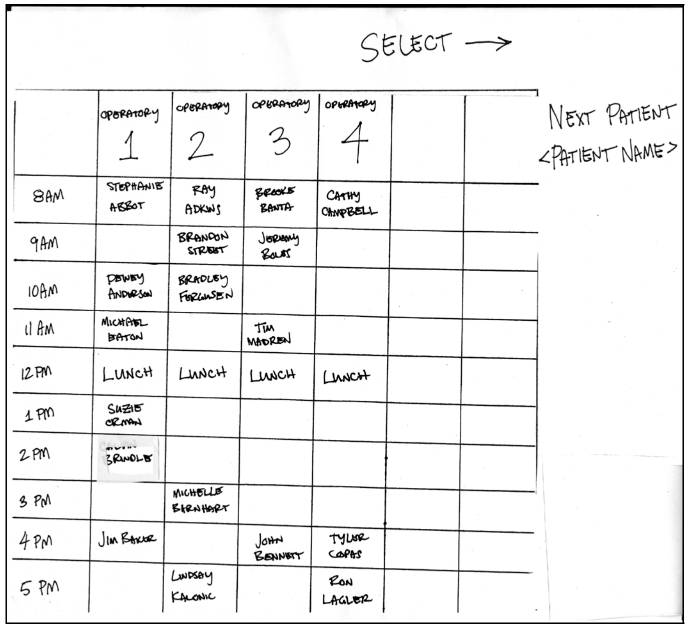


Figure 19. Screenshot of the Paper Prototype Showing the Calendar View

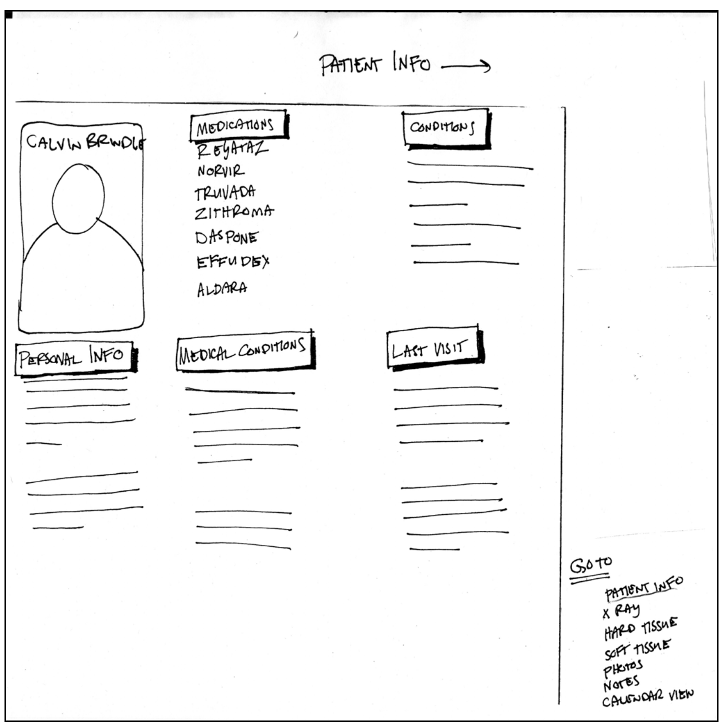


Figure 20. Screenshot of the Paper Prototype Showing the Patient Overview Page

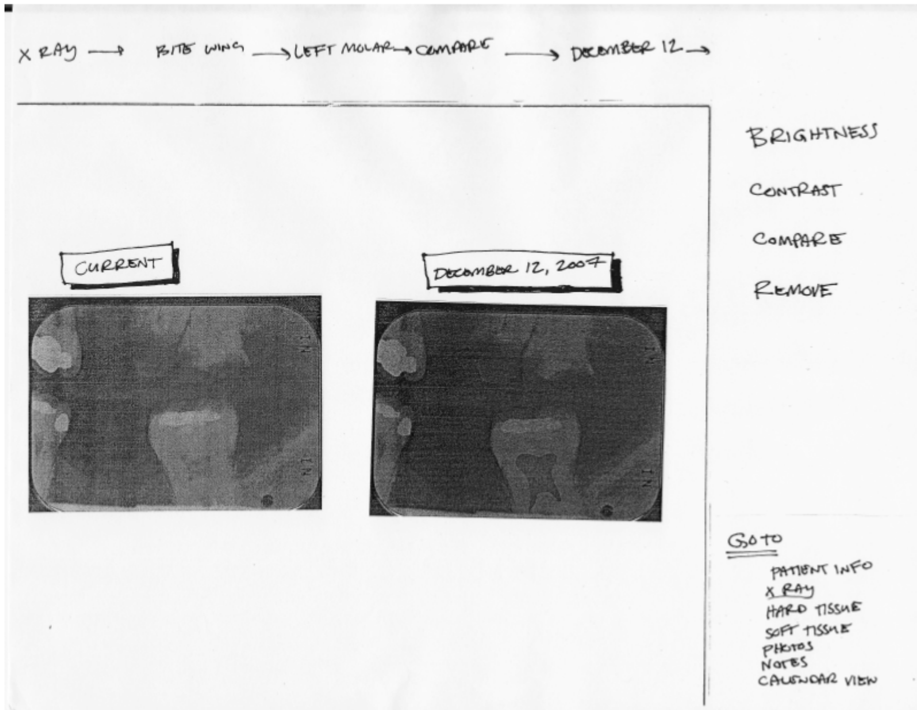


Figure 21. Screenshot of the Paper Prototype Showing the Comparisons of Two Radiographs

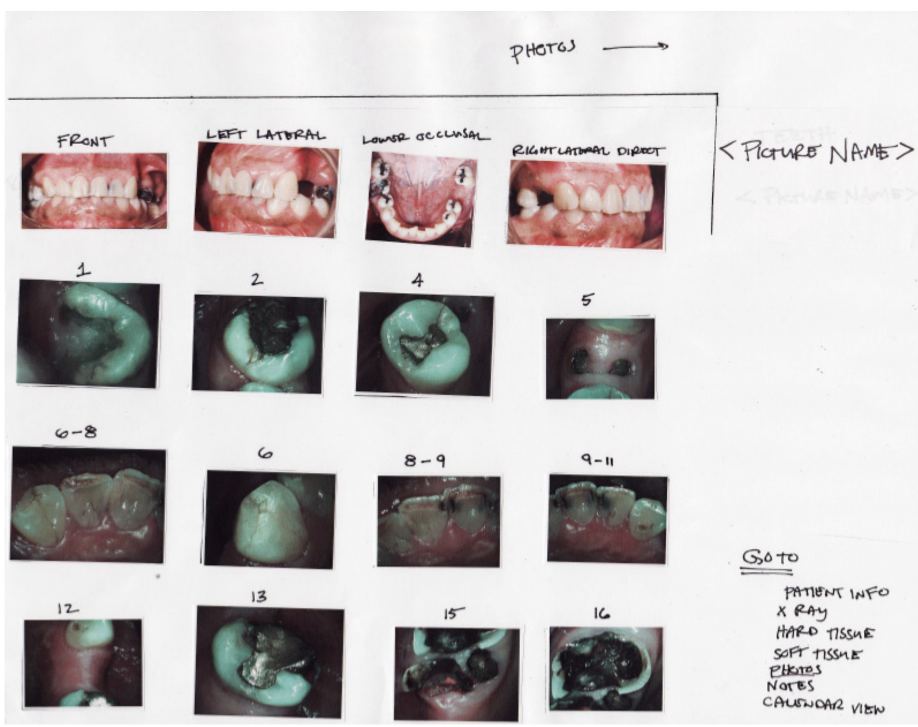


Figure 22. Screenshot of the Paper Prototype Showing Layout of the Photos

Overall, the twelve participants liked the idea of using voice and touch screen to enter data. They also liked the overview page that displays the patient's photo, chief complaint, medical history, allergies and details from the last visit and the ability to compare historic X-rays side-by-side. The participants also liked the ability to access all the radiographs relevant to a single tooth. The changes made during iterative testing were mainly related t changing the terminologies, rearranging the location of information and determining the scope of the voice-based and touch screen systems for data entry. For instance, the term 'calendar view' for the scheduled appointments screen was confusing to the participants. As per their suggestion, the 'calendar view' was changed to 'today's scheduled appointments'. Participant suggestions included:

- Show patient's medical conditions and allergies in the upper middle of the chart and display them in red to highlight their critical nature.
- Show personal patient information and the last progress note on the patient overview page.
- Place most time-dated information on a timeline to enable rapid scanning across time.
- Enable side-by-side comparison of previous and current X-rays.
- Add annotation tool to facilitate drawing for illustrating conditions for the patient to encourage patient ownership and compliance.

The changes made during the three iterations with the paper prototypes and the high-fidelity prototype are documented in Appendix B. The next section describes the features present in the high-fidelity prototype, which was named DMD Prototype.

8.4.2.1 High Fidelity "DMD Prototype" The final high fidelity prototype, the *DMD Prototype*, has the following features:

1. an overview of the patient's information (demographics, medical and dental history)
2. radiographs and photos (including tools to better understand these images)
3. a 3D model of the patient's oral cavity for diagnostic purposes and for patient education
4. a drawing system for patient education
5. hard tissue chart and periodontal chart with relevant conditions of the teeth

6. view by tooth where all relevant information for single tooth (or a sextant region) is shown

The selected screenshots of the high-fidelity prototype are shown next in Figures 23-29.

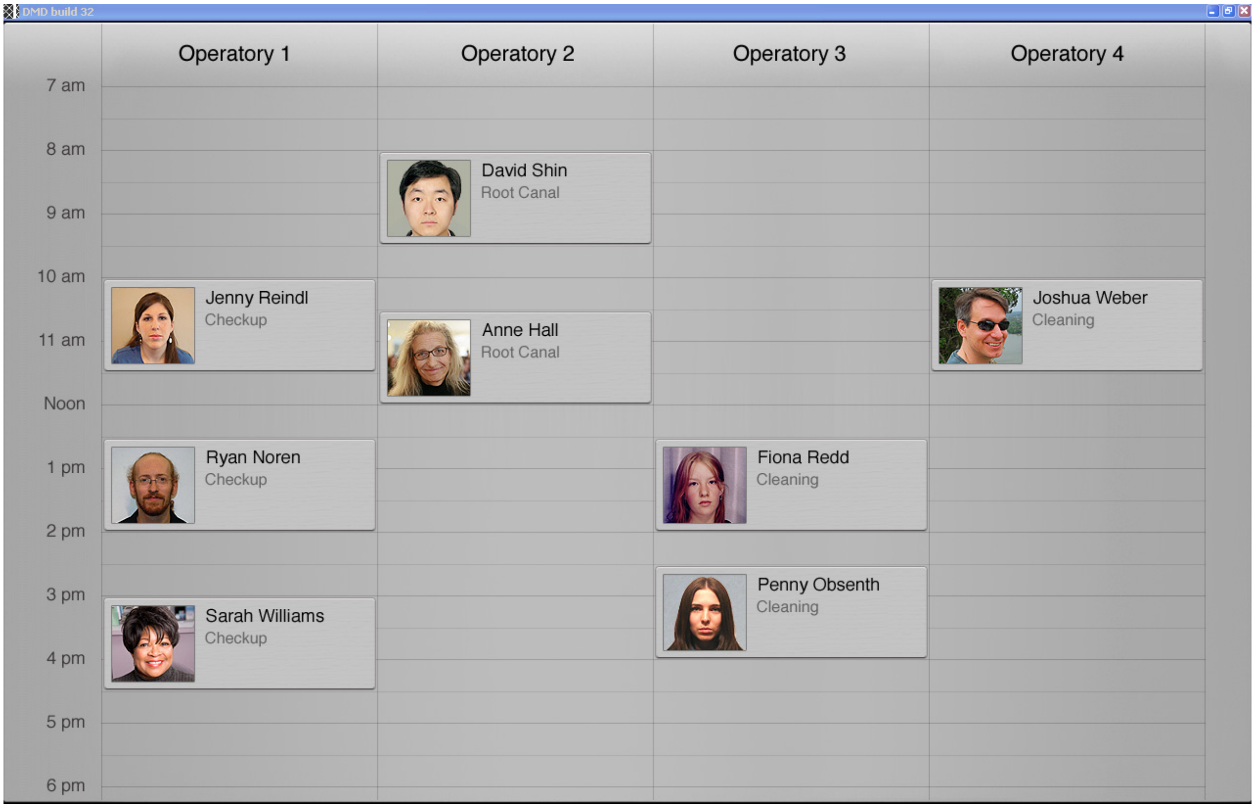


Figure 23. Screenshot of the DMD Prototype Showing the Schedule of the Dental Office. (This page also enables the user to switch between patients.)

Figure 24. Screenshot of the DMD Prototype Showing the Patient Overview Page. (This page provides a summary of patient information,)

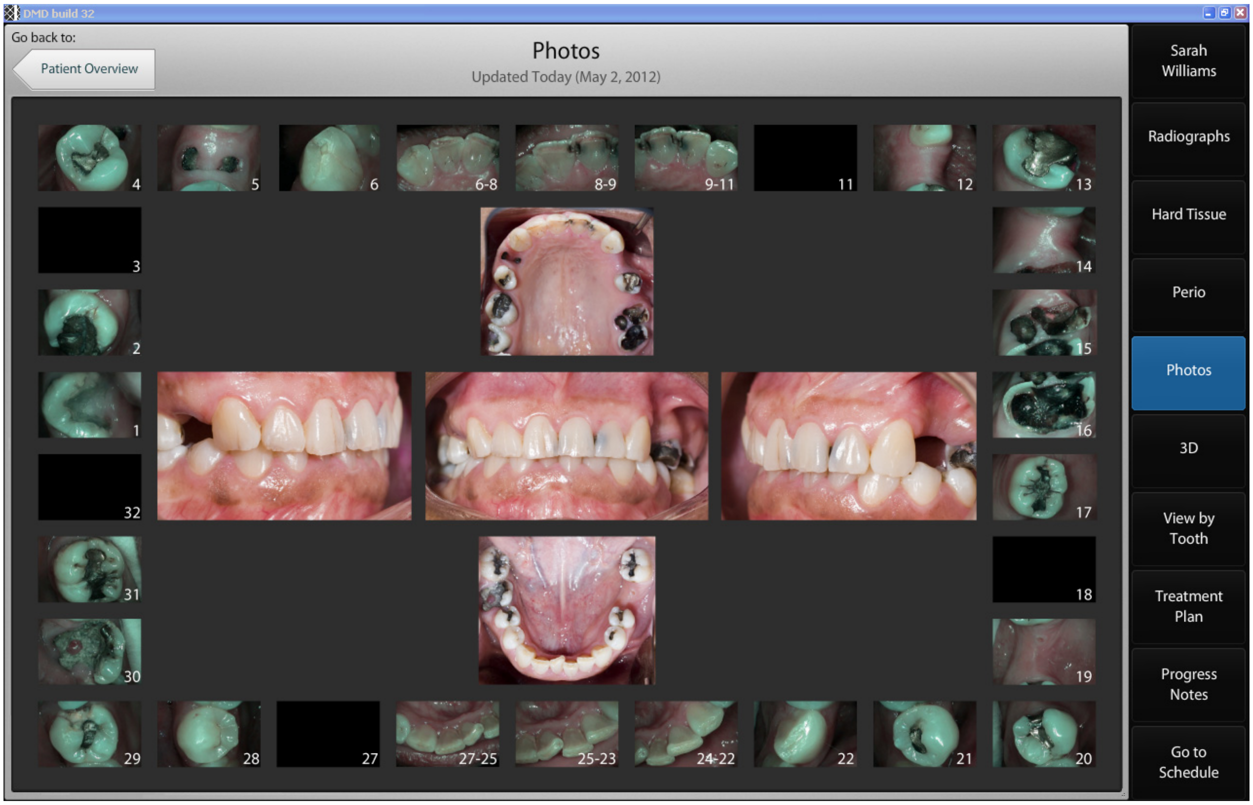


Figure 25. Screenshot of the DMD Prototype Showing the Photos Page. (Photos are arranged to simulate the patient's oral cavity.)

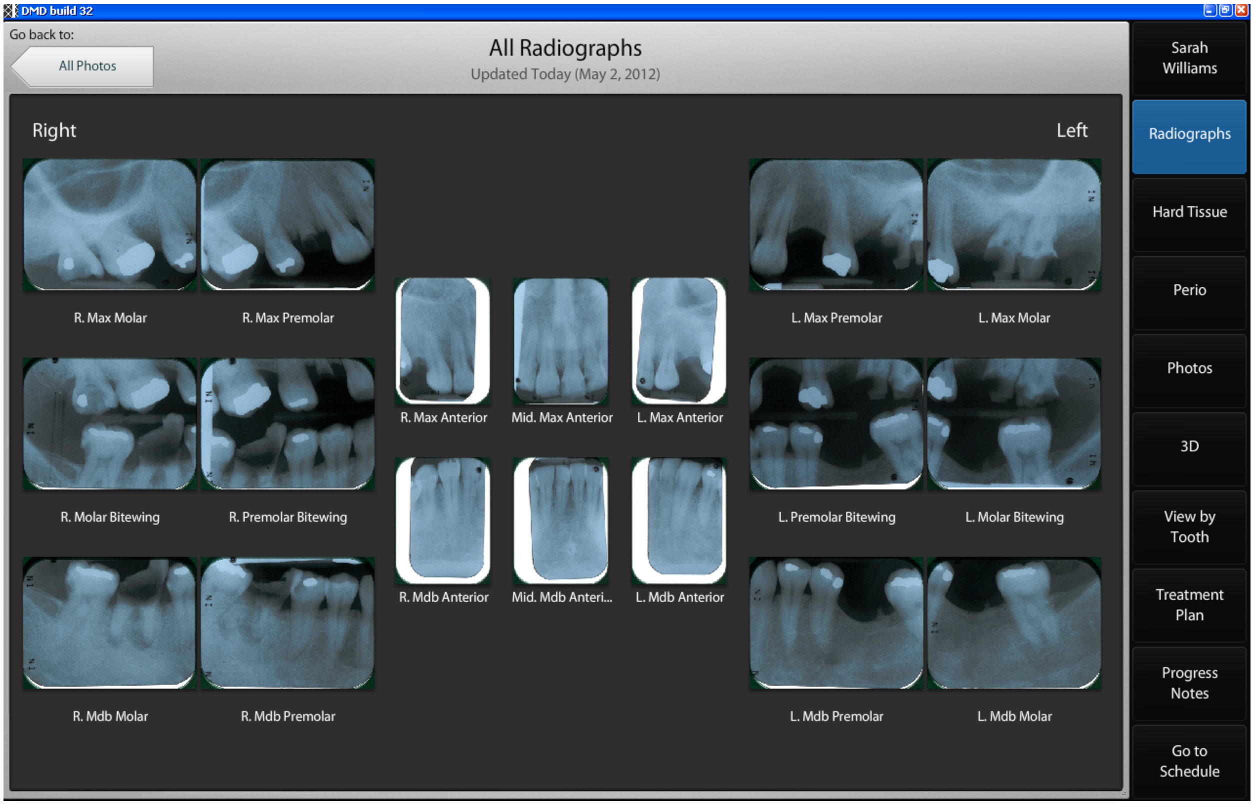


Figure 26. Screenshot of the DMD Prototype Showing the Patients' Radiographs Page (This page shows the standard dental radiographs layout. Users can select a specific radiograph simply by pressing or clicking on it.)

Figure 27. Screenshot of the DMD Prototype Showing the Enlarged View of the Radiographs Page

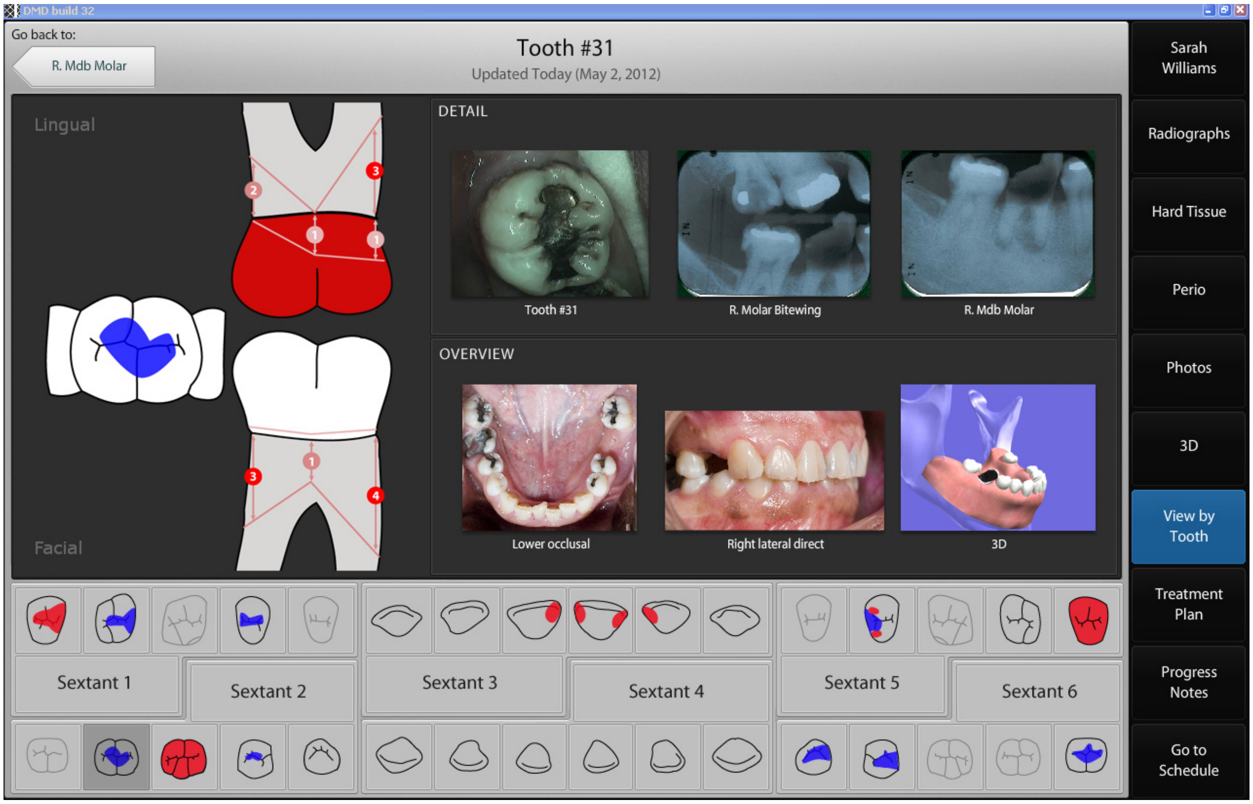


Figure 28. Screenshot of the DMD Prototype Showing the View by Tooth Tab (This is one location where relevant information for a single tooth is available.)

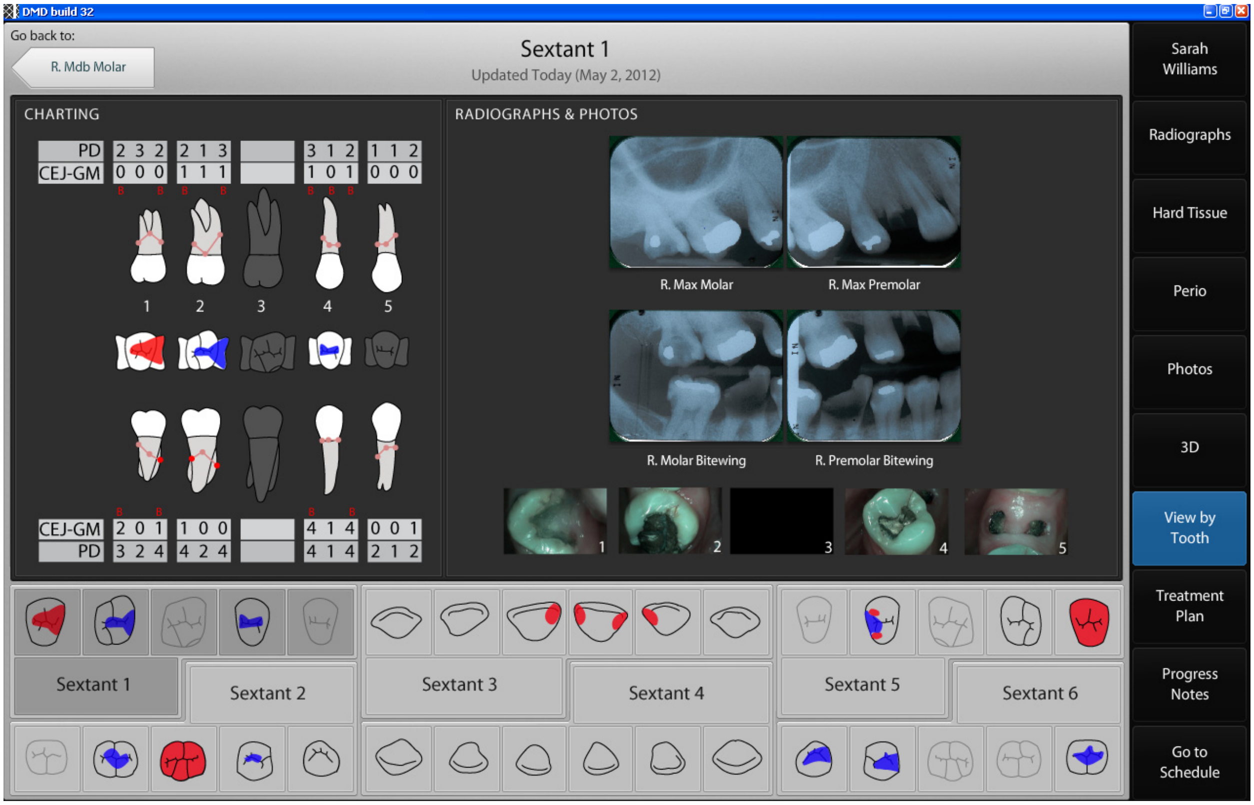


Figure 29. Screenshot of the DMD Prototype Showing the View By Tooth Tab (This is one location where relevant information for a sextant region is available.)

8.4.2.2 Usability Test Results for the DMD Prototype Since the users were not trained to use the system, all participants spent some time getting familiar with the system in the beginning. Users liked the patient overview page that displayed a snapshot of the patient's general status such as the chief complaint, insurance information, allergies, medications, medical history, dental history and the last progress note. Further details about the medications could be accessed by left clicking or pressing on the 'look up medications' button. Many users clicked on various parts of the page such as the insurance information, medical alerts and the dental history to access more detailed information. Participants also liked the single tooth view where all the information related to a specific tooth is displayed in one screen. This view was developed in an attempt to reduce the user's need to click through multiple screens to access all the information needed to make a diagnosis and treatment plan for a tooth or a specific region of the oral cavity.

A few participants expressed the desire to also have a split view of the radiographs and photos or the hard tissue chart or the periodontal chart side by side on the same screen to obtain a full view of the oral cavity. The participants liked the three dimensional (3D) view of the upper and lower jaw even though they experienced difficulty with interacting with the 3D model in the beginning. They viewed the 3D model to be beneficial for obtaining information on the patient's bite and occlusion and also for educating and demonstrating the proposed treatment plan to the patients.

Participants also suggested improvements, such as the ability to have more information on issues such as the medical history and dental history, automated detection of potential drug to drug interactions, the patient's extraoral findings related to the temperomandibular joint, symmetry of the face, and the presence or absence of palpable submandibular lymph nodes. In summary, the participants believed the DMD Prototype supports reviewing clinical information for patient education and treatment planning. Table 16 below shows the eight participants' responses to the Questionnaire for User Interface Satisfaction (QUIS). On a scale ranging from 0 (least satisfaction) to 9 (most satisfaction), the average scores were above 7 for all the four categories. The category 'learnability' earned the highest average score of 8.13.

Table 16. Individual and Average Responses of the Eight Participants (U1-U8) to the Questionnaire for User Interface Satisfaction (QUIS)

Criterion	**Mean rating from eight participants**								**Average**	**Standard Deviation**
	U1	U2	U3	U4	U5	U6	U7	U8		
Overall reaction to software	7	7.3	8	8	7.8	8.16	7	9	**7.8**	0.95
Screen	6.5	6.5	8.3	8.3	7.8	6.6	7.5	8.5	**7.5**	1.12
Terminology and system information	6	7.7	8.25	7	7.5	7.3	7.7	9	**7.54**	1.28
Learnability	7	8.2	8.5	8.75	8	7.8	7.75	9	**8.13**	0.95
System capabilities	7.4	8	8	7.6	5.33	8.25	8.7	8.8	**7.8**	1.4

8.4.3 Key-stroke Level Modeling Results

The objective of the Key-stroke Level Modeling (KLM) is to determine how quickly an expert user can navigate through a system. It does not take into account the cognitive aspects of a program. For instance, a dentist may require more time to understand the hard tissue chart in one program than in another, but KLM does not take that into account.

A set of representative tasks that could be performed in both the DMD Prototype and in EagleSoft version 14 were selected by two dental faculty. Both systems had several comparable functions in the radiographs section, and therefore these made up the bulk of the tasks. Other tasks included gathering general information about the patient (such as date of birth and insurance information), retrieving medical history, and reviewing the patient's hard tissue and periodontal chart. Table 17 shows the results from the Key-stroke Level Modeling for the DMD Prototype and for EagleSoft v14. As shown in the table, the total time taken by the DMD Prototype was reduced to one-third of the time taken in the EagleSoft.

Table 17. Keystroke-Level Modeling Results for the DMD Prototype and EagleSoft v14

Tasks	**Time in seconds**	
	EagleSoft	**DMD Prototype**
View patient's picture	8.9	1.9
View the hard tissue chart	7.1	2.0
View all radiographs for tooth 6	2.2	1.9
Open one of these radiographs	2.0	1.8
Change the brightness/contrast	4.0	3.4
Invert	2.3	1.9
Undo/reset radiograph	7.8	1.9
View the periodontal chart	7.7	1.9
Look for patient's birthday, insurance	10.4	3.9
View patient's medical history	6.9	1.7
View R Bitewing, change brightness/contrast and reset	14.3	7.5
Compare bitewing to last visit's bitewing	24.2	1.9
View today's bitewing in full screen	9.6	3.5
Total	107.4	35.2

The reason for this significant reduction in time may be due to the number of steps involved to complete a task in EagleSoft. For instance, in EagleSoft, the user had to perform the following to compare a bitewing with another from a previous visit:

- file, browse images
- find the correct dates, click on the '+' sign to expand the list, check off the desired radiographs and click OK
- click on one thumbnail to select it, then shift-click on the other to highlight them both

- file, open tiled vertically.

In the DMD Prototype, the user clicks the ‘last visit’ button to the left of the radiograph. In EagleSoft, relevant information was hidden in different layers behind many tabs and menu items and this design forced the user to click on multiple tabs to complete a task. For example, if a user clicked on the tooth in the hard tissue chart in EagleSoft, a list of radiographs for that tooth appeared on the screen. When the user clicked on one of these radiographs, a larger version of the radiograph appears on the screen. However, while this window offered the same features offered in the 'advanced imaging' section of the system, the 'revert to original image' button is absent. As a result, the user had to perform multiple undos' to 'revert to original image'. These multiple steps of completing a simple task clearly highlighted the flexible navigation designed in the DMD Prototype.

The DMD Prototype was further developed to provide realistic tooth images and flexible navigation. The screenshots of the final DMD Prototype are shown in the Appendix C.

8.5 COMPARATIVE EVALUATION

A convenience sample of ten dental clinicians consisting of five senior dental students and five full-time dental faculty with in-depth experience in using cEDR evaluated the information organization, navigation and usability of the cEDR version 5.13 and the DMD Prototype. They watched three sets of videos that showed how to perform three tasks in both the systems. The tasks included:

1. Obtain an overview of a patient's general status and the reason for the dental visit.
2. Review all information pertaining to a tooth #30 and
3. Review the radiographs to identify missing teeth.

The participants were provided with the opportunity to interact with the two systems. A student researcher subsequently interviewed them to determine their perception on the navigation, information organization and usability of the two systems. The interviews were transcribed and analyzed using thematic analysis. Tables 18, 19 and 20 show the summary of the participants' responses to questions on their perception on the navigation, information organization and usability of the two systems. As shown in the Tables 18 and 19, all the participants perceived the navigation, information organization and usability of the DMD Prototype to be better than the cEDR. They especially liked the concept of having a 'central location' that provides an overview of the patient's status on one screen and then enables navigation to other information items such as the radiographs, intraoral photos, hard tissue chart and the periodontal chart. Two participants were concerned with having too much information on one screen that could potentially cause information overload for the users. They suggested that improving the information organization and information presentation could potentially enhance the performance of the DMD Prototype.

Table 18. Participants Responses Regarding Information Navigation and Organization in cEDR and the DMD Prototype

	Interview Questions	Main Responses	Number of Main Responses	Sub responses	Number of sub responses
1	**Was it easy to get from one view of information to the next?**				
	cEDR	It is easy but requires multiple clicks and switching between screens	3		
		It is not easy	7		
				Difficulty finding and accessing information	4
				Requires multiple clicks and switching screens	3
	DMD Prototype	It is easy	10		
				All relevant information in one screen	7
				Intuitive and user friendly	2
				Easy to find information	1
2	**Were program controls labeled so that you could understand what they did?**				
	cEDR	Labels are clear but	7		
				Require training to understand the labels	5
				Not self explanatory	1
				Require switching between screens	1
		Labels are not clear	3		
				Require training for new users	2
				Difficult to find information	1
	DMD Prototype	Labels are clear	9		
				Intuitive and logical	5
				Descriptive and self explanatory	4
		Labels are clear but	1	Too much information in one screen	1
3	**Was it clear what information you would see when pushing a button or menu item?**				
	cEDR	Labels are clear to provide guidance if you know the location of information	5		
		Labels provide no guidance without training in cEDR	5		
	DMD Prototype	Labels are clear to provide guidance	10		
				Self explanatory	7
				Relevant information organized in one screen	3

Table 18 (continued)

4	**Did you see all the information needed for the task, single tooth evaluation?**				
	cEDR	All information available	10		
				but require back and forth clicking	8
				All information available	2
	DMD Prototype	All information available	10		
				Clinically relevant information grouped and available in one screen	7
				All information available	3
5	**Were there information displayed in places you did not expect them?**				
	cEDR	Information not displayed in expected places	10		
				Require training and significant navigation through the tabs	5
				X-rays are not integrated with cEDR	3
				Information not displayed or grouped in expected places	2
	DMD Prototype	Information displayed in expected places	10		
				Information grouped and displayed meaningfully	9
				Did not expect to see photos and radiographs together	1
6	**Were the items grouped in a way that facilitated the task?**				
	cEDR	Items grouped to facilitate the task	5		
				Grouped to facilitate the task but not logically	3
				Information grouped to facilitate the task	2
		Items not grouped to facilitate the task	5		
				Information hidden and separated under different layers of tabs and menu items	4
				Information not grouped to facilitate the task	1
	DMD Prototype	Items grouped to facilitate the task	9		
		Items not grouped to facilitate the task	1		
				Clinical attachment loss and some radiographs missing from the single tooth view	1
7	**Did the way of navigating through the information follow a logical order?**				
	cEDR	Navigation not logical	8		
		Sometimes logical	2		
	DMD Prototype	Navigation is logical	10		

Table 19. Responses from the Participants Comparing DMD Prototype with cEDR

Responses	Number of responses
DMD supports easy and quick navigation	7
Not much difference from cEDR	2
Potential to replace the shortcomings in cEDR	1

Table 20. Suggestions from Participants for Improving DMD Prototype

Responses	Number of responses
Focus on information organization	2
Show more information especially the medical history	2
Display oral cavity changes over time	2
Develop efficient data entry mechanism and solutions to support the DMD Prototype interface	1
Provide manipulation functions for the radiographs	1
Enable comparison between old and new radiographs	2

Despite these comments for improvements, all the participants unanimously agreed that the information is much better organized in the DMD Prototype, that it shows all the relevant information in an intuitive manner and the navigation through the information follows a logical order that supports how a clinician thinks during diagnosis and treatment planning a patient case. Table 21 shows selected quotes by the participants on the information organization, navigation and usability. These quotes clearly indicate that the participants perceived the DMD Prototype to be intuitive, easy to learn and easy to navigate. They rated the patient overview page and the single tooth view page very favorably in terms of information presentation and organization. In contrast, the participants perceived cEDR to have a steep learning curve and fragmented information presentation across multiple screens. As a result, they have to make extra effort to learn and remember the system's information flow. With training and experience, the users do become proficient in using cEDR.

Table 21. Selected Participants Responses on the DMD Prototype and the cEDR

DMD Prototype	cEDR
Ease of Navigation	
'Everything you need is on the overview patient screen. I like the sidebar. This program eliminates the problem of flipping back and forth between information.'	'No, because, you have to know the program in order to find certain info. If you are not familiar with it, there is nothing intuitive that would remind you to view certain info, other than your own intuition. Given that the info isn't present all at once, it may cause you to forget to look at certain info.'
Understanding the labels function	
'I think they are labeled well and that it is very intuitive. It is very visually pleasing. I could find my way through this program with very little training, whereas in cEDR, I need lots. ' 'Yes, but it looked busy. There is too much on the screen at one time overall.' 'It looks easier to navigate. I think this would be useful to a practicing dentist- much better visually-from a dentist' perspective, this program functions equivalent to the way a dentist would logically think'.	'Yes, but the icons are just pictures rather than words'. 'They are adequate, but again I have familiarity with it. I know I need to go to MiPACS to view X-rays. If you were a new user …No, I remember learning how to operate cEDR; it was tough. You have to know exactly where to click to find info. Whereas in prototype it is well labeled and logical.'
Perception of what information you expect to see when pressing a button or menu item	
'It seems that the info is labeled clearly and gives info that you would think you would receive. Sextant info was a little hard to find, but with more practice, it would be more intuitive.' 'Yes, buttons were labeled with words not just a pictogram as in cEDR'.	'Yes, it is pretty clear. If you know where you are going, it is not bad. It can be tough transitioning from one set of info to the next'. 'Not necessarily. I know what info would be there as being an experienced user; new user would need lots of practice'.
Seeing all the information needed to evaluate tooth #30	
'Yes, looks very slick the way you can see so much info at one time. I wonder how much time it takes. It is very helpful to have that info right at your fingertips.'	'You do see all of the information, but it is not all to be found on the same page. If you are bouncing to different views of info at a time, you are bound to miss information which can lead to mess ups.'
Was information displayed in expected places? Were items grouped to facilitate the task?	
'I thought it was cool, that all info was linked to the one tooth. Yes, I thought everything was clearer in DMD and I liked how you could click on the tooth and view occlusal view of tooth and view all info pertaining to that tooth.'	'I have been working with cEDR for a long time, but for first time users, it would be difficult to navigate. No, not very well at all'
Did navigation through information follow a logical order?	
'Yes, I thought it was much more logical and intuitive. You can click on what you need to see and all info is present at once.' 'There is a difference in the number of clicks and the amount of information displayed on each page between the two systems. It was much easier navigating in prototype.'	'I don't think it's very logical or intuitive, but you can find all the info you need in cEDR, but a lot of back and forth switching.' 'You have to create the order in cEDR; nothing prompts you to view the next set of information. However, everything is there, you just navigate how you wish to.'

The participants liked the ability to view all the information related to a single tooth on one screen. They liked the 'sextant view' in the single tooth view that showed the information related to the adjacent tooth as well. According to the participants, having all the information needed for diagnosis and treatment planning on one screen reduced the need to go back and forth between screens, which could be labor intensive and create more chances for errors. One participant also expressed the concern that the DMD Prototype forces the user to spend too much time on the individual tooth information, as opposed to the entire teeth or oral cavity. He feared that the user might miss obtaining an overall picture of the patient's oral cavity. Another participant commented that certain single tooth view pages didn't have any radiographs and wondered whether it was a glitch. The radiographs were missing for the teeth that were missing in the patient oral cavity. Two participants also commented on the need for a more detailed medical history page and pointed out that the periodontal measurements such as the clinical attachment loss and Periodontal Screening and Recording scores were missing in the DMD Prototype.

The participants' biggest concern with cEDR was the steep learning curve to use the system and the way information was fragmented across multiple screens and hidden behind the tabs and menu items. This information design required users to spend a lot of time going back and forth between many screens and to remember information when transitioning from one screen to the next. Users ended up spending a lot of time trying to access all the information needed for diagnosis and treatment planning. They also expressed concern that they may miss or forget information. However, they agreed that with training and experience, they were able to use cEDR efficiently and effectively. Despite their familiarity and comfort in using cEDR, all the participants unanimously agreed that a system designed with a logical and intuitive navigation and information organization will be far more beneficial than one that is not.

Tables 22 and 23 shown below display the results from the QUIS administered to the ten participants. As indicated in the tables, the participants expressed significantly higher levels of satisfaction with the DMD Prototype than with the cEDR, especially on the measure for learnability. Table 23 shows the individual and average responses of the ten participants, senior dental students and dental faculty, who comparatively evaluated the DMD Prototype with the cEDR using the Questionnaire for User Interface Satisfaction (QUIS). The QUIS used a scale of 0-9 with “0” indicating least satisfied and “9” most satisfied. Table 22 shows the cumulative average responses on the Questionnaire for User Interface Satisfaction (QUIS) of the ten participants (senior dental students and dental faculty) who comparatively evaluated the DMD Prototype with the cEDR. The paired t-test results showed statistically significant ($p<0.001$) differences in the participants' QUIS responses to cEDR and the DMD Prototype.

Table 22. Cumulative QUIS Ratings of Participants for DMD Prototype and cEDR

Criterion	DMD Prototype	Standard Deviation	cEDR	Standard Deviation	p-value
Overall reaction to software	8.03	0.76	4.18	1.5	p<0.001
Screen	8.5	0.6	3.9	2.15	p<0.001
Learnability	8.2	0.46	3.3	2.13	p<0.001

Table 23. QUIS Ratings of the Students (U1-U5) and Faculty (U1-U5) Participants for DMD Prototype and cEDR

QUIS for	DMD Prototype							cEDR						
	U1	**U2**	**U3**	**U4**	**U5**	**Average**	**Standard deviation**	**U1**	**U2**	**U3**	**U4**	**U5**	**Average**	**Standard deviation**
Students														
Overall reaction to software	7.5	6.2	8.6	8.2	8.3	7.8	0.98	3	3.2	4.6	5.8	6.3	4.6	1.5
Screen	7.7	7.3	9	9	8.3	8.27	0.76	3	3	4	6	7	4.6	1.8
Learnability	7.8	7.5	8.5	8.5	8.5	8.15	0.49	4.8	2.5	6.3	5	6.25	5	1.54
Faculty														
Overall reaction to software	8	8	8.3	8.17	9	8.3	0.42	2.2	4.2	4.2	6	2.3	3.8	1.6
Screen	9	8.7	8.3	9	9	8.8	0.3	0.33	2.3	3	7	3.3	3.2	2.4
Learnability	7.8	8	8.5	8.25	9	8.3	0.48	0.5	1.25	1.8	3.3	1.5	1.65	1.01

9.0 DISCUSSION

The objective of this research was to enhance knowledge on how cognitive engineering methods can be optimally applied to inform the system design process. The study's goals were to design a system that provides clinicians' with enhanced cognitive support during patient care by first, conducting a study of the cognitive processes and information management strategies used by dentists during a typical patient exam, and then using these results to display clinical information that offered cognitive support to dentists during patient centered decision-making activities. The resulting 'proof of concept' prototype was then evaluated to determine its effectiveness in supporting the clinicians' review, diagnosis and treatment planning for patient exams. This chapter will begin with a discussion of the approach used to achieve this objective, including the motivation for doing this research, followed by a discussion of the research findings from the four studies: cognitive task analysis study, contextual inquiry, proof of concept development and formative evaluation and comparative evaluation. This is followed by the limitations of this research study and finally the conclusion of this research.

9.1 MOTIVATION AND RESEARCH APPROACH

The beneficial effects of using health information technology (HIT) are well documented. They include timely access to patient records, increased adherence to preventive management and chronic disease guidelines, enhanced medical alerts and enhanced communication with other providers (10, 53). Despite these benefits, numerous reports and studies also demonstrated the steep learning curve and the unintended adverse consequences when using HIT (9, 56, 57, 68, 69, 71, 72, 74, 160). While the steep learning curve caused users to make mistakes and delays during patient care, the adverse events included unfavorable workflow issues, medication errors and even increased mortality rates. Problems in the human-computer interaction design are a major reason for these adverse consequences. For instance, the cluttered screen designs and separation of information across multiple screens makes it difficult for clinicians to obtain an overview of the patient's status. As a result, clinicians sometimes miss key information required to make decisions. The cumbersome interfaces also forces nurses to delay their medication charting until the end of their shifts. This in turn results in inaccurate recording of medication times and dosage and inefficient communication between nurses and physicians. Thus, the poor interface design forces the user to shift their attention from completing the task at hand to searching for information which in turn increases the chances of making errors.

Studies in dentistry as well, a primary care discipline with approximately 137,000 practicing dentists in the United States indicate that the poor usability of dental clinical systems (18-23) makes it difficult for providers to navigate and obtain an integrated view of patient data during patient care. Four studies conducted by the Center for Dental Informatics at the University of Pittsburgh School of Dental Medicine (20-22, 91) collectively demonstrated that poor usability and a steep learning curve are major barriers for use of dental electronic health records (EHR) systems in clinical settings and retard the adoption of EHR systems in dental practices. These results were comparable to results from physicians' studies where investigators found that usability problems and the resultant loss of time and productivity were significant barriers to adopting a CPR system (92-94). These studies suggested that there is significant room for improvement for dental EHR systems in dentistry. Empirical studies reported that clinical performance improved when information displays matched the users' mental models and their clinical work processes (78). Clinicians then are able to focus their attention more on the patient's problem and are able to devote more cognitive resources toward clinical reasoning, strategy and treatment planning (26). These observations led to the application of techniques and methodologies adapted from applied cognitive psychology to study human-computer interaction (98, 102, 104). However, they have yet to become widely accepted methods for the design of clinical systems. It is this gap in knowledge – how cognitive engineering methods can optimally be applied to inform the system design process – that was addressed in this research.

The novel aspect of this research is that it is the first research project that employed cognitive engineering methods to inform the design of a dental EHR. Previous studies that employed cognitive a engineering approach was mostly performed in large healthcare settings such as hospitals and other major academic health care organizations to redesign existing clinical applications (54). Very few studies exist using these approaches in ambulatory settings and primary care settings (161, 162). These studies, conducted by Ash et al., used focus groups and semi-structured interviews in community hospitals and clinics to understand the clinicians' needs to develop and implement a clinical decision support system. Thus, this research project would be one of the very few studies where two cognitive engineering methods, cognitive task analysis study using the think-aloud protocol and contextual inquiry were conducted to understand the cognitive and workflow processes observed in dental care settings. While this research project was built on a previously conducted study by Jaspers et al. who employed similar think-aloud studies, a novelty in this research is the new knowledge contributed on the dentists' patterns of information retrieval and review of information (navigation through information) during a patient exam. These findings helped with designing the presentation of clinical information that supported clinicians' flexible navigation through the information. Thus, the results from this research project contributed to the knowledge on how cognitive engineering methods could be applied to inform the system design process that has the potential to enhance the quality and safety of patient care.

9.2 PATTERNS OF INFORMATION REVIEW, PROCESSING AND DECISION MAKING USED BY DENTISTS

The cognitive task analysis results provided a rich understanding of how dentists review and process information during a patient exam. This section discusses the findings on how dentists used the information sources. In general, the process of reviewing patient information was similar to how it is described in the textbooks that are used to teach oral examination, diagnosis and treatment planning in the dental schools (163). Typically, dental students are taught to take a complete health history that includes both medical history and dental history to determine there are no contraindications for patients to undergo dental treatment. This is followed by a complete oral exam that includes, examining the soft tissue consisting of the oral mucosa and gingiva and examining the hard tissue that includes the teeth and the upper and lower jaw bones and tempero-mandibular joints. Participants showed a similar process but no two participants followed the same order of accessing and reviewing the information when diagnosing and treatment planning the three patient cases. Therefore, it was important to characterize their varied approaches to performing a new patient exam.

The results from the cognitive task analysis study contributed towards identifying these variations and making meaningful insights on how the patient information could be presented and visualized in a dental electronic health record to support the decision making activities of the dental clinicians. For instance, although all the participants had their own order of reviewing patient information, all of them had reviewed the patient information, medical history, medication history and the dental history before they made their first decision on the general status of the patient. Next, they reviewed the radiographs and photos when diagnosing, and treatment planning a case, and integrated information from the hard tissue and periodontal chart as they finalized the diagnosis and treatment plan. From a design perspective, these findings indicated that the groups of information that are reviewed together or in sequence when making decisions should be shown together to minimize distraction to the clinicians' thought processes.

Another key finding was that the participants first scanned for important findings and then searched for more details. For example, all the participants first looked for significant medical findings, vital signs and allergies and then moved to more detailed medical history. Similarly, they always wanted to learn about significant dental histories such as the last time the patient visited a dentist, any previous history of dental anxieties and the procedures they have undergone. This information provided cues to the clinicians to review further details of the patient's dental history. They also wanted to have a general understanding of the patient's oral problems before examining each tooth individually. These findings point that clinicians first scan for problem areas and then move into details of the problem.

Two previous studies, the first by Nygren et al. (41, 42) and the second by Jaspers et al. (15) reported similar sequences of reviewing information among physicians. Nygren et al. (41, 42), who studied how physicians read the medical record, observed that physicians typically scanned the patient record to obtain an overview of the patient and, once they became familiar with the patient, they moved to the specific details of the problem to explore their hypotheses. The authors also observed that a disordered record severely slowed the searching and reading the text and therefore recommended exposing a lot of information to the user and providing better information orientation and navigation when reading a patient record. In the second study, Jaspers et al. (15) used the think aloud method to learn how pediatric oncologists searched through the paper-based patient records when preparing a patient visit. The authors found that the information needs were identical across all the participants and they reviewed the information in the same sequence when reviewing patient demographics, history of cancer and its treatment, medical history, patients' complaints and symptoms and findings. Some variations were observed when the pediatric oncologists reviewed the medication history, smoking and drinking history, family history and laboratory/additional test results. Our study results found similar observations with the dentists and, in addition, identified what information elements need to be clustered together to make the navigation easy for the clinicians.

An important finding that our study revealed was the patterns in which the dentists reviewed patient information sources when examining the patient cases. Participants exhibited three patterns of reviewing information sources: 1) reviewing information in a linear sequence which was mostly observed when they reviewed the low complexity case; 2) rapid switching between different information sources when they needed additional information or confirmation to make a decision on a finding, diagnosis or treatment; and 3) reviewing more than one information source simultaneously. These findings are significant because previous studies on the dental electronic health records (EHR) indicated significant usability problems because the current EHRs have fragmentation of information across multiple screens thus making it difficult for users to access information to make decisions (19, 21, 23, 91). A usability evaluation of four major dental EHRs identified significant usability problems due to problematic interface and interaction designs in the systems. The problematic designs included counterintuitive sequence of steps to document findings, poorly organized controls to enter findings and treatment and separation of clinically related information on multiple screens that made it difficult for users to navigate through the information.

Similar findings were reported by other studies that interviewed the users of the dental EHRs in dental school settings (19, 23). Even though the EHR resembled the paper record format, users struggled to access information which was scattered across different screens. They had to remember key information while they navigated through the different forms thus requiring them to shift their attention from their patients to the EHR to locate the information and avoid mistakes. In contrast, the paper-based records provided significant flexibility of comparing information on the different forms by placing it side by side. Therefore, supporting these patterns of navigating through information identified in our study may enhance easy access and navigation through the information and thus support the users' clinical decision-making process effectively.

9.3 DENTISTS' INFORMATION SOURCE USAGE

The cognitive task analysis study also examined what information the dentists used mostly when making decisions. The participants mostly used the radiographs and intraoral photos when reviewing the three patient cases. The use of intraoral photos may have been more because they had access to only patient information and not to the 'real' patient. Together, the radiographs and intraoral photos made up 72% of the time participants used these information sources. This finding is significant because to our knowledge, this study is the only empirical study that has studied what information dentists use to make clinical decisions. Determining how dentists use patient information will provide valuable insights for designing clinical information systems that better support the clinician's decision making activities. Historically, radiographs are used for diagnosing and confirming oral pathologies such as caries, bone loss and other pathologic conditions. Our study provided additional knowledge on the sequence in which the radiographs are reviewed and what information dentists reviewed along with the radiographs. For instance, participants reviewed the radiographs along with intraoral images or hard tissue or periodontal chart when confirming the patient findings, diagnosis and treatment. This finding highlights the fact that the dentists use multiple information sources when examining and diagnosing a patient and there is a need to explore innovative visualizations to present clinically relevant information together and to present information in context so that the clinician do not lose the big picture.

The finding that participants reviewed the intraoral images the most is attributed to the fact that the study was conducted in a laboratory setting and the images took the place of a real patient. In a typical patient exam in the dental office, the real patient's oral cavity will replace the intraoral images; however, with the widespread availability and cost effectiveness of using digital cameras, an increasing number of dentists are taking extraoral and intraoral images for documentation and treatment planning purposes (164, 165). Treatment plans for patient cases that require detailed planning are often completed by the dentists after the first patient appointment when all the information is gathered. The treatment plan is then presented at the next appointment for the patient's review and acceptance. The extraoral and intraoral images also are increasingly used by the dentists for educating and communicating with patients about their oral status and to help them understand the rationale for the recommended treatment (166). Current dental EHRs such as Dentrix, EagleSoft and cEDR have integrated the images into the patient records. However, it is still cumbersome to navigate through the images and the results from this study will provide guidance to vendors and developers for presenting images along with other information sources to support the clinicians' decision-making processes.

The study participants in this research study also had additional information needs depending on the nature of the patient case. Most of them wanted information on whether the patients had any pain, especially toothache. The presence or absence of toothache helps the dentists in prioritizing and addressing the patient's complaint and with planning treatment to relieve pain. Another interesting finding was the participant's need to check the patient's bite and occlusion and rule out parafunctional habits. Historically, the dentists used study models to gather information on the patient's bite and occlusion. Anecdotal reports suggest that the study models continue to be used by the dentists even when they have moved from paper-based to electronic health records. Although specialist dentists such as orthodontists and prosthodontists increasingly use the digital models, they are yet to become a part of the dental EHR. There is a need for further studies to explore how digital models will be best integrated with other information sources in the dental EHR to support the dental clinicians' information needs instead of being hidden under another tab or an icon.

Financial information also played a crucial role when the participants planned and finalized treatment for the patient cases. Currently, all the dental EHRs provide the patients' financial and insurance information separately from the patient's clinical information. This is because front desk personnel typically handle the patients' financial transactions. Based on our study results however, it appears that the dentists do consider the patient's financial status when deciding on treatment, and they also use this information while discussing treatment choices with the patient. Therefore, it is important that dental clinicians have easy access to the patient's financial information and to take it one step further this information may also need to be shown along with the different treatment options that could be performed for the same dental problem.

Another significant aspect of this research project was understanding how dentists processed information during patient exam. Coding the think-aloud protocols on how dentists processed information provided valuable information on their information management strategies during patient exam. The findings that dentists retrieved and reviewed information during the initial phase of a patient exam and made very few decisions in the beginning of the exam helped with identifying what groups of information should be presented on the system interface. Other findings such as participants confirming their findings and diagnosis by reviewing more than one information sources such as radiographs and photos or the intraoral charts led to the conclusion that these information needed to be either displayed side by side or should be easy to access.

9.4 IMPACT OF CONTEXTUAL INQUIRY ON THE DESIGN OF A DENTAL ELECTRONIC HEALTH RECORD

The finding that dentists use multiple sources of information, and that the separation of information on multiple screens could compromise the clinicians' decision-making, is the most significant finding in our study that would have a profound impact on the design of future clinical systems. The results from the contextual inquiry study were consistent with the results reported by Irwin et al. (91). The Irwin et al. study provided a rich understanding of the workflow and information management during a typical dental patient exam and our study results provided an-depth understanding of the socio-technical context in the dental office during clinical work processes and the design implications of a system that supports these processes. As reported by Irwin et al. and by our study, collaboration among the dental staff that includes dentists, dental hygienists and dental assistants is vital for the efficient management of a dental office. Often times, an overlap in the roles played by the dental personnel was observed, with everybody involved with creating and maintaining the records, patient examination, patient education and with reviewing the patient records. This finding indicates that any dental system should allow the workflow and personnel roles to remain flexible to support the dental team's needs.

Another significant finding from our study is the need to design systems to fit the small size of the dental operatories where patients are treated. Although the large size monitors would provide more information in one screen, thus eliminating the need to go back and forth between the screens, the small size of the operatories would not accommodate these big screens. In addition, the dentists tried hard to integrate the hardware, especially the keyboard and mouse, within their limited workspace. Often times, they were forced to place the keyboard and mouse in the most inconvenient place, which then hindered their work efficiency. Therefore, there is a need to explore other types of interactions with the system, such as voice recognition, gesture recognition and touch screen that could work well within a limited workspace. These types of interactions will also resolve the infection control issues the dental staff experience while interacting with the clinical systems during patient care.

The observation that the dental team used multiple sources of information to make decisions during patient care confirmed our findings from the cognitive task analysis study. The dental team reviewed the radiographs, hard tissue chart, periodontal chart and other sources of information to make meaningful diagnostic and treatment plan decisions. We also observed that the dentists, dental hygienist and dental assistants had trouble with switching between screens when trying to access all the information they needed to diagnose and plan treatment. This finding signifies the critical need to display information in ways that facilitate easy access to all the information with minimum numbers of clicks and the least amount of switching between screens. Such a design would enhance the clinicians' access to information, and thus minimize the need to remember information from previous screens, and help focus their attention on the patient's rather than the system needs. It also highlights the importance of showing information from multiple sources on the same screen or in the same place for the problem at hand. While our study targeted how dentists review and process information during a typical dental patient visit, the findings and design implications call for similar studies in the fields of medicine especially in ambulatory and community care settings that could guide the design of clinical systems to provide clinicians with enhanced support during patient care.

Another important finding is the extreme value of time and efficiency in the dental offices, which was also reported by other studies (91, 167). This finding highlights how an increased time from interacting with the dental EHR or other dental clinical systems can negatively influence the workflow of dental clinicians (19, 23). To summarize, the contextual inquiry results provided valuable insights on the roles played by the dental staff and signified how the highly collaborative environment of the dental office is very important when designing dental EHRs and how each member of the staff need to be well tuned to what other members are doing. In addition, the results also confirmed our findings from the cognitive task analysis study on how the dentists and the dental team access and use multiple sources of information during diagnosis and treatment planning.

9.5 VALUE OF USABILITY TESTING AND FORMATIVE EVALUATION DURING PROOF OF CONCEPT DEVELOPMENT

The cognitive task analysis study and the contextual inquiry results provided valuable design insights into the types of information that need to be displayed together, the patterns of information review the system navigation should support and the organization of the information presented to the user. The concept validation and the iterative usability testing performed during the proof of concept development helped with identifying the users' understandability of the labels and navigation and with determining what technology is appropriate for clinician workflow. The section below describes selected changes made during the iterative usability testing.

In the early prototypes, the vital signs and allergies were initially shown on the lower left corner of the patient overview page. During usability testing, the participants recommended moving this information to the middle part of the screen and using red fonts so that the users would not miss the information. The usability results also helped with improving the understandability of the labels. Another significant finding that came out during the concept validation was the appropriateness of using technology during the different phases of clinical care. The three dentists who participated in the concept validation ranked voice recognition as the top choice for interacting with the dental EHR or any clinical systems. When the scenario of using voice commands to call out a specific image was enacted, it became evident that voice would not be valuable for these scenarios because accessing an image is relatively easy and the dentist could seek the dental assistant's help to access relevant information from the system. Despite these findings, voice recognition remains a significant technology that will play a crucial role in supporting the clinicians' need for hands-free interaction with systems due to infection control reasons. The three dimensional view of the oral cavity was also considered a highly ranked concept during the concept validation. However, during the usability testing rounds, the participants valued the single tooth view higher than the three dimensional view for viewing information relevant for diagnosis and treatment planning.

These results confirmed the findings reported by previous studies (25, 33, 101, 145) that emphasized the significance of performing user testing during the development phases of clinical systems and software applications. The results also confirmed the argument by Kushniruk and Patel et al that humans are much better at recognizing than at recalling from memory (79, 102). Users are also better with identifying what is wrong with the system but are unable to provide solutions and express their needs (108, 109). For instance, the three dentists rated the three dimensional model of a jaw as the most needed concept during the concept validation phase. However, during usability testing, the participants rated the single tooth view page higher than the three dimensional view of the oral cavity. As stated at the beginning of this chapter and in Chapter 2, these insights have been available at least since the 1970s and have led to the application of techniques and methodologies adapted from applied cognitive psychology to study human-computer interaction. However, they have yet to become widely accepted methods for the design of clinical systems. Today, according to anecdotal reports, all the major commercial dental EHRs are developed based on the users' feedback. According to the director of the development division of a major dental EHR (oral communication), one-third of the development is based on user input, the second one-third is based on market competition and the last one-third is based on the developers' input. The results of the cognitive task analysis study, contextual inquiry and the iterative usability testing illustrate the benefits of applying cognitive engineering methods for the design of clinical systems.

9.6 IMPACT OF THE DMD PROTOTYPE DESIGN ON KEYSTROKE-LEVEL MODELING RESULTS

The significant reduction of the time taken to access patient information in the DMD Prototype when compared with the EagleSoft may be due to the differences in the information presentation and navigation in the DMD Prototype and EagleSoft. Using the DMD Prototype, it took participants about 35 seconds to complete all the tasks, as opposed to about 106 second using EagleSoft. These results answered, to a certain extent, the research question about whether or not a prototype designed on the basis of the cognitive engineering methods supports the clinicians' review of a patient case better than a system that is not. The results from the cognitive task analysis study and contextual inquiry clearly showed how clinicians reviewed more than one type of information to diagnose and treatment plan a patient case. The results also uncovered how clinicians went back and forth between certain information. The increased time required with the use of EagleSoft was attributed largely to the many clicks required to complete certain tasks. In the DMD Prototype, it was possible to jump to any other page using the tabs on the vertical bar. The vertical bar containing different tabs (see Figures 24-28) to access different information sources was designed to support the clinicians rapid switching between different information sources during diagnosis and treatment planning. The results from the formative evaluation provided new empirical evidence on the difference between a system designed by applying cognitive engineering methods and one that was not.

9.7 COMPARING A PROTOTYPE DESIGNED FROM COGNITIVE ENGINEERING METHODS TO ANOTHER SYSTEM

In this evaluative phase of the research project, the DMD Prototype was comparatively evaluated against a commercial dental electronic health record (EHR) system, cEDR to determine the users' perception on navigation, information organization and usability of the prototype. The results of this study answered the overall research question, "Will a prototype designed on the basis of the cognitive engineering methods support clinicians'’ review, diagnosis and treatment planning of a patient case better than a system that is not?" The responses from the ten participants in this study supported that the users perceived the DMD Prototype to have an improved navigation flow, information organization and system usability. The results of this study are the most significant outcome of the entire research and add new empirical evidence to the few previous studies (15, 41-43, 103) that sought to understand the cognitive processes and information management strategies used by clinicians during patient care in order to inform the design of the system. These results demonstrated its effectiveness for the design of systems that provide cognitive support during patient care and thus raised the potential to enhance the quality and safety of patient care. Extensive research exists on applying cognitive engineering methods during the design and development phases of clinical systems (101, 102, 152-155). Most of these studies were applied to evaluate the design of systems after they have been developed. Therefore, these results provided enough evidence to recommend the need to apply cognitive engineering methods to inform clinical systems design and thus prevent the unintended adverse consequences reported by recent studies when health information technology was implemented in clinical settings.

The results of this study are also noteworthy because they showed how displaying clinically relevant information in one screen, or in the same place as in the patient overview screen (see Figure 24), and the single tooth view page (see Figure 28) had a profound impact on the participants' positive perceptions about navigation through the information, information organization and the usability of the system. The need to show clinically relevant information that contributed to making a decision would not have been possible without having the results from the cognitive task analysis study and the insights from the contextual inquiry. Thus, the studies not only contributed to the significance of applying cognitive engineering methods but also to expand existing knowledge on refining cognitive engineering methodologies and analysis for future use in dentistry, and in other domains as well.

While the participants expressed positive attitudes towards the DMD Prototype when compared with the cEDR, it was interesting to notice that they appeared to have adapted to the way the tasks were performed in cEDR. They claimed that, with training and experience, they are now familiar with using cEDR. A previous study reported similar results when the investigators evaluated a redesigned clinical reminder system against the current system. The users who evaluated the two systems did not notice much improvement with the redesigned system. This finding indicates that with time, users adapt to the way a task is designed to perform in a system. Patel and colleagues (14) reported similar results in a study where the content and information organization of the computer-based patient records influenced the physicians' data gathering and reasoning strategies. They concluded that technology has a profound influence on cognitive behavior and called for further studies to determine whether these changes have a positive or negative impact by assessing and characterizing the effects. They also commented that it is important we keep in mind that "as we update the technology with new designs, human cognition will also change." The results from this study, along with that of Saleem et al (168) and Patel et. al (14) strongly indicate the need for more research to explore the influence of present day technology on the cognitive behavior.

Despite the participants' familiarity with and ease of using cEDR gained through training and years of experience, all the participants in this study unanimously agreed that the navigation through the information is logical and intuitive in the DMD Prototype, and all the information is available in one place or in one click. This result once again confirms how the clinical system designed based on cognitive task analysis and contextual inquiry results in providing clinicians with improved cognitive support. Such a system would contribute to enhancing the quality and safety of patient care, because clinical performance improves when information displays match the users' mental model work processes (26, 74, 77, 78).

9.8 SUMMARY

In summary, the results of this project indicate that a prototype designed based on cognitive engineering methods supported the clinicians' review, diagnosis and treatment planning of a patient case better than a system that is not. The finding that dentists use multiple sources of information, and that the separation of information on multiple screens could compromise the clinicians' decision-making, is the most significant finding in our study that would have a profound impact on the design of future clinical systems. In addition, the results from the cognitive task analysis and contextual inquiry studies provided meaningful insights to designing information presentation and navigation through information to support clinical decision-making. For instance, the cognitive task analysis study identified the groups of information that need to be shown together and also identified the patterns of navigation through information such as reviewing the radiographs, photos and periodontal chart together when confirming diagnosis and finalizing treatment. Although none of the participants showed similar patterns of accessing and reviewing information, the study results helped with characterizing these variations and with creating optimum navigation designs and information display that support these variations. This flexible navigation and displaying relevant information in one screen had a profound impact on the users' perception on information organization and navigation of the DMD Prototype. The cognitive task analysis results also provide a rich data set on how dentists accessed and processed information during patient exam, which is a major accomplishment in dentistry and dental informatics. The contextual inquiry results confirmed the findings observed in the cognitive task analysis study on how the clinicians used multiple sources of information during patient care and the difficulty they experienced when switching between screens to access information in the dental electronic health records. The high level of collaboration among the dental team stresses the need to support this collaborative activity in any system designed for dental practices. In addition, the small size of the dental operatories observed in the dental practices further confirmed that any systems designed for chairside use should fit these small size operatories. Finally, the usability study conducted during formative evaluation further confirmed its value in identifying the users' understandability with the labels and navigation of the system interface. It also demonstrated that while the usability study is beneficial to identify the problems when users interact with the system, it has limited value in generating solutions to the users' needs and in understanding the users' needs. These findings again highlighted the significance of conducting cognitive engineering methods to understand user needs.

9.9 STUDY LIMITATIONS

There are several limitations in this study as with any research. One limitation of the study was the small sample size and the convenience sample of dentists and senior dental students in Pittsburgh area who participated in the four studies. It is unknown whether the study results will be generalizable to the national population of US dentists. Attempts were made to recruit dentists who graduated from different dental schools for the cognitive task analysis study. However, it was not possible to detect any differences in how dentists review and process information when developing treatment plan in this study due to the small sample size.

The second limitation was the laboratory settings where the cognitive task analysis study was conducted in contrast to the clinical settings where dentists typically reviewed patient information and develop a treatment plan. Dentists do not generally verbalize their thoughts while examining and assessing patient's problems. However, they might verbalize their thoughts while discussing the case with a colleague. The cognitive task analysis study was conducted because clinical decision-making is not easily studied in a field study. As observed in the study by Irwin et al. (91), dentists often combined data gathering and treatment planning into a single activity, especially with patients of low to medium complexity. Therefore, it seemed reasonable to conduct the laboratory study where dentists were provided with complete patient documentation and asked to review and develop a treatment plan. The dentists were then able to focus their attention completely on the patient case and verbalize their thoughts, thus enabling data capture, which would have been impossible in clinical settings. To a certain extent, the drawback of the laboratory nature of cognitive tasks analysis study was counterbalanced by conducting contextual inquiry in five dental offices.

The third limitation is the formative and comparative evaluation of the DMD Prototype with limited functionalities and EagleSoft and cEDR with complete functionalities of a dental EHR. Therefore the DMD Prototype appeared to be simple than cEDR. These differences in functionalities between the two systems were minimized by showing videos of how the three tasks were performed in both the systems. However, the results will be valuable and contribute to the knowledge on the impact of using cognitive engineering methods to inform the design of clinical systems.

9.10 CONCLUSION

There are numerous significant outcomes from this research study. The first and foremost, this study demonstrated the significance of applying cognitive engineering methods to inform the design of a clinical system. The greatest benefit of this study is the rich characterization of dentists' varied approaches to using information when performing a new patient exam. The new knowledge on the dentists' patterns of information retrieval and review contributed significantly to designing the presentation of information to support the dentists' flexible navigation through the information. It is also the first empirical study on how and what information dentists use to make clinical decisions. Thus, the study results contributed rich information to generate new hypotheses towards understanding the information management strategies used by dental care providers. The results of this dissertation study also highlighted the findings from previous studies on how the users' feedback through surveys, interviews and usability testing help only with identifying what is wrong with the system and do not help with finding solutions. This is because users are in general unable to express their needs and provide solutions. This finding is significant because currently, majority of the health information technology developed rely on users feedback and only very few systems are developed based on rigorous needs analysis conducted by applying cognitive engineering methods during the design cycle of the system. A major criticism of using cognitive engineering methods is the significant time commitment needed for these methods. While this is true, the results of this study contribute to the few studies that illustrated the value of performing these methods to "identify the physical, informational and value constraints on the design from the outset to produce a useful and usable design" (169). In addition, the relatively low cost of making changes during the design phases of the system when compared with the cost after system development and implementation makes it worthwhile to invest the time and effort during the early stages of needs analysis. Another significant outcome of this dissertation is the finding on how the users with training and experience adapt over time to the way a system or technology is designed. As noted by senior researchers in the cognitive science and medical informatics field, this is of great concern that warrants more attention than it has now. The study results from this dissertation highlight the critical need for further research on how the information presentation and visualization in current systems influences the decision-making activities of clinicians and determine whether it is improving or hindering their decisions with possible impact on the quality of patient care.

9.11 FUTURE WORK

The results of this project provide a basis for future studies and development of specific clinical decision support systems that would improve clinicians' decision-making and patient care. The rich data set of the cognitive task analysis study offer sufficient information to design interventions that have the potential to support and improve preventive management during patient care. In addition, the rich characterization of the dentists' use of information during patient exam could be translated into a set of functional requirements for a dental electronic health record system. This could be a blueprint for the vendors and developers when designing dental clinical systems. Further, the cognitive task analysis results could also contribute to developing a standard information model and ontologies for dental electronic health records and decision support systems that support health information exchange. The observation that users adapt to even sub-optimally designed technology warrants further studies on how technology introduced in clinical settings impacts dentists' and dental students' decision- making and learning during patient care. Finally, the DMD Prototype could be developed into an application that provides a front-end "universal interface" so that dentists could access and review patient information irrespective of what system they use.

9.12 PROPOSED PUBLICATIONS

1. Decision-making and information management strategies of dentists during patient visits
2. Cognitive engineering approach to visualizing clinical data
3. Impact of an interface designed using cognitive engineering methods

APPENDIX A

PATIENT CASES

This appendix contains complete patient documentation for three cases that were used during this dissertation project as they were presented to the participants. Permission to use this documentation was granted by the University of Pittsburgh School of Dental Medicine, 3501 Terrace St, Pittsburgh, PA 15261. Duplication or use of these scenarios without permission from the School of Dental Medicine is prohibited.

A.1 LOW COMPLEXITY CASE

Gender: Asian female

Age: 40 years old

Chief Complaint: Patient wants to get her teeth cleaned.

Dental history:

- Patient's last dental visit was 1 year ago
- Previous dental treatments included restoration, extractions for orthodontic treatment, and routine cleaning

Medical History:

- Physical Status I
- Allergic to shrimps

Vital signs: BP= 95/70 HR= 74

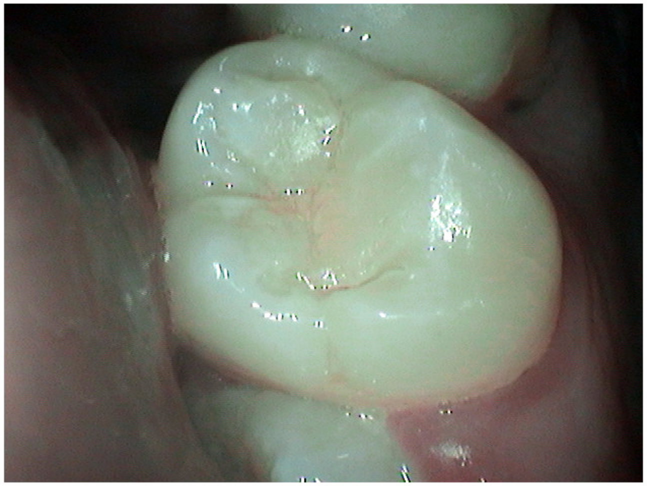
Maxillary Occlusal View

Mandibular Occlusal View

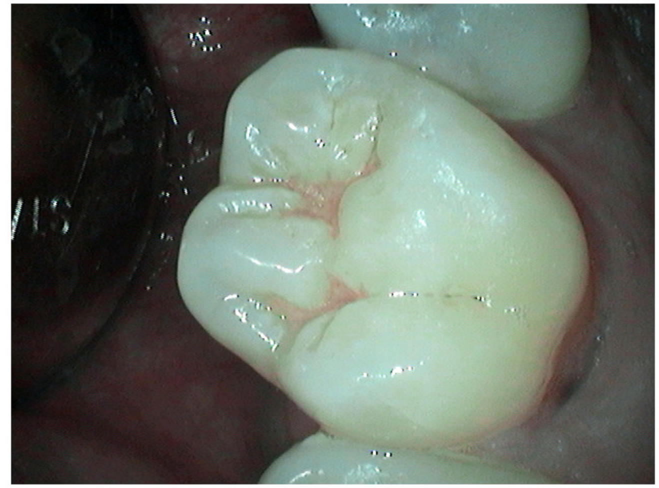
Left Lateral View

Right Lateral View

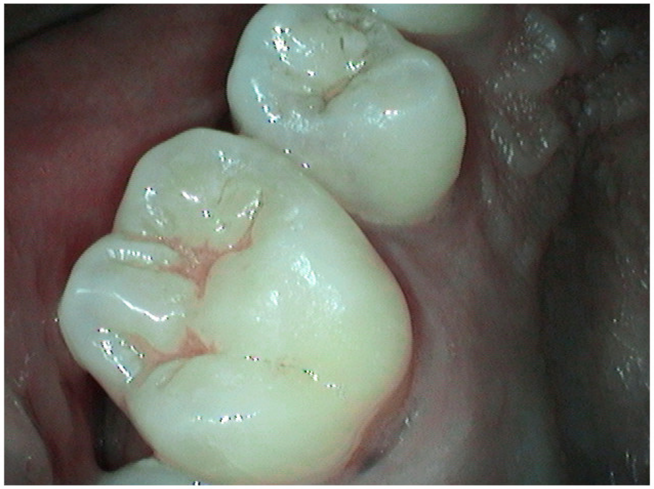
Frontal View



Tooth #2

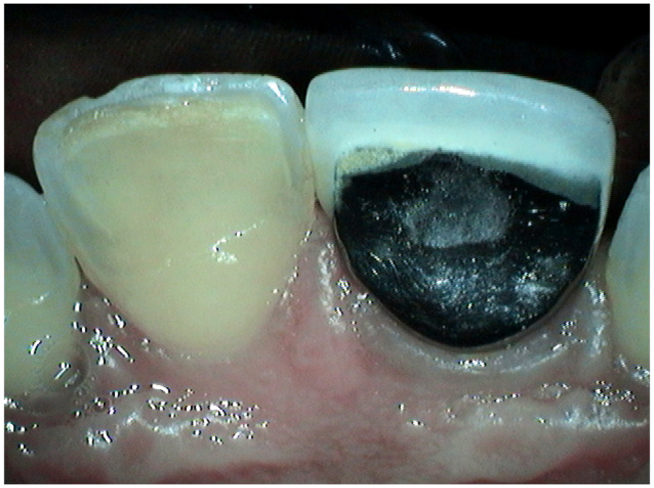


Tooth #3

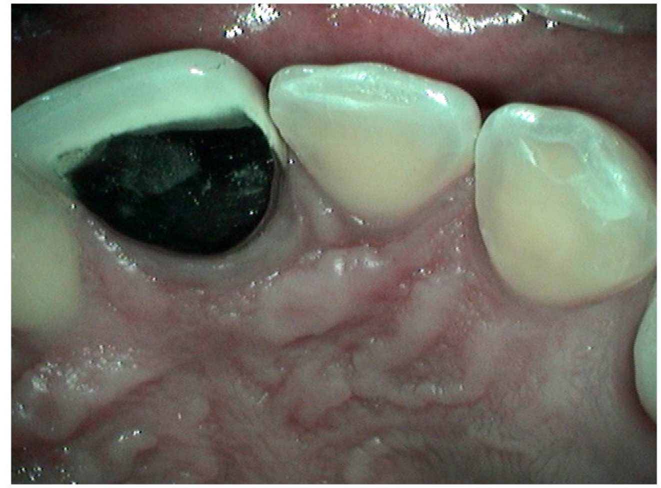


Teeth #3-4

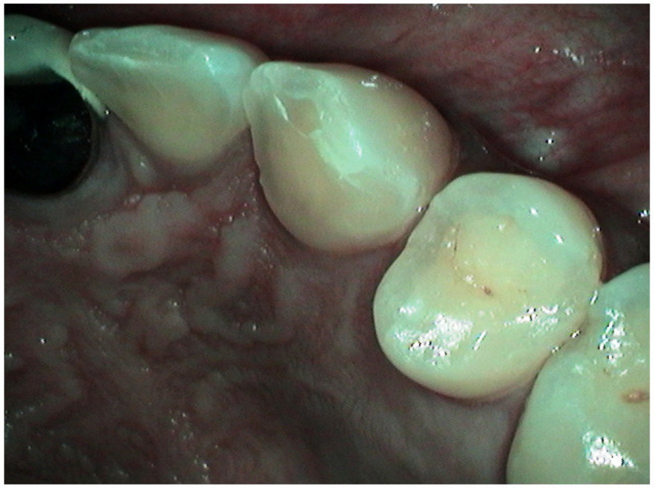
Teeth #6-8



Teeth #8-9

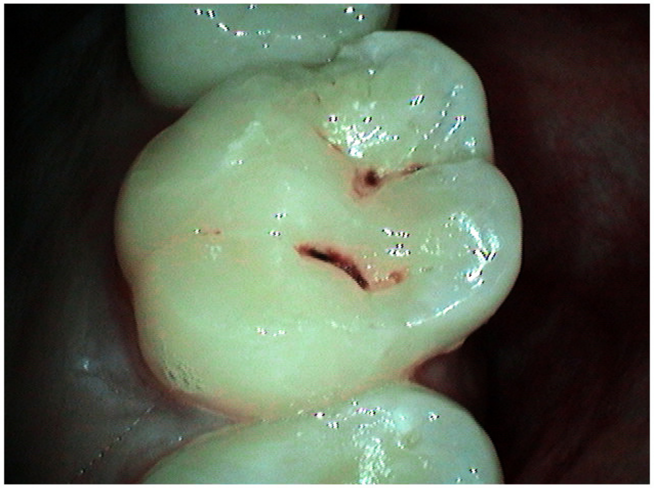


Teeth #9-11

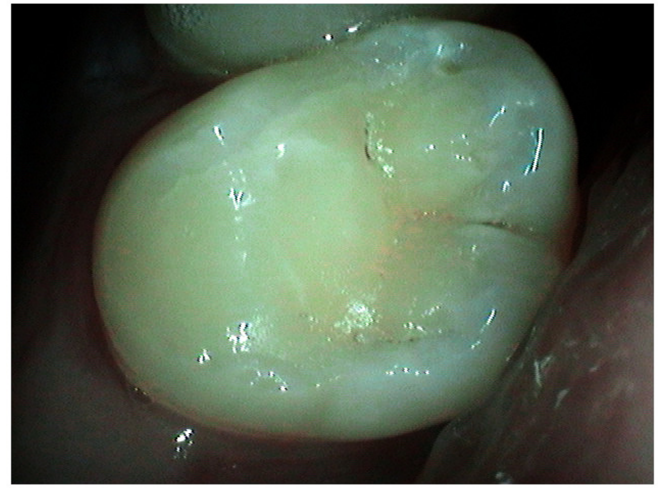


Teeth #10-13

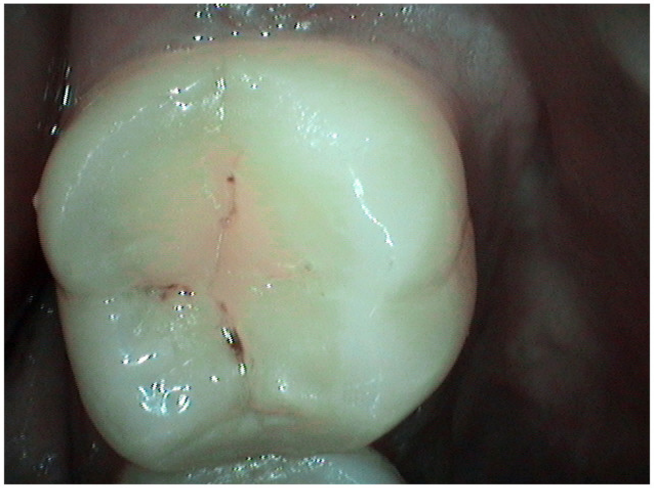
Teeth #13-14



Tooth #14

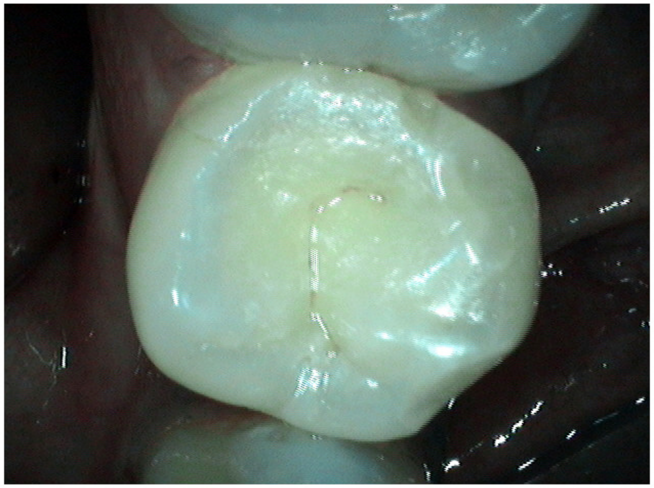


Tooth #15



Tooth #18

Tooth #19

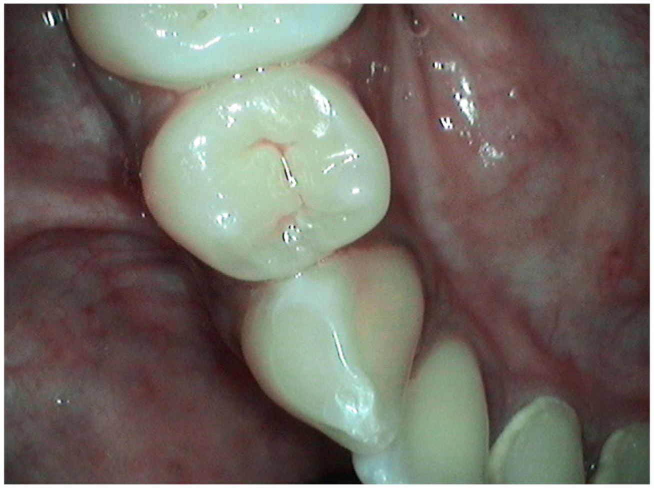


Tooth #20

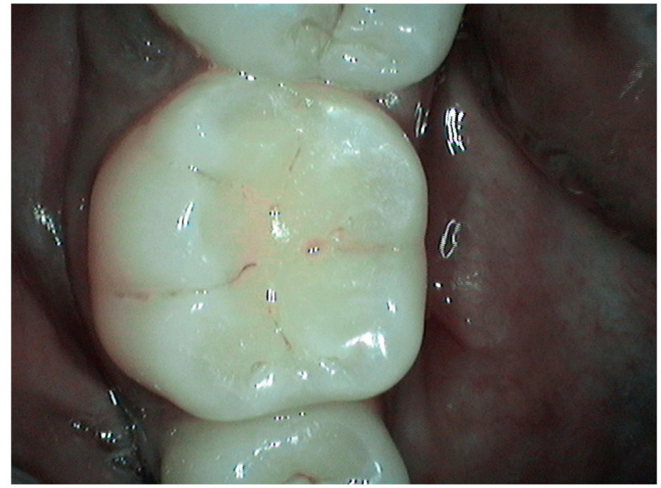
Teeth #20-23

Teeth #23-26

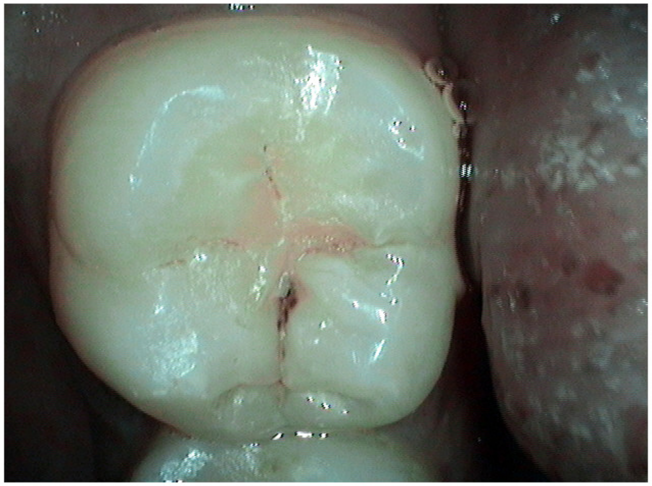
Teeth #23-25 (Lingual)



Teeth #27-29



Tooth #30



Tooth #31

Panorex Radiograph

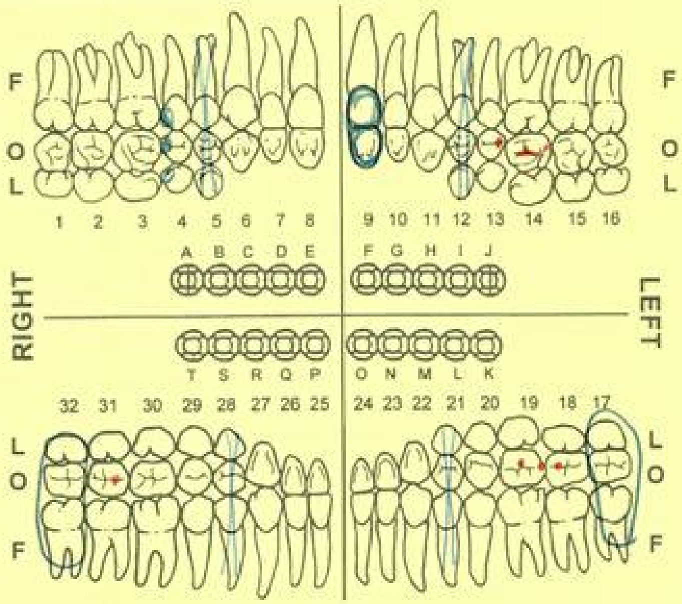
Full Mouth Series Radiographs

Charting and Treatment Plan

HARD TISSUE EXAMINATION:

Patient Name:____________________

Account Number:__________________



Periodontal Screening & Recording

Sextant Score

Month Day Year

Existing Prosthesis:

Maxilla:	Approximate date placed:	Condition:
Mandible:	Approximate date placed:	Condition:

RADIOLOGY REPORT: ☐ PAN ☐ FMX ☐ Bite Wings

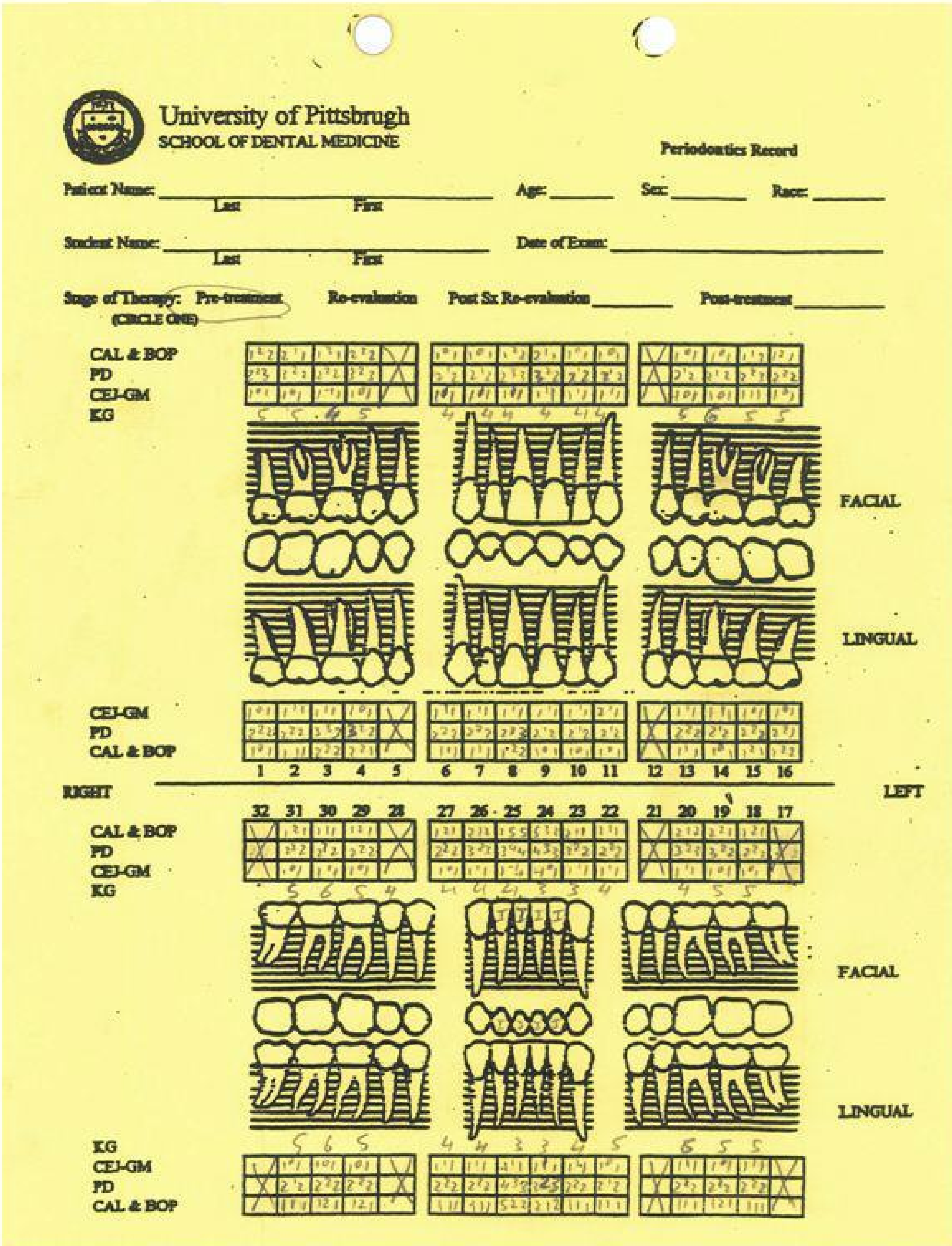
☐ Other____________________ Date of Radiographs:____________

FINDINGS (All areas described in radiolucent/radiopaque terms):

IMPRESSIONS (Differential diagnosis of findings):

Student:____________________ Faculty:____________________ Date:____________

Hard Tissue Examination



University of Pittsbrugh
SCHOOL OF DENTAL MEDICINE

Periodontics Record

Patient Name: ______________________ (Last) (First) Age: ______ Sex: ______ Race: ______

Student Name: ______________________ (Last) (First) Date of Exam: ______________

Stage of Therapy: Pre-treatment Re-evaluation Post Sx Re-evaluation ______ Post-treatment ______
(CIRCLE ONE)

CAL & BOP
PD
CEJ-GM
KG

FACIAL

LINGUAL

CEJ-GM
PD
CAL & BOP

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

RIGHT LEFT

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17

CAL & BOP
PD
CEJ-GM
KG

FACIAL

LINGUAL

KG
CEJ-GM
PD
CAL & BOP

Periodontal Examination

A.2 MEDIUM COMPLEXITY CASE

Gender: African American female

Age: 43 years old

Chief Complaint: Patient interested in getting her "teeth fixed"

Dental history:

- Patient's last dental visit was 13-14 years ago
- Previous dental treatments included restorations, extractions, and routine cleaning

Medical History:

- Physical Status II
- Allergic to Erythromycin and Penicillin

Vital signs: BP= 123/82   HR= 92

Maxillary Occlusal View

Mandibular Occlusal View

Mandibular Occlusal View

Right Lateral View

Left Facial View

Right Facial View

Frontal View

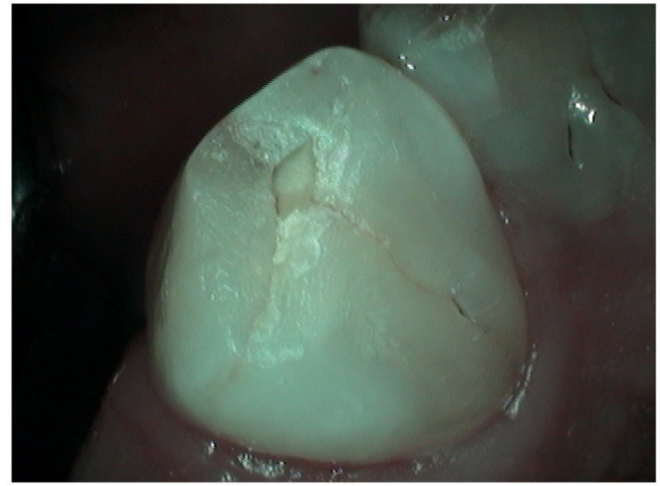
Tooth #1

Tooth #2

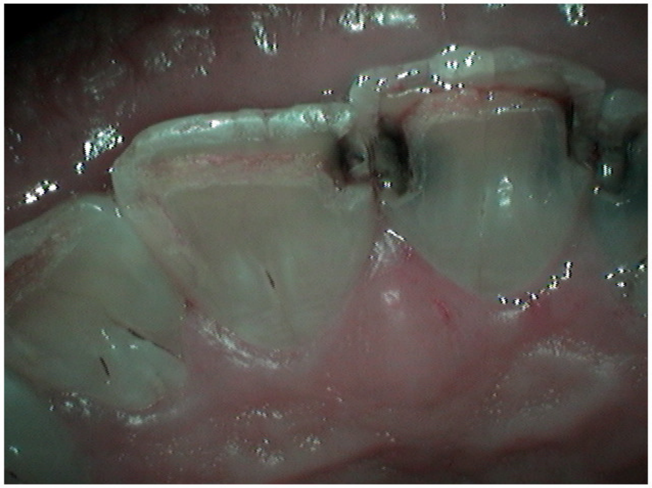
Tooth #4

Tooth #5

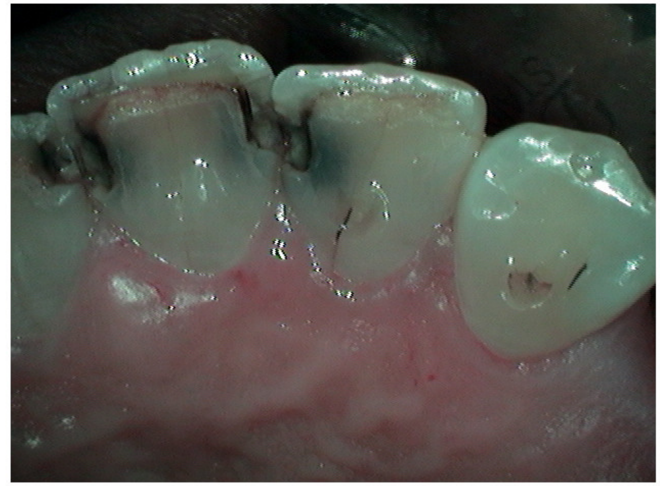
Tooth #6-8



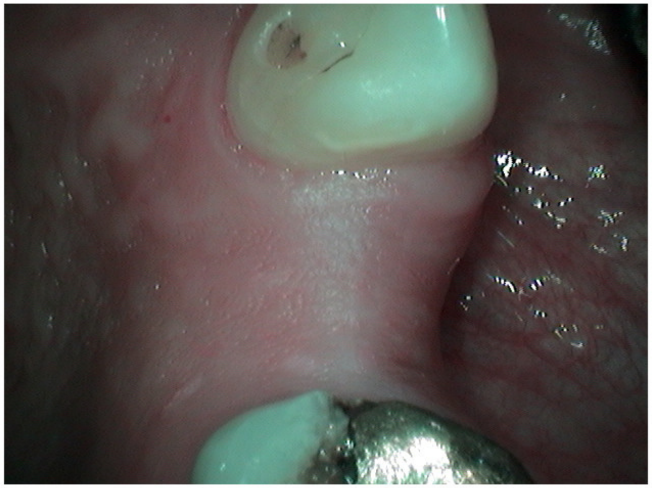
Tooth #6



Teeth #8 and #9

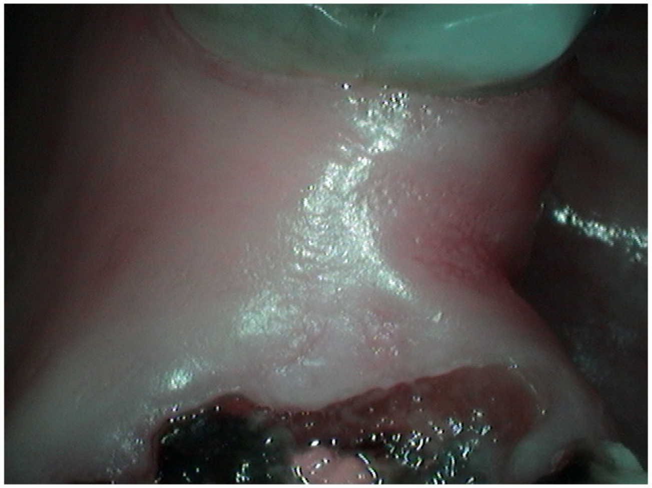


Teeth #9-11



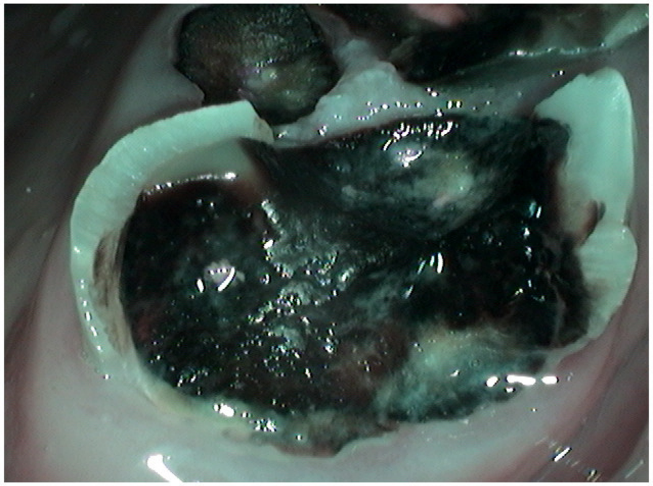
Tooth #12

Tooth #13



Tooth #14

Tooth #15



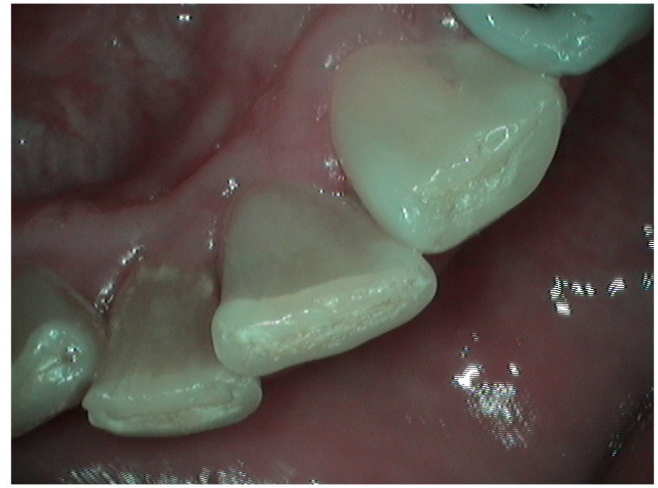
Tooth #16

Tooth #18

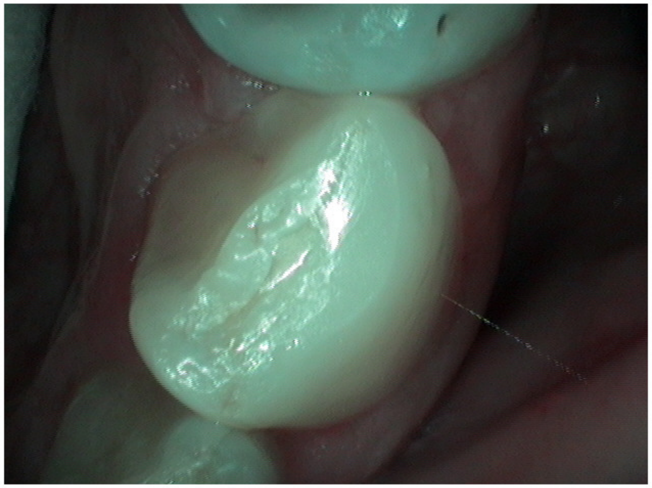
Tooth #19

Tooth #20

Tooth #21



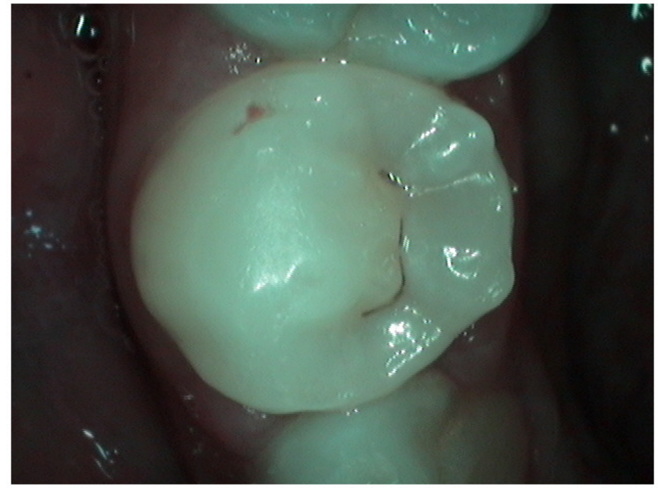
Tooth #22-24



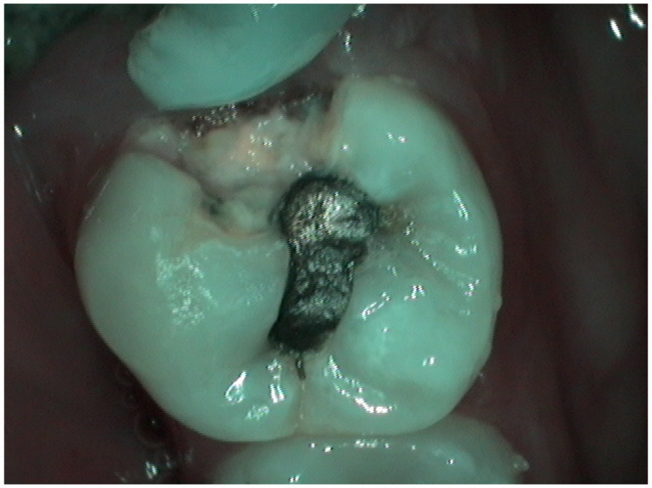
Teeth #22

Tooth #23-25

Teeth #25-27

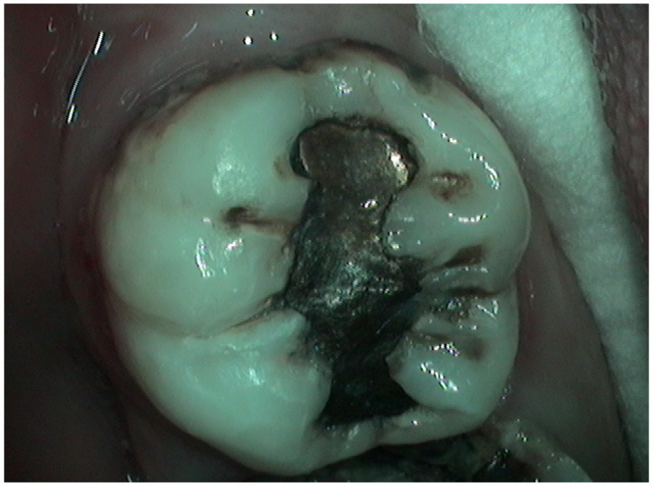


Teeth #28

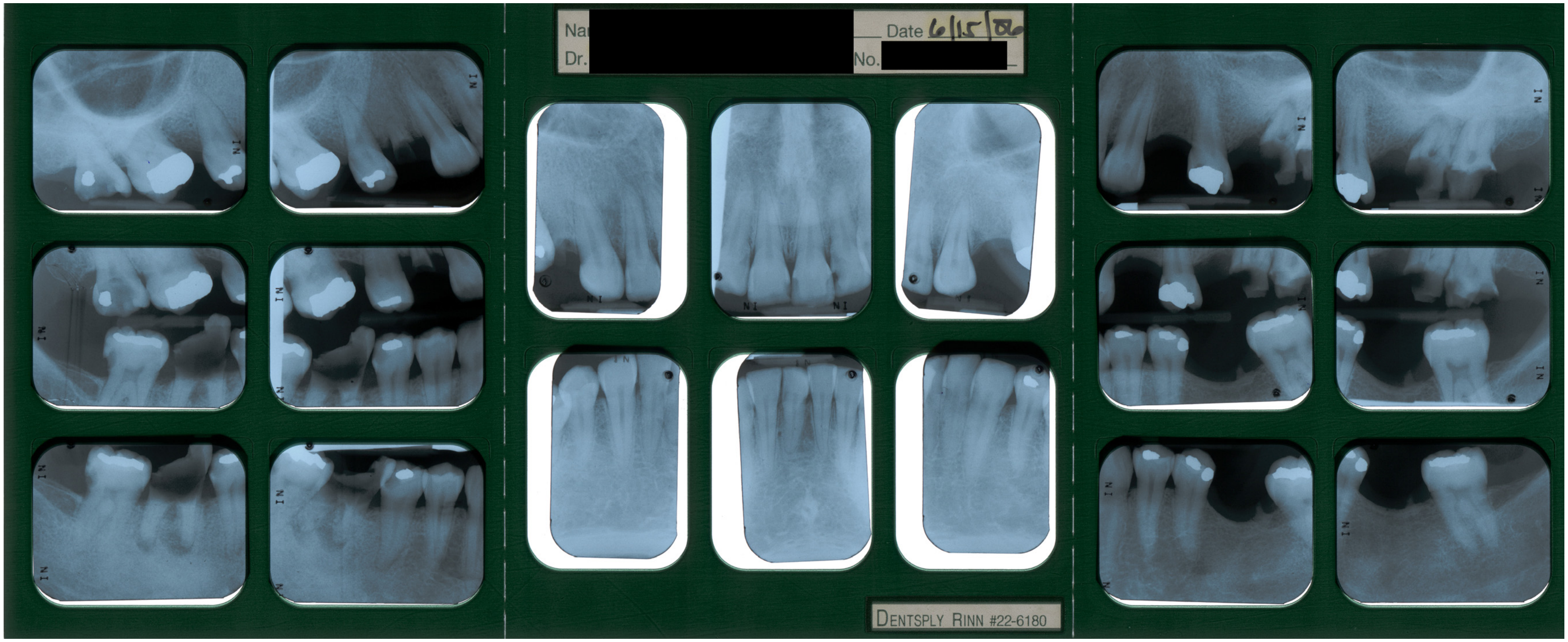


Tooth #29

Tooth #30



Tooth #31

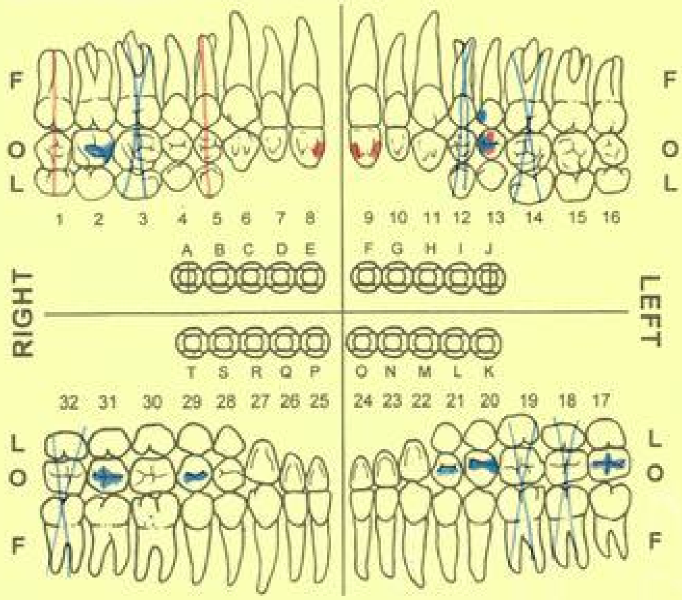


Full Mouth Series Radiographs

Tooth #29

Charting and Treatment Plan

HARD TISSUE EXAMINATION:



Patient Name:________________

Account Number:________________

2	1	2	**Periodontal Screening & Recording**
3	3	2	

Sextant Score

Month Day Year

Existing Prosthesis:

Maxilla:	Approximate date placed:	Condition:
Mandible:	Approximate date placed:	Condition:

RADIOLOGY REPORT: ☐ PAN ☐ FMX ☐ Bite Wings
☐ Other________________ Date of Radiographs:________

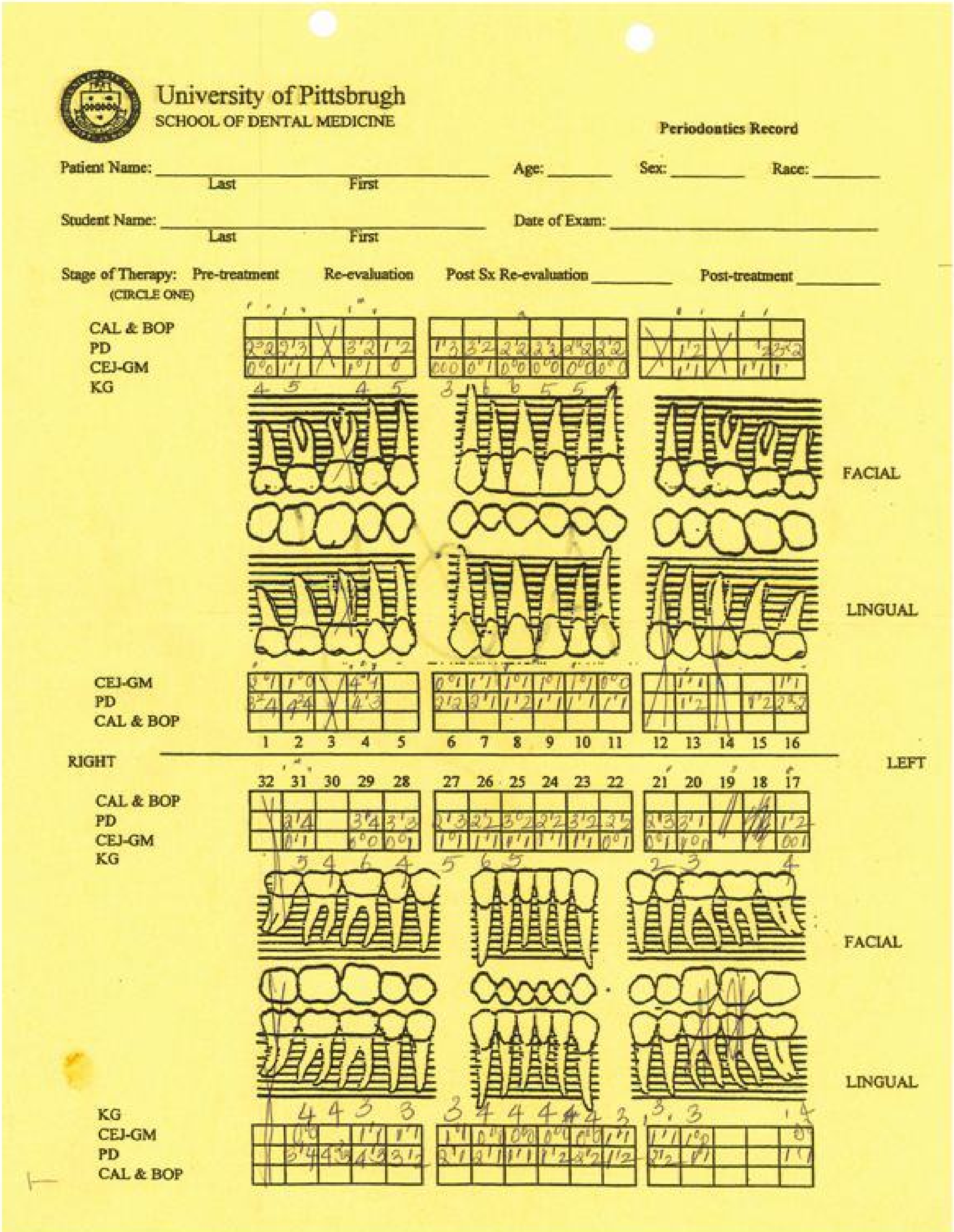
FINDINGS (All areas described in radiolucent/radiopaque terms):

IMPRESSIONS (Differential diagnosis of findings):

Student:________________ Faculty:________________ Date:________

UMC 92196B

Hard Tissue Examination



University of Pittsbrugh
SCHOOL OF DENTAL MEDICINE

Periodontics Record

Patient Name: ____________ Last ____________ First ____________ Age: ______ Sex: ______ Race: ______

Student Name: ____________ Last ____________ First ____________ Date of Exam: ____________

Stage of Therapy: (CIRCLE ONE) Pre-treatment Re-evaluation Post Sx Re-evaluation ______ Post-treatment ______

CAL & BOP
PD
CEJ-GM
KG

FACIAL

LINGUAL

CEJ-GM
PD
CAL & BOP

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

RIGHT LEFT

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17

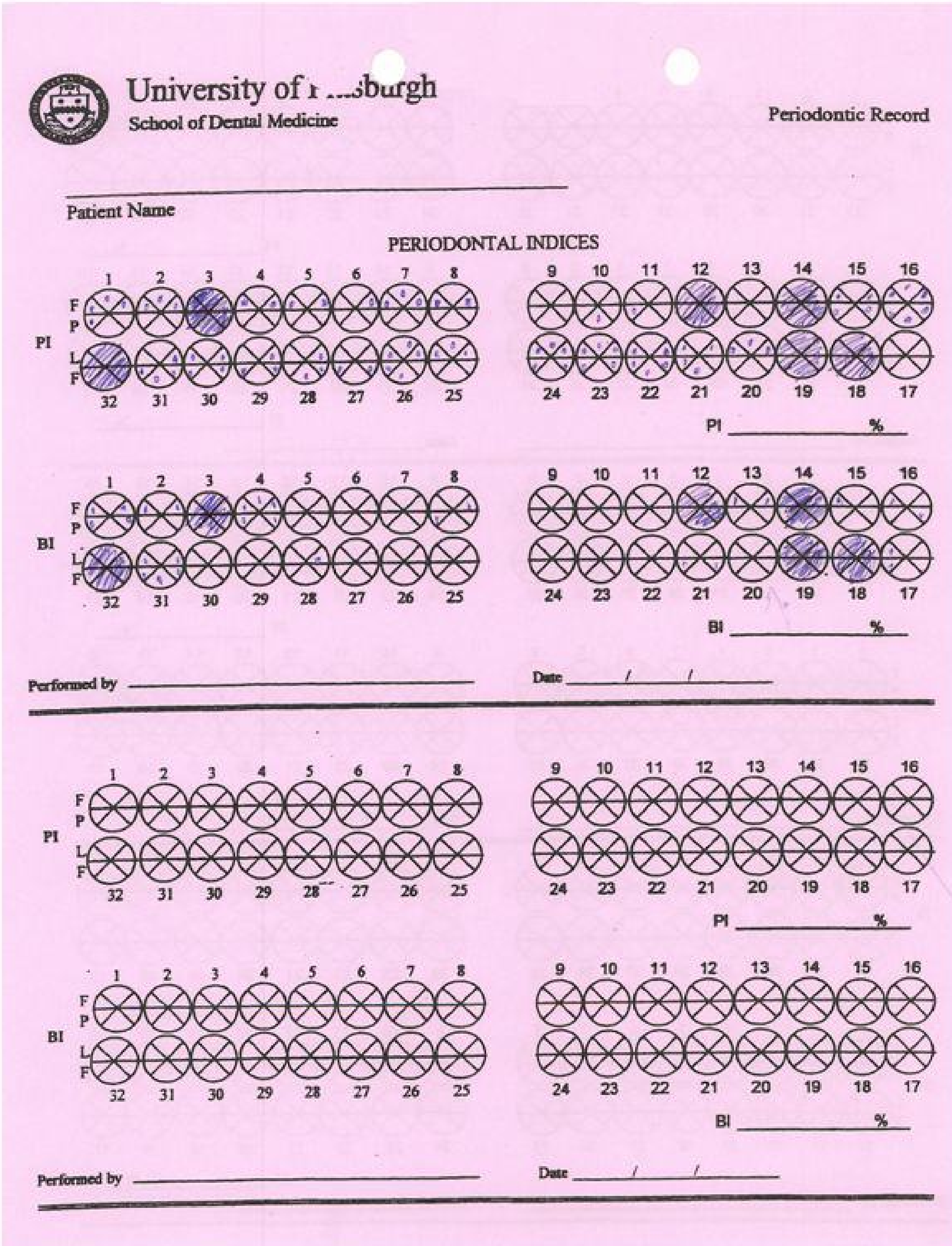
CAL & BOP
PD
CEJ-GM
KG

FACIAL

LINGUAL

KG
CEJ-GM
PD
CAL & BOP

Periodontal Examination



University of Pittsburgh
School of Dental Medicine

Periodontic Record

Patient Name ______________________

PERIODONTAL INDICES

PI

F
P
L
F

1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16

32 31 30 29 28 27 26 25 | 24 23 22 21 20 19 18 17

PI ________ %

BI

F
P
L
F

1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16

32 31 30 29 28 27 26 25 | 24 23 22 21 20 19 18 17

BI ________ %

Performed by ______________________ Date ___/___/___

PI

F
P
L
F

1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16

32 31 30 29 28 27 26 25 | 24 23 22 21 20 19 18 17

PI ________ %

BI

F
P
L
F

1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16

32 31 30 29 28 27 26 25 | 24 23 22 21 20 19 18 17

BI ________ %

Performed by ______________________ Date ___/___/___

Periodontal Indices

A.3 HIGH COMPLEXITY CASE

Gender: Latino male

Age: 44 years old

Chief Complaint: "I have some cavities, need teeth extracted, and my front teeth need fillings"

Social history

- The patient was born in El Salvador and moved to the United States when he was 20 years old.
- Prior to being hospitalized, he was employed as an electrician.
- He was on temporary disability from February 2005 to February 2006.
- Currently he is employed in residential construction.

Dental History:

- Patient had limited access to fluoridated water and dental care as a child in El Salvador.
- Since moving to US he has visited the dentist inconsistently.
- In 2000, patient was visiting a dentist regularly and was planning on having dental procedures done. The work was not completed because of financial reasons.
- The patient's oral health has been in a state of neglect since he was admitted into the hospital in February 2005.

Medical History:

- HIV positive (diagnosed February 2005)
  - hospitalized for 45 days from February to March 2005
- history of bacterial endocarditis with heart valve damage
- HSV type I and II
- Allergic to Septra
- Smokes 1 pack cigarettes per week

Vital Signs: BP: 138/93   Pulse: 76

Medications:

- Reyataz
- Norvir
- Travada
- Zithromax
- Dapsone
- Effudex and Aldara for topical application

Medical Consult and Management

- Medical consult sent concerning possible heart valve damage due to prior bacterial endocarditis

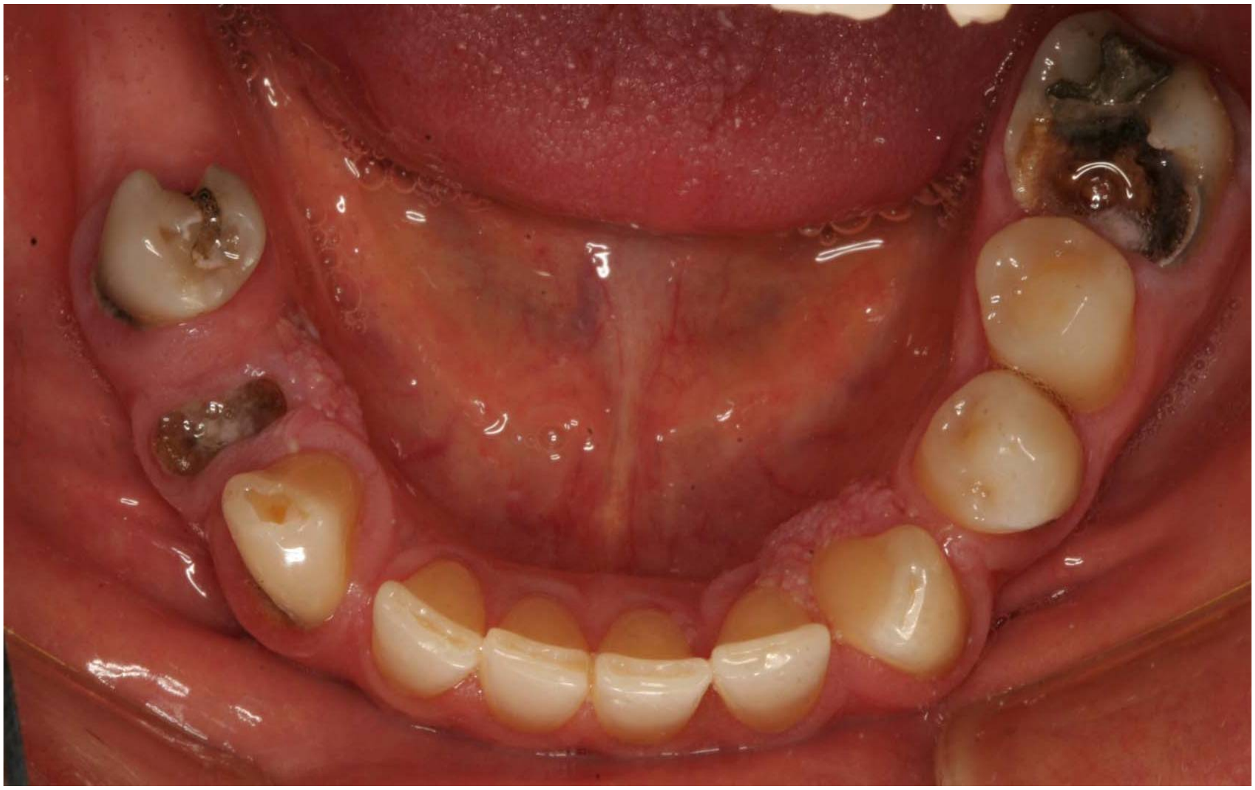
- Response: Patient has history of bacterial endocarditis, patient requires antibiotic prophylaxis for dental treatment according to the current AHA guidelines. He was prescribed Amoxicillin by his physician and instructed to take 2 g 1 hour prior to dental treatment.

- Monitor lab values for HIV. New labs required every 6 months.

Medical Consult and Management

- Critical values:
  - CD4 above 200—labs every 6 months, no other precautions
  - CD4 100-200—labs every 3-6 months, no other precautions
  - CD4 <100—labs every 3 months, evaluate pt for severe opportunistic disease
  - Viral load >5,000—indicates disease progression, ↑ risk of opportunistic infection
  - WBC count <2,000—consider AB with invasive procedures; delay elective tx
  - Neutrophils <1,000—consider AB with invasive procedures; delay elective tx
  - Platelets <60,000—delay elective tx; consult MD prior to invasive procedures
  - Hematocrit <10%--consult MD; consider red cell transfusion

Maxillary Occlusal View



Mandibular Occlusal View

Right Lateral View

Left Lateral View

Frontal View

Teeth #22-26

Extraoral exam – soft tissue exam

- Papillary proliferations on hands and face surrounding lips
- Papillary lesions on lips
- Swollen lymph nodes right and left neck

Intraoral exam – soft tissue exam

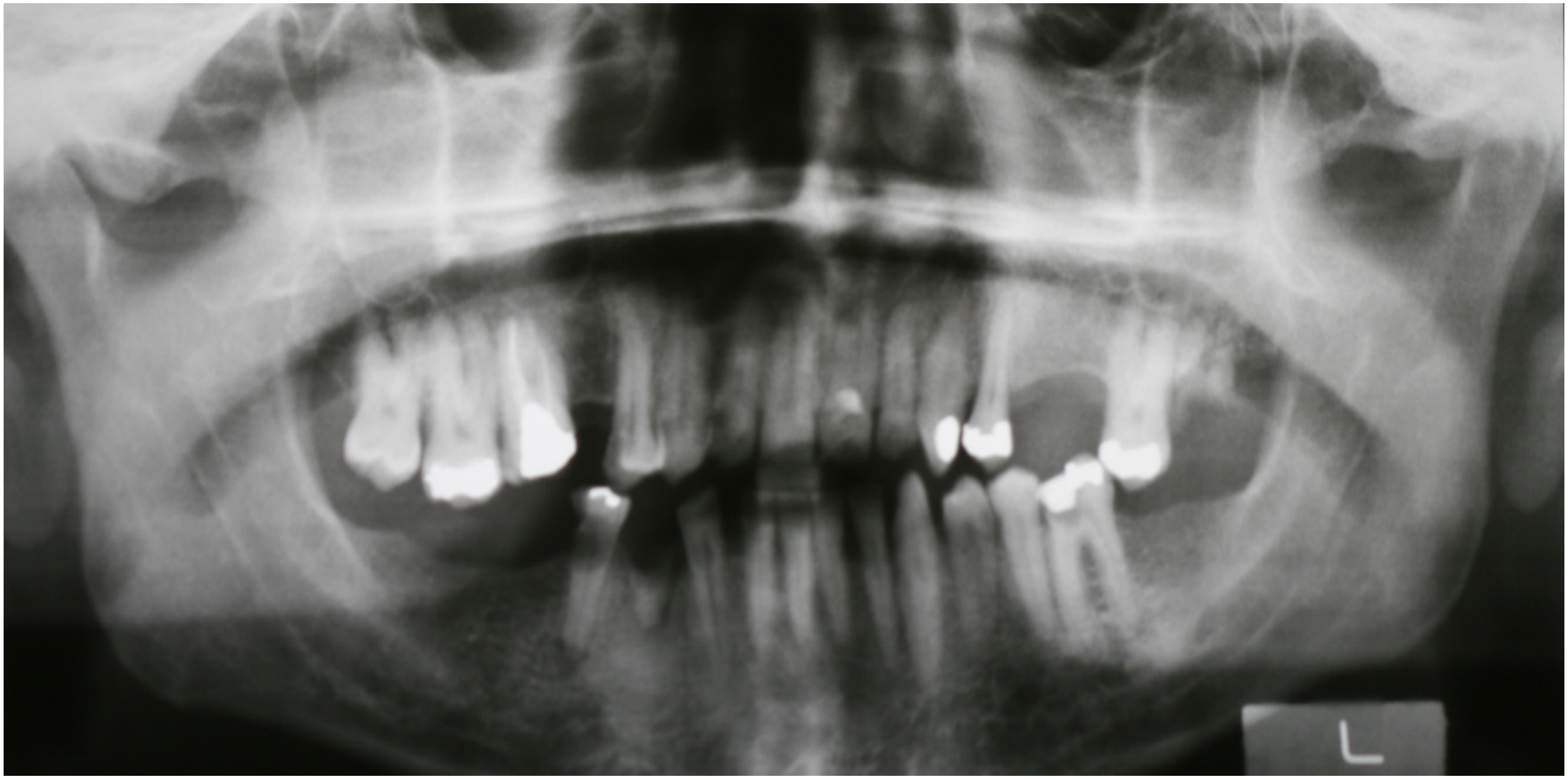
- Papillary lesions distal to #27, lingual #23-24, lingual #28, dorsal to tongue

Oral pathology consultation for the extra-oral and intra-oral lesions

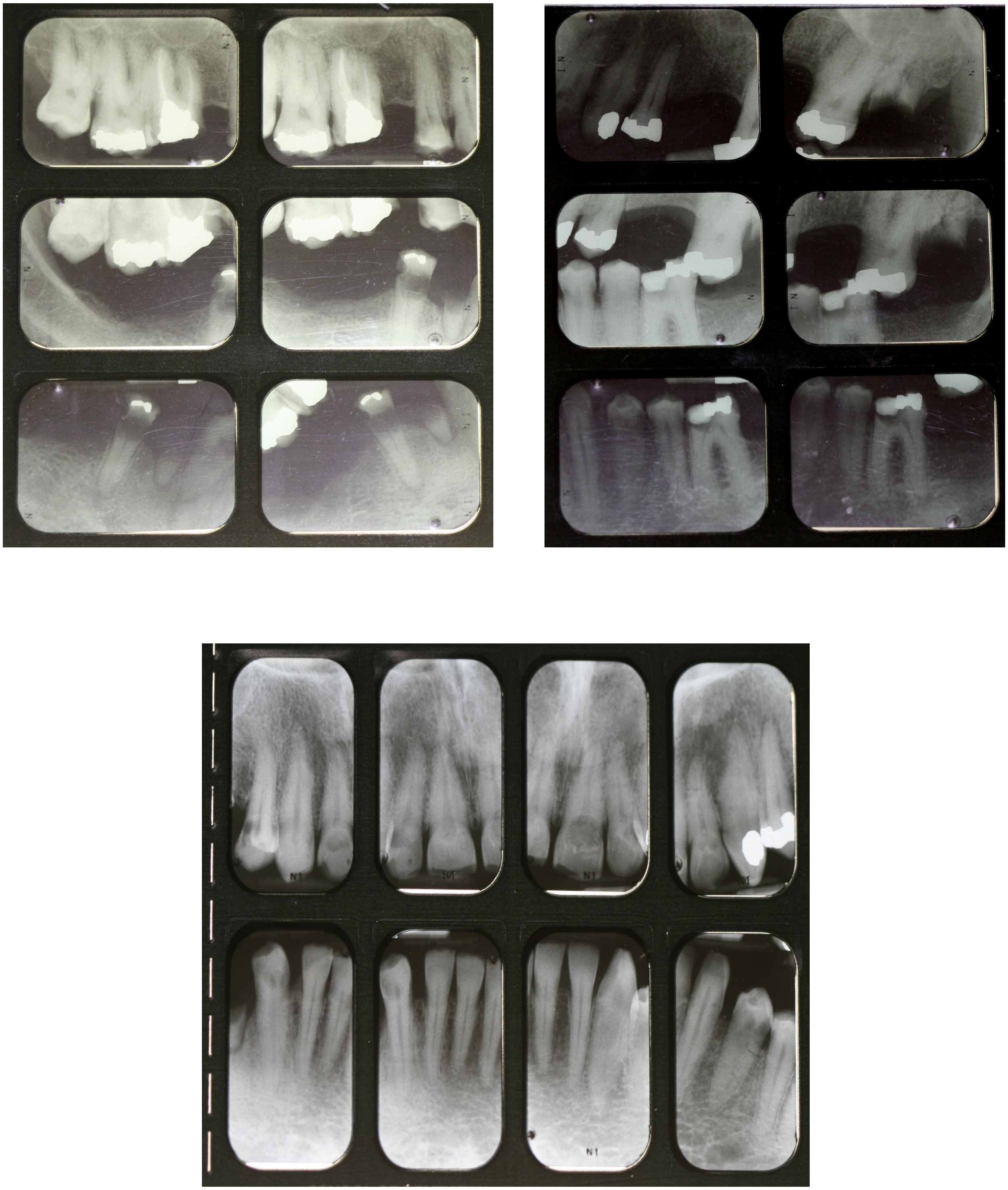
- Diagnosis: Condyloma Acuminatum

- Recommendation: Monitor lesions and consult Oral Surgeon for possible Laser Excision.

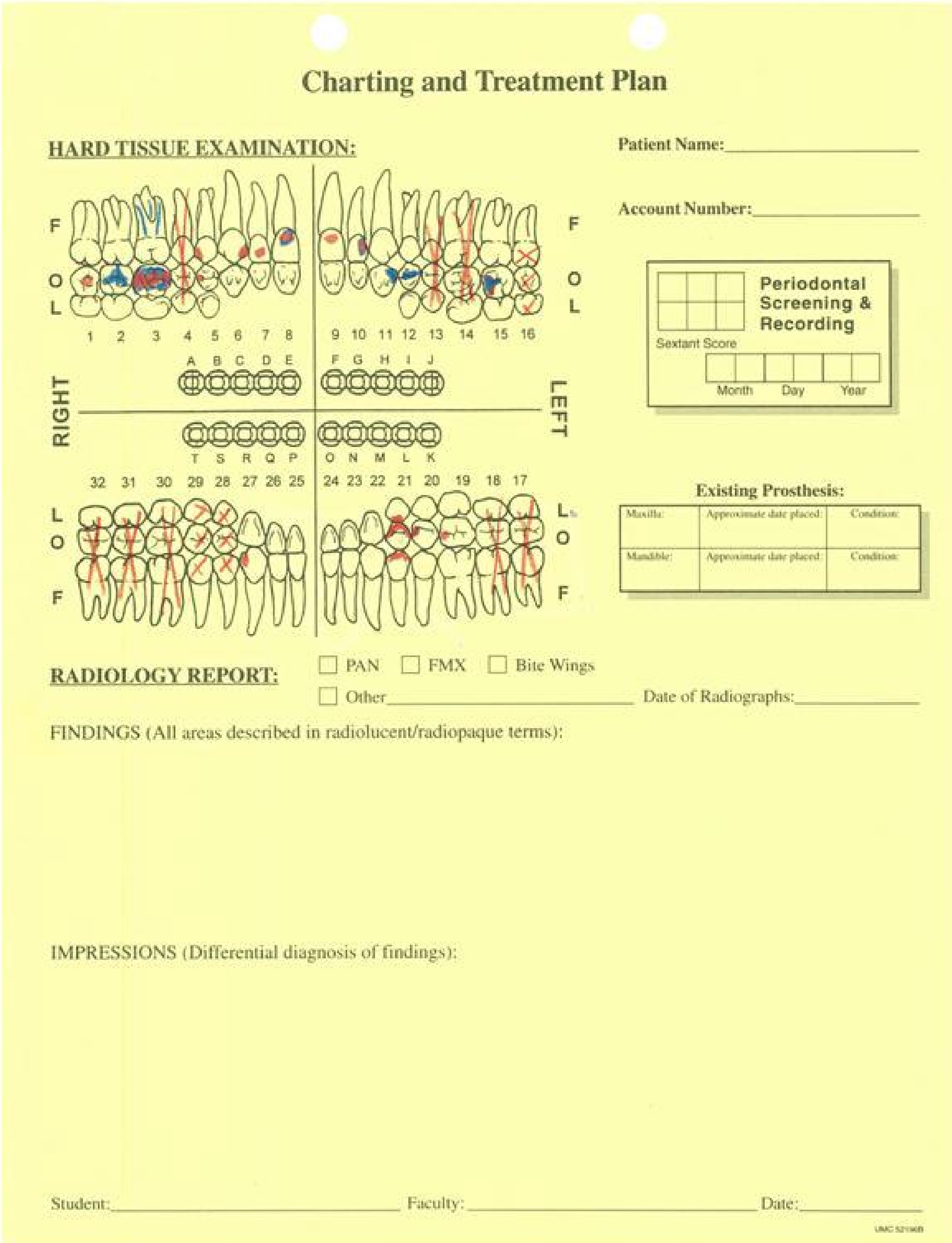
  Note: Lesions resolved as of April 2006.



Panorex Radiograph



Full Mouth Series Radiograph



Charting and Treatment Plan

HARD TISSUE EXAMINATION:

Patient Name:____________________

Account Number:__________________

RIGHT LEFT

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

A B C D E F G H I J

T S R Q P O N M L K

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17

Periodontal Screening & Recording

Sextant Score

Month Day Year

Existing Prosthesis:

Maxilla:	Approximate date placed:	Condition:
Mandible:	Approximate date placed:	Condition:

RADIOLOGY REPORT: ☐ PAN ☐ FMX ☐ Bite Wings ☐ Other________________ Date of Radiographs:__________

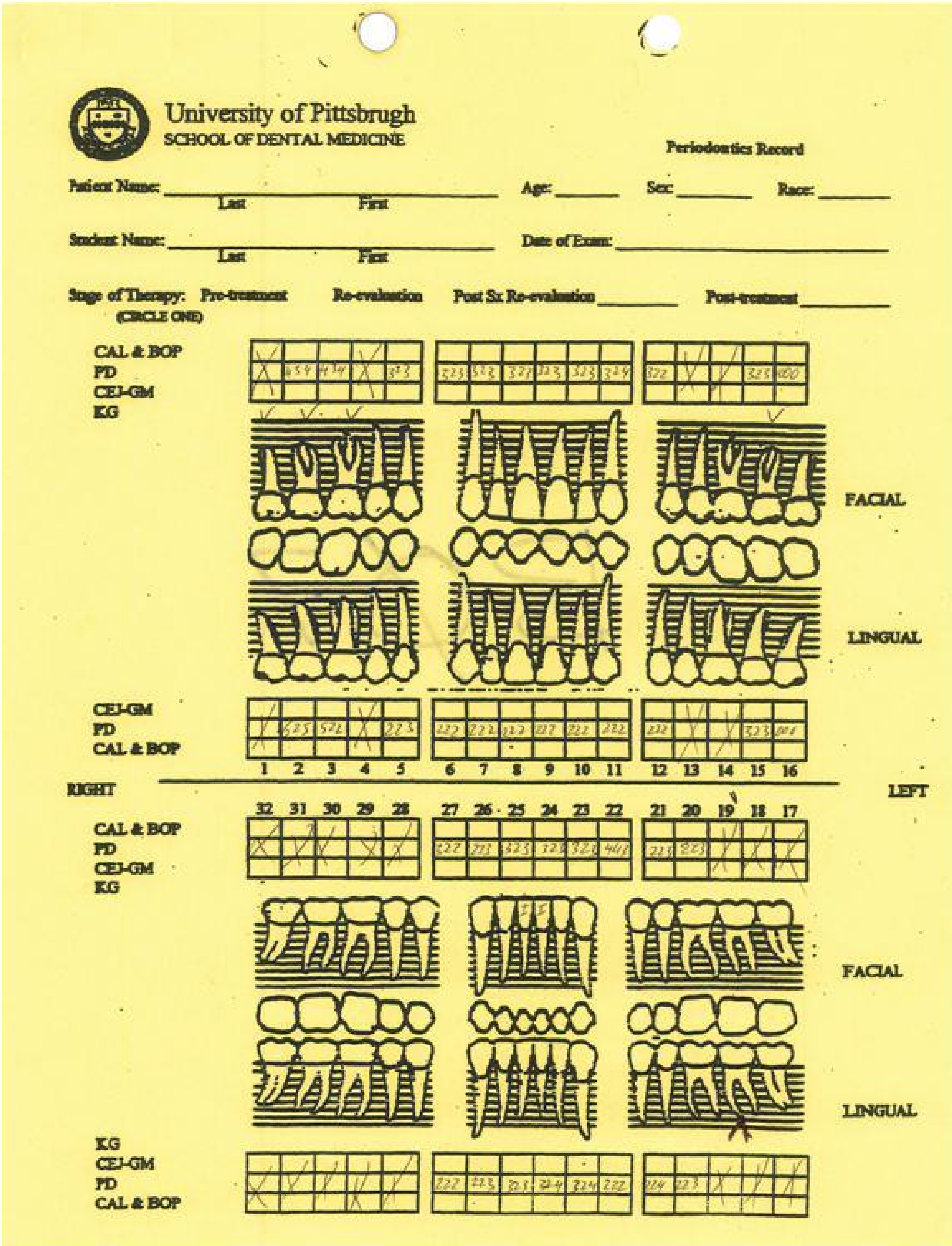
FINDINGS (All areas described in radiolucent/radiopaque terms):

IMPRESSIONS (Differential diagnosis of findings):

Student:____________________ Faculty:____________________ Date:__________

UMC 52196B

Hard Tissue Examination

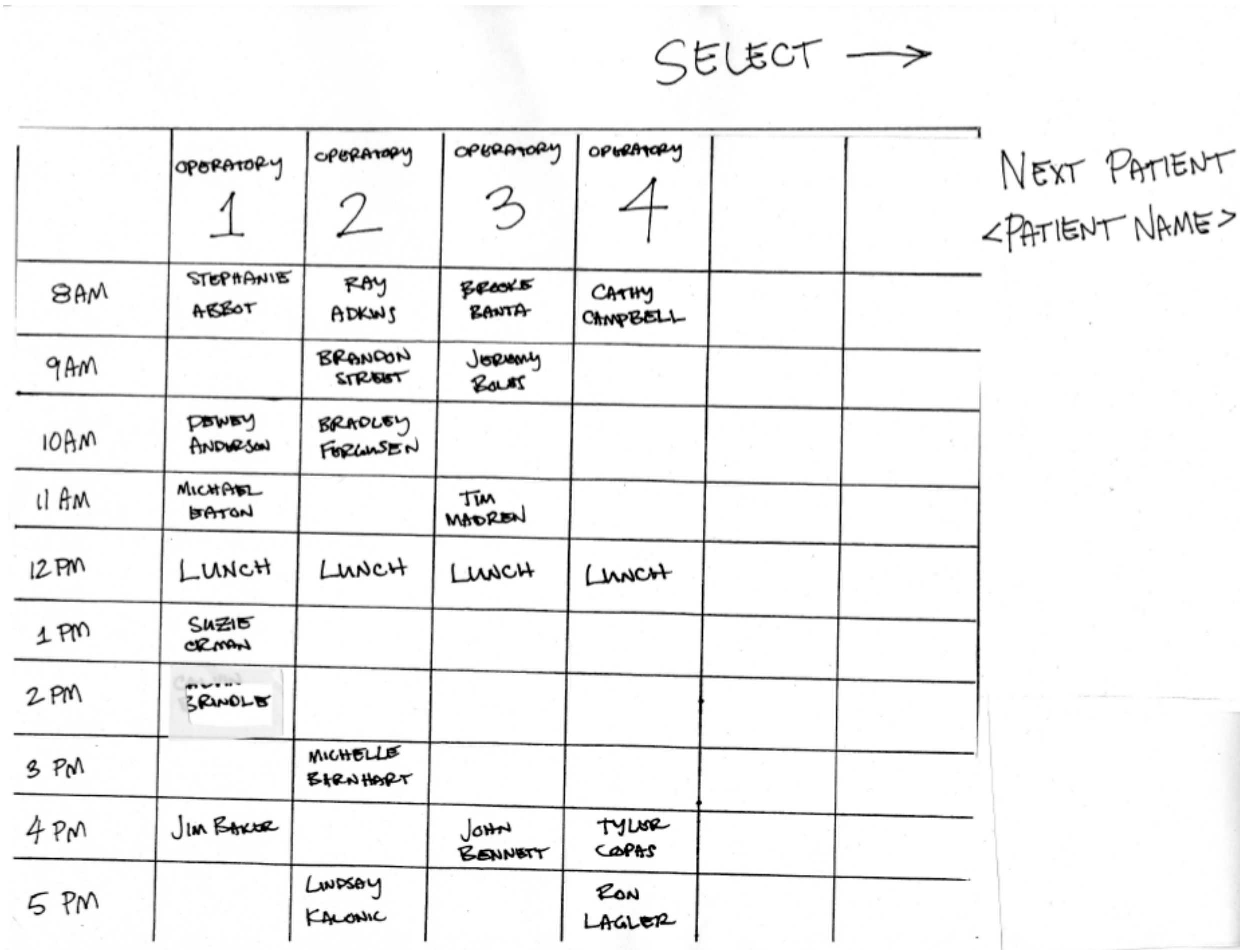


Periodontal Examination

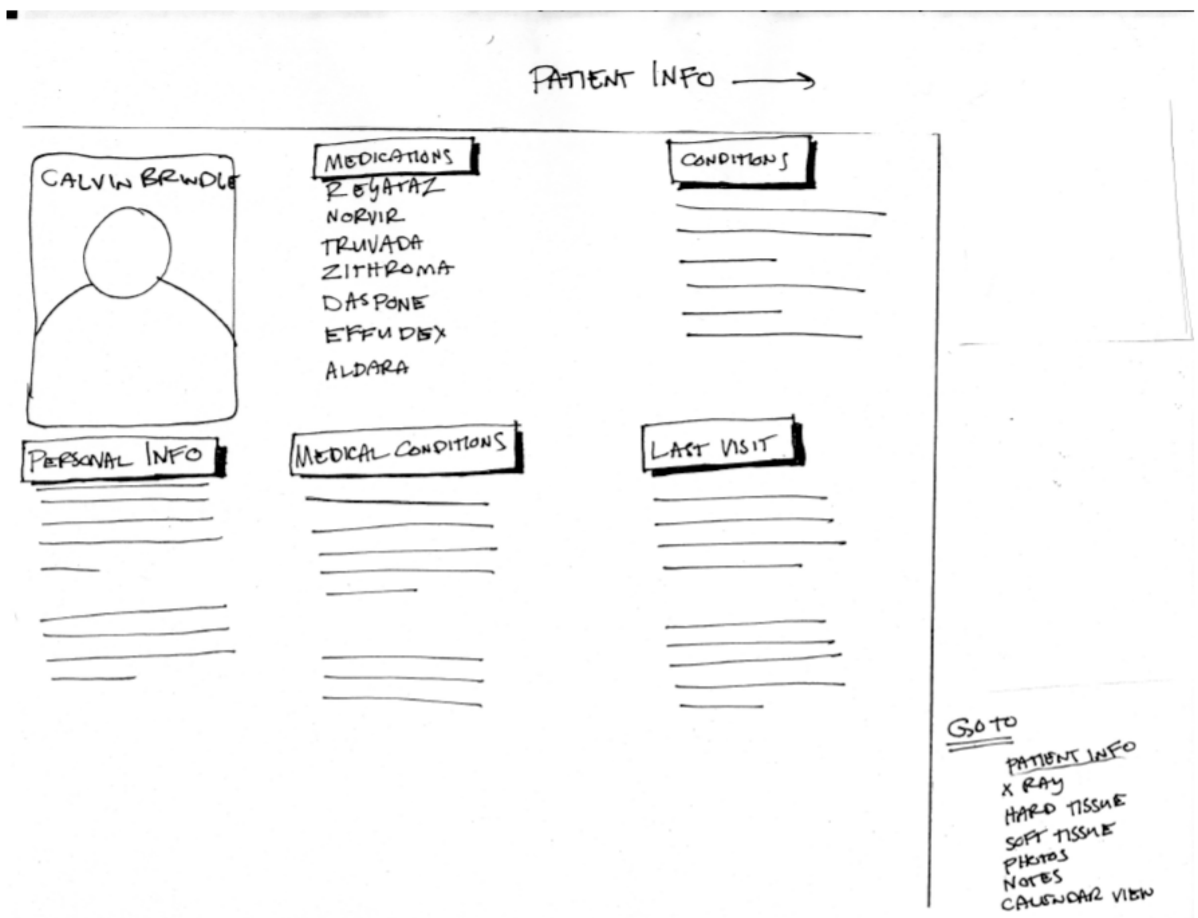
APPENDIX B

SCREENSHOTS FROM THE FOUR ITERATIONS OF PROTOTYPE DEVELOPMENT

B.1 PAPER PROTOTYPE 1

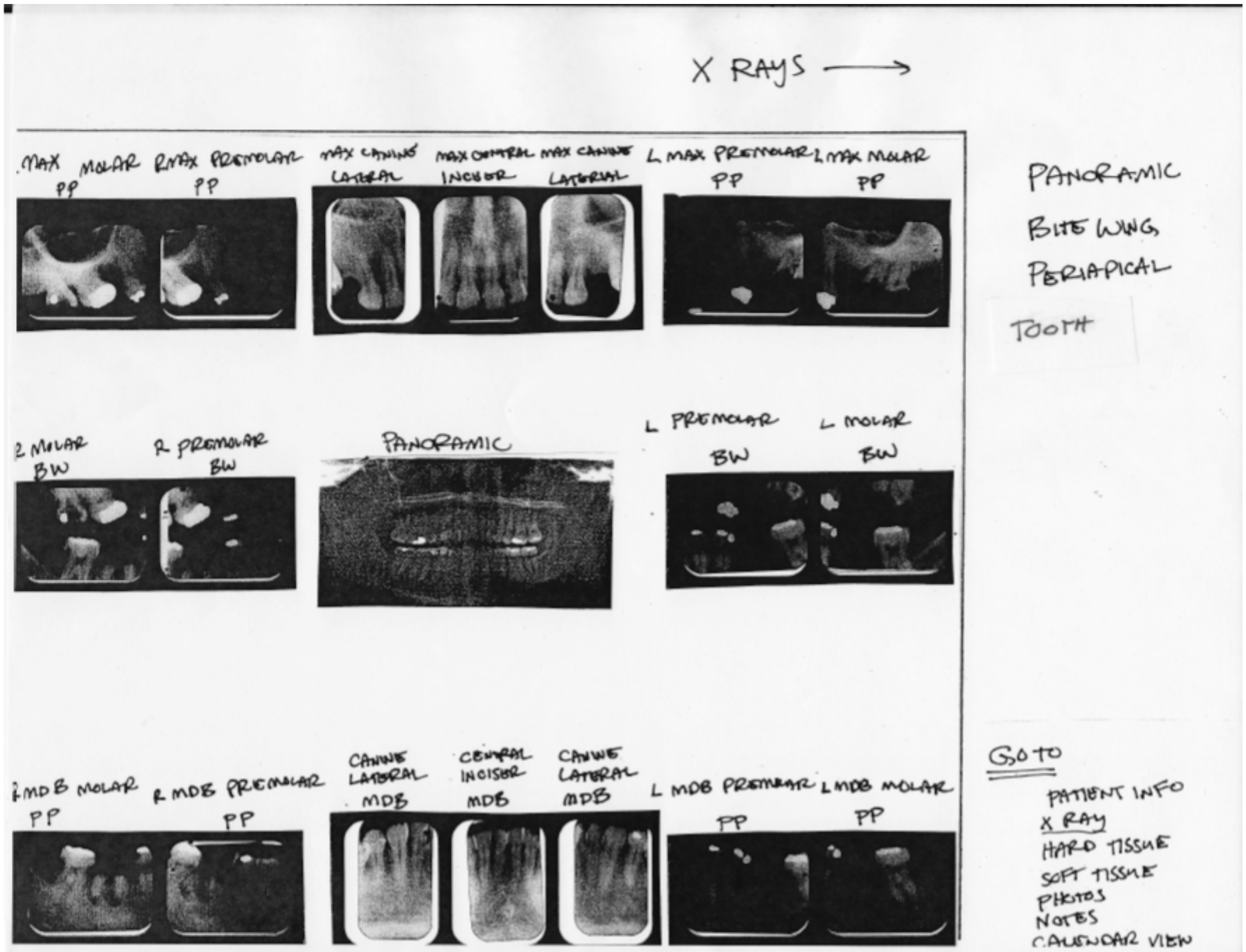


Paper Prototype 1: Voice-based System: Calendar View Showing Patient Appointments
Possible Commands are Listed on the Right Hand Column

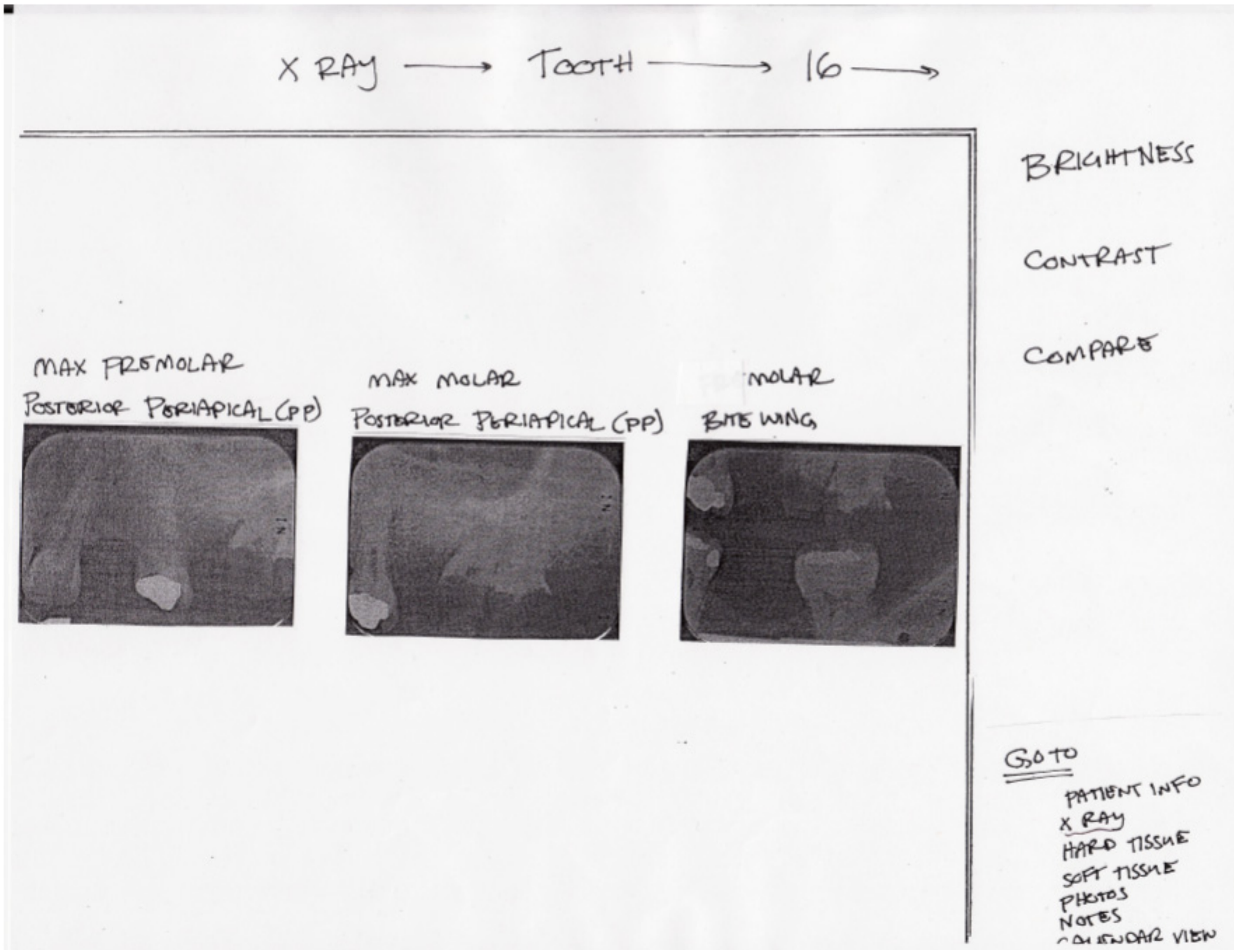


Paper Prototype 1: Voice-based System:

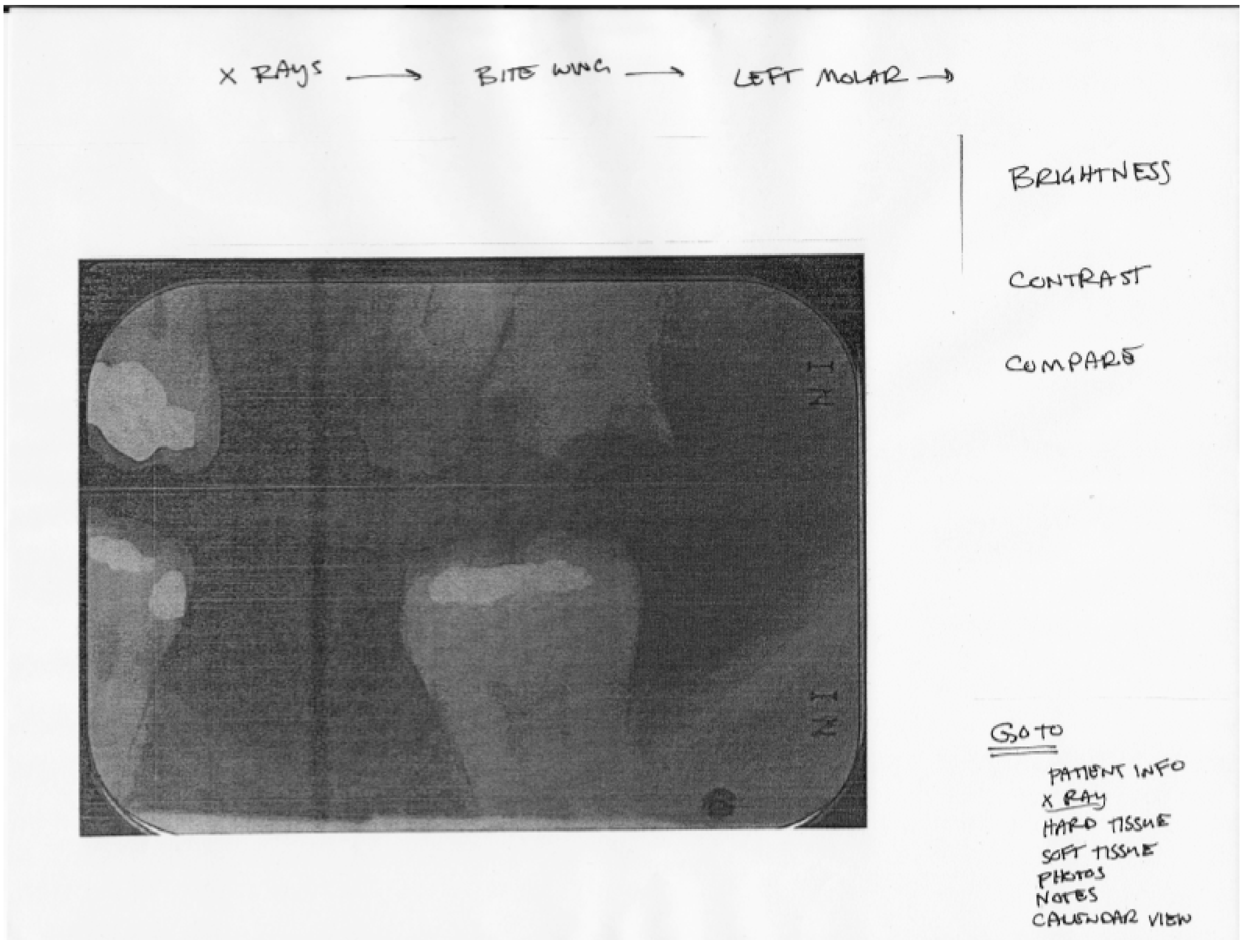
Possible Commands are Listed on the Right Hand Column



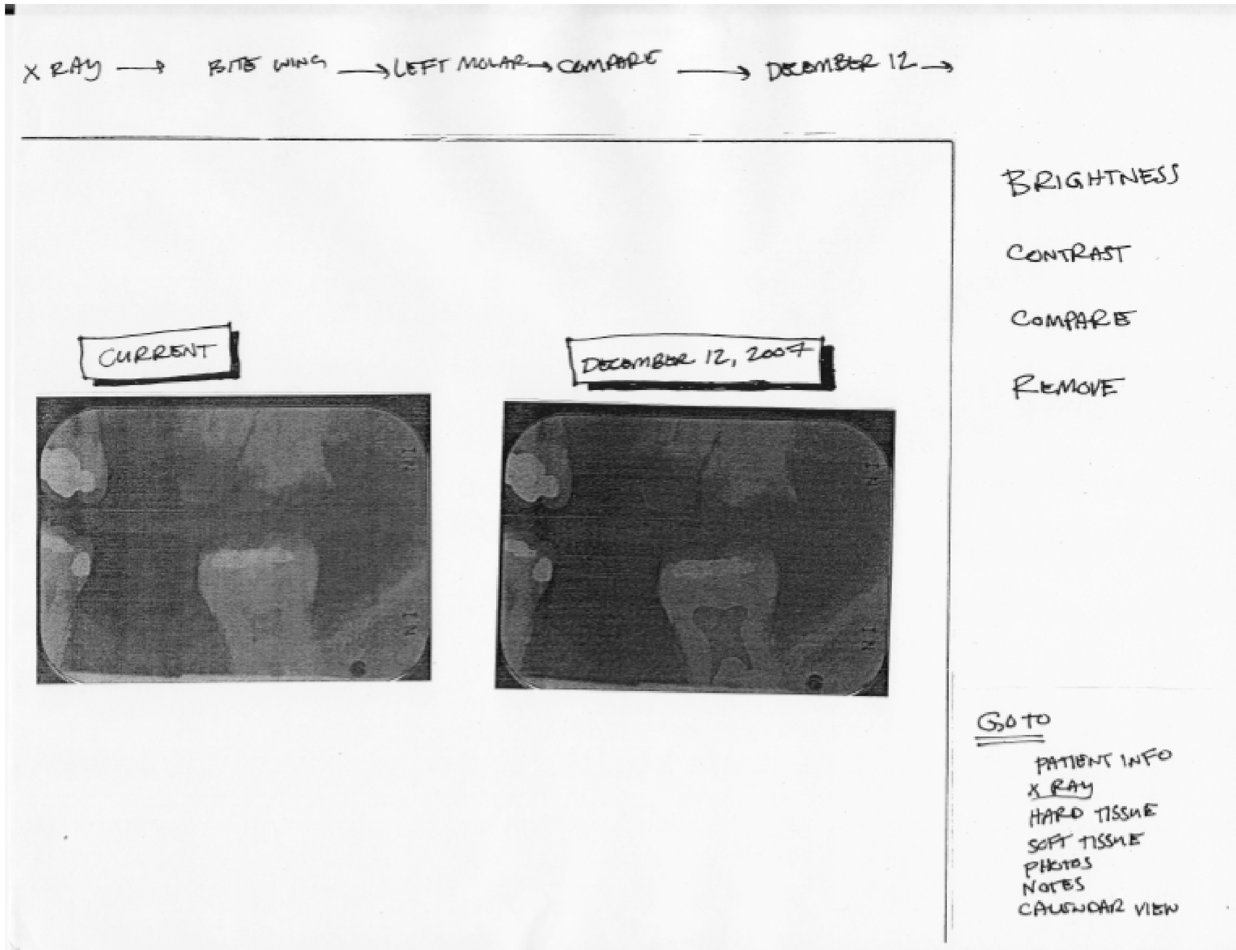
Paper Prototype 1: Radiographs Layout Page



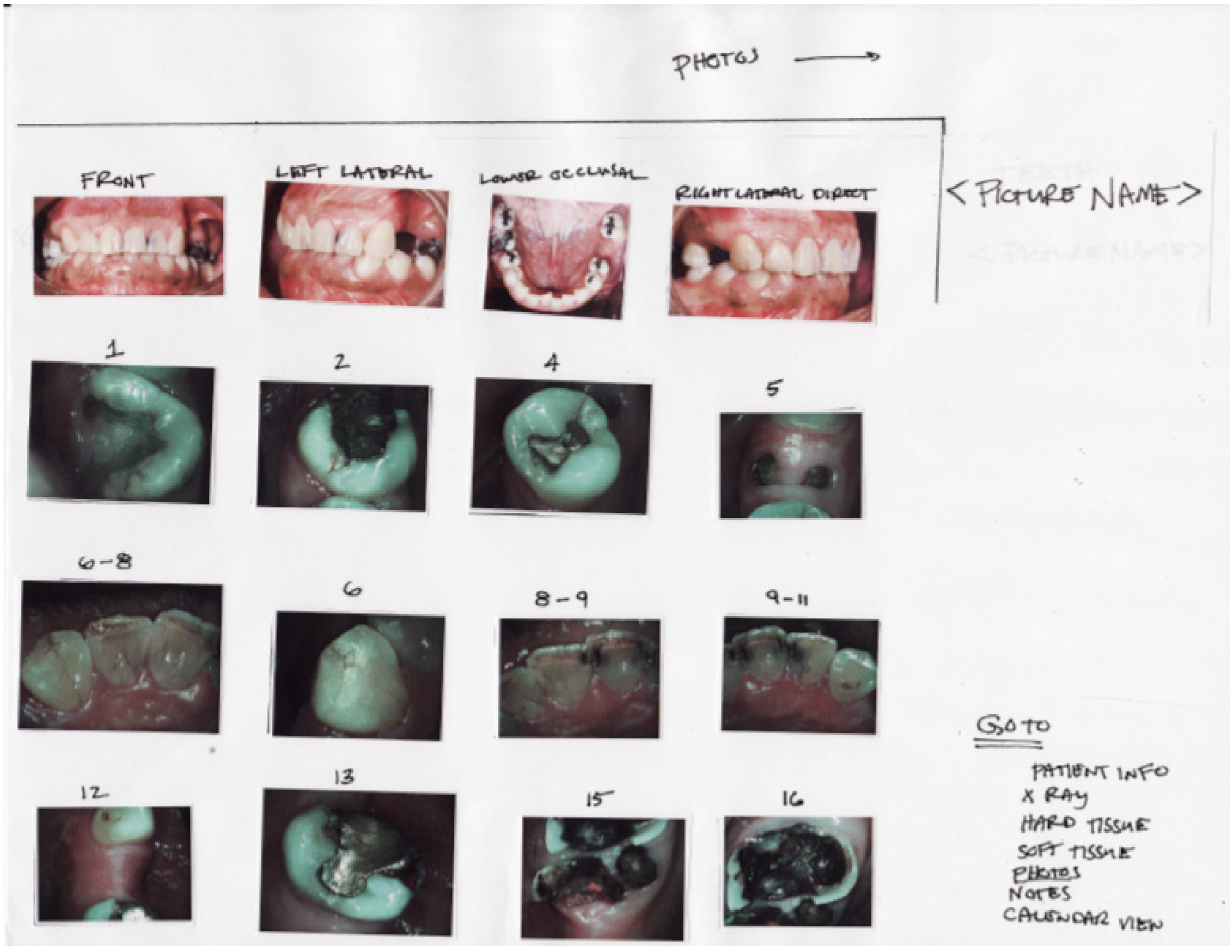
Paper Prototype 1: Screen showing Radiographs for a Specific Tooth (Tooth #16)



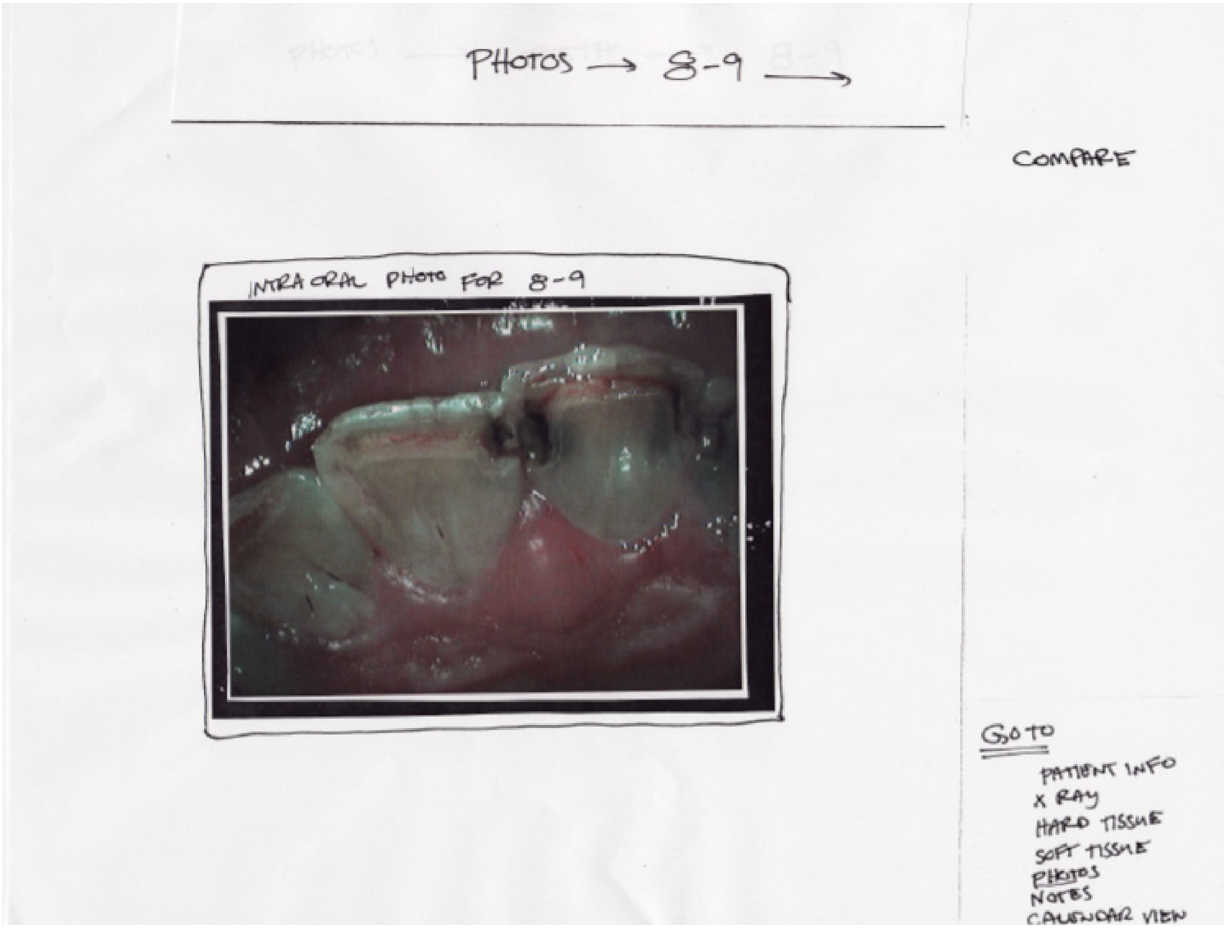
Paper Prototype 1: Screen showing Zooming in on one Radiograph for a Specific Tooth (#16)



Paper Prototype 1: Screen Comparing Radiographs From Different Dates (Tooth #16)



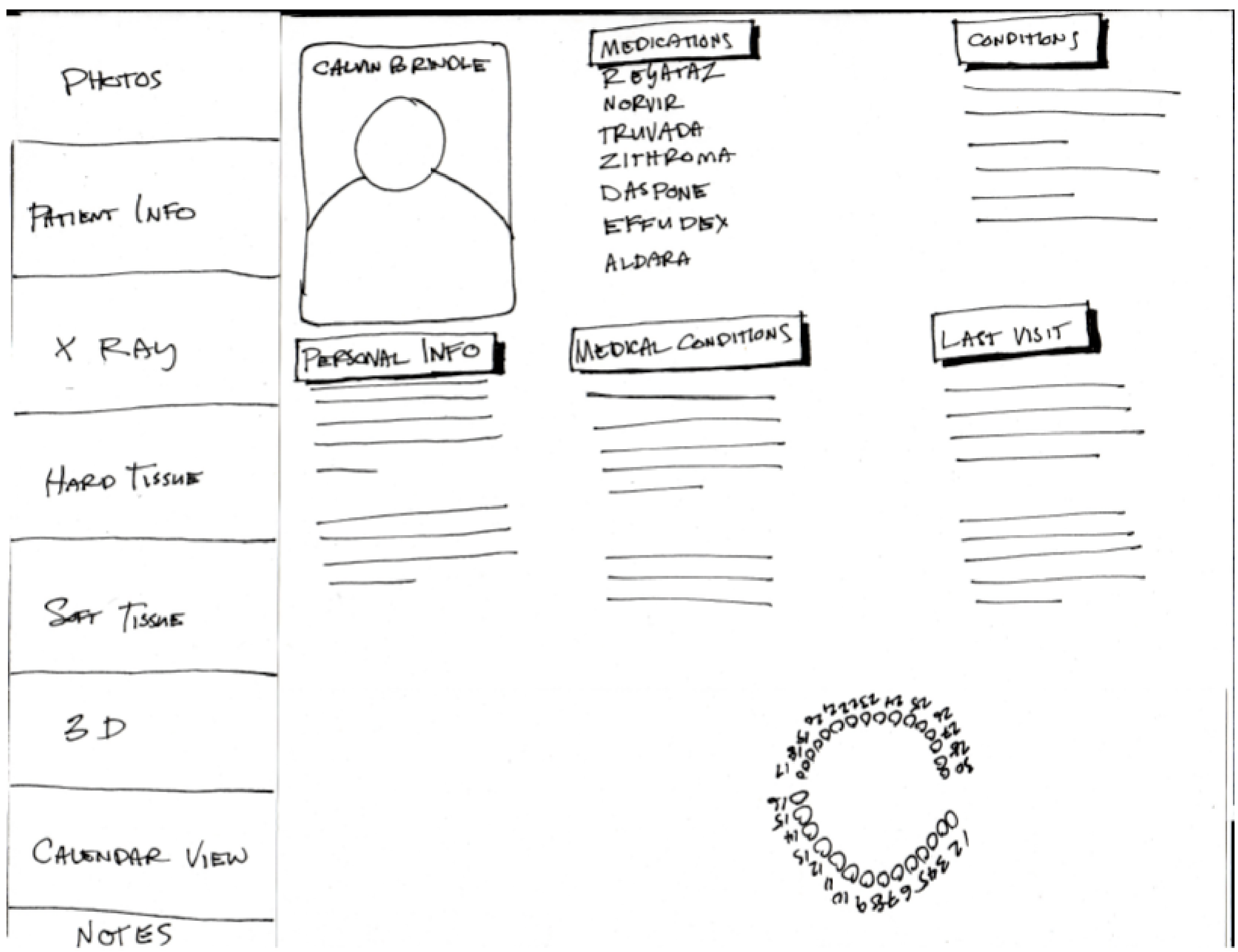
Paper Prototype 1: Photos Layout Page



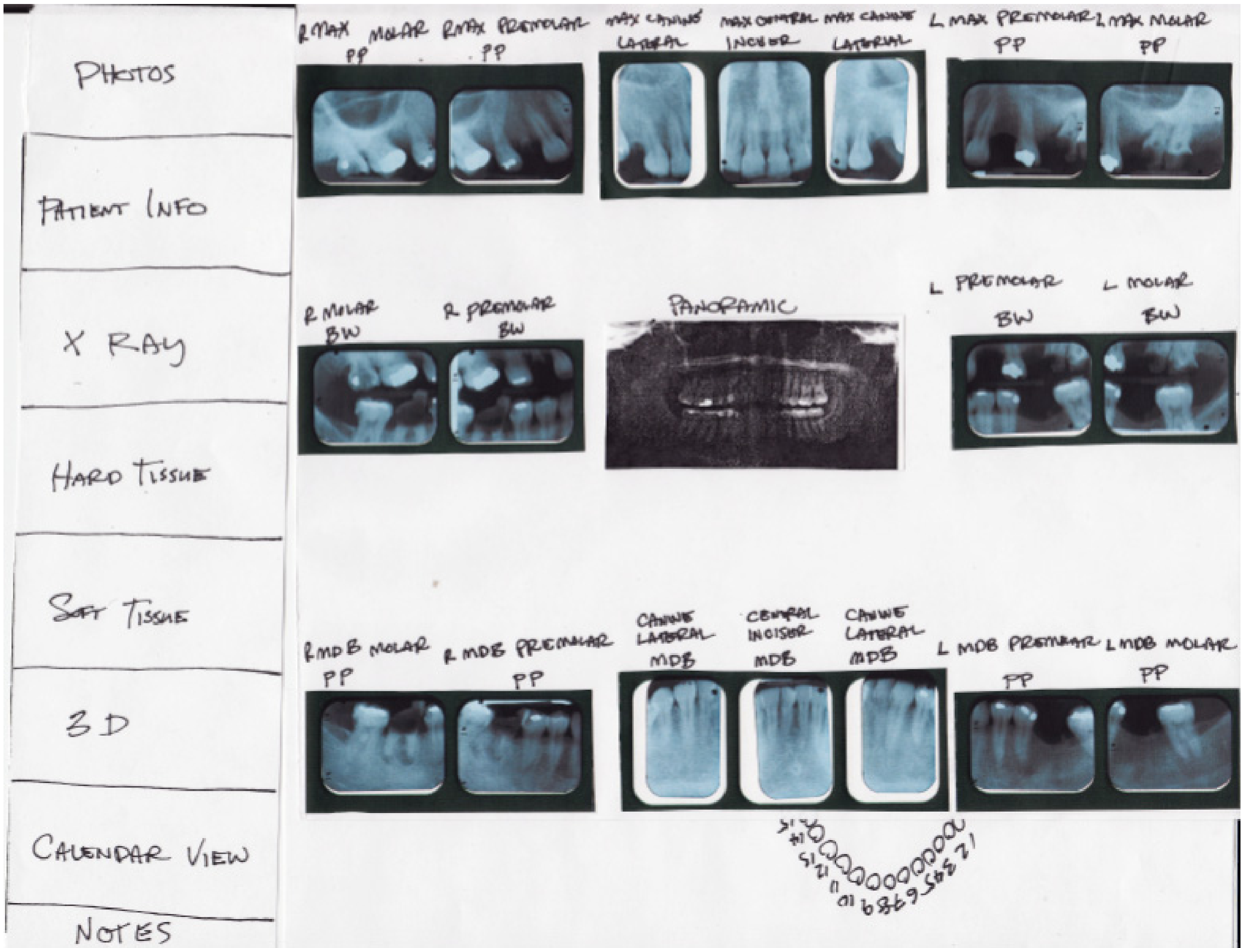
Paper Prototype 1: Zoom-in on one photo for a specific tooth

B.2 ITERATION 1: VOICE BASED SYSTEM 2

All words on the pages act as commands. A context menu pops up next to a word after the command is spoken.

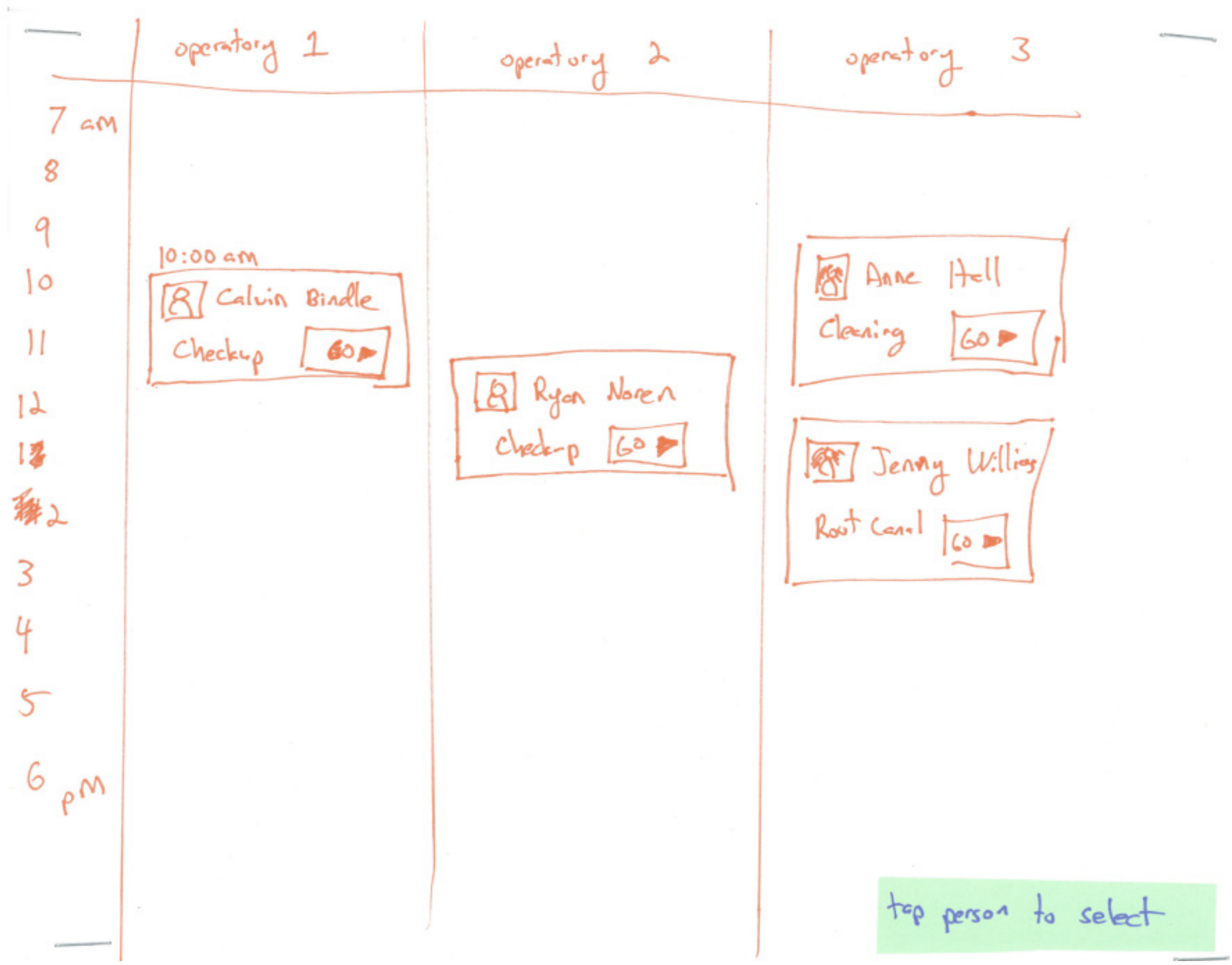


Iteration1: Voice Based System 2: Patient Overview Page

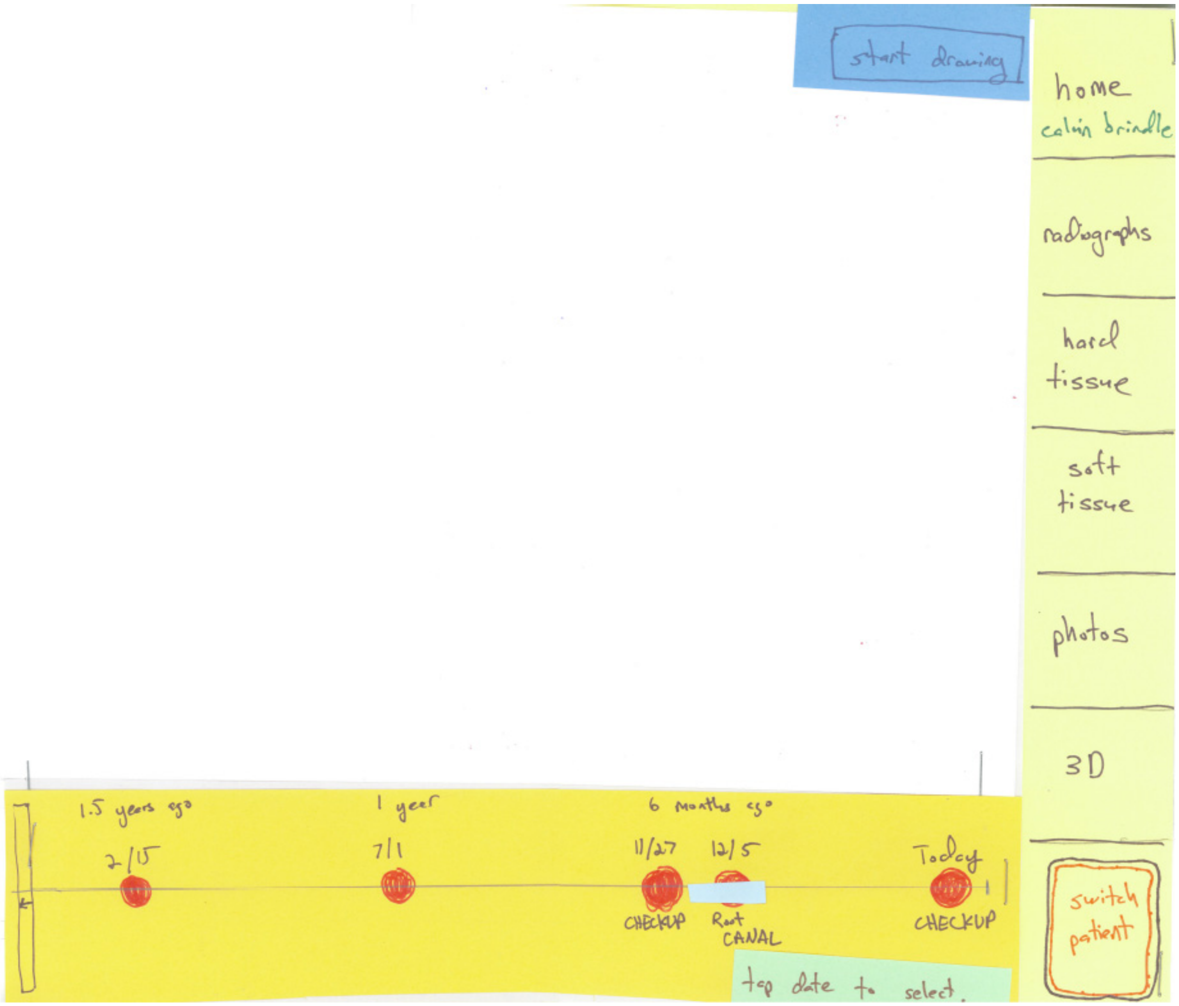


Iteration 1: Voice Based System 2: Radiographs Page Layout

B.3 ITERATION 2: TOUCH BASED SYSTEM

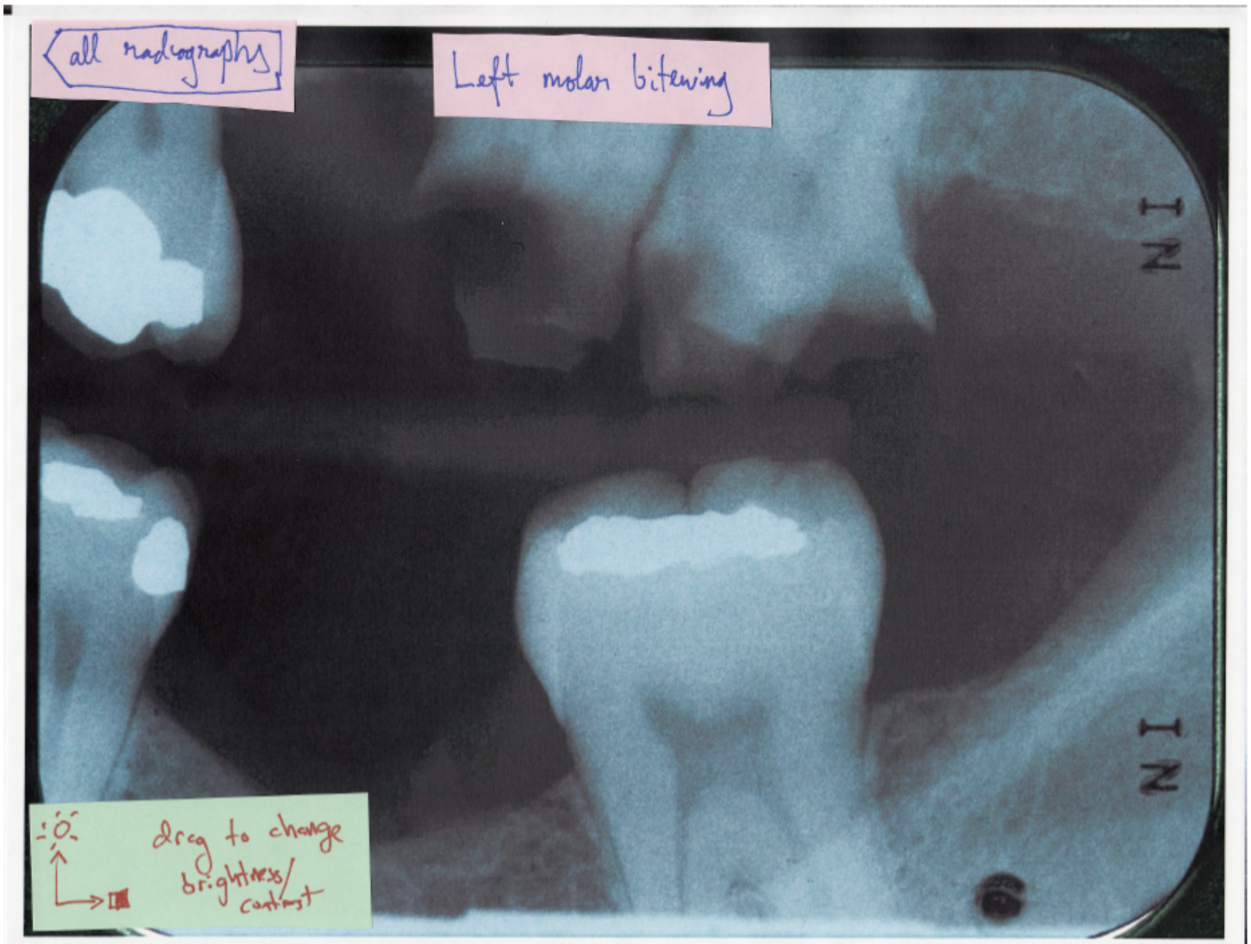


Iteration 2: Touch Based System: Calendar View Showing Patient Appointments



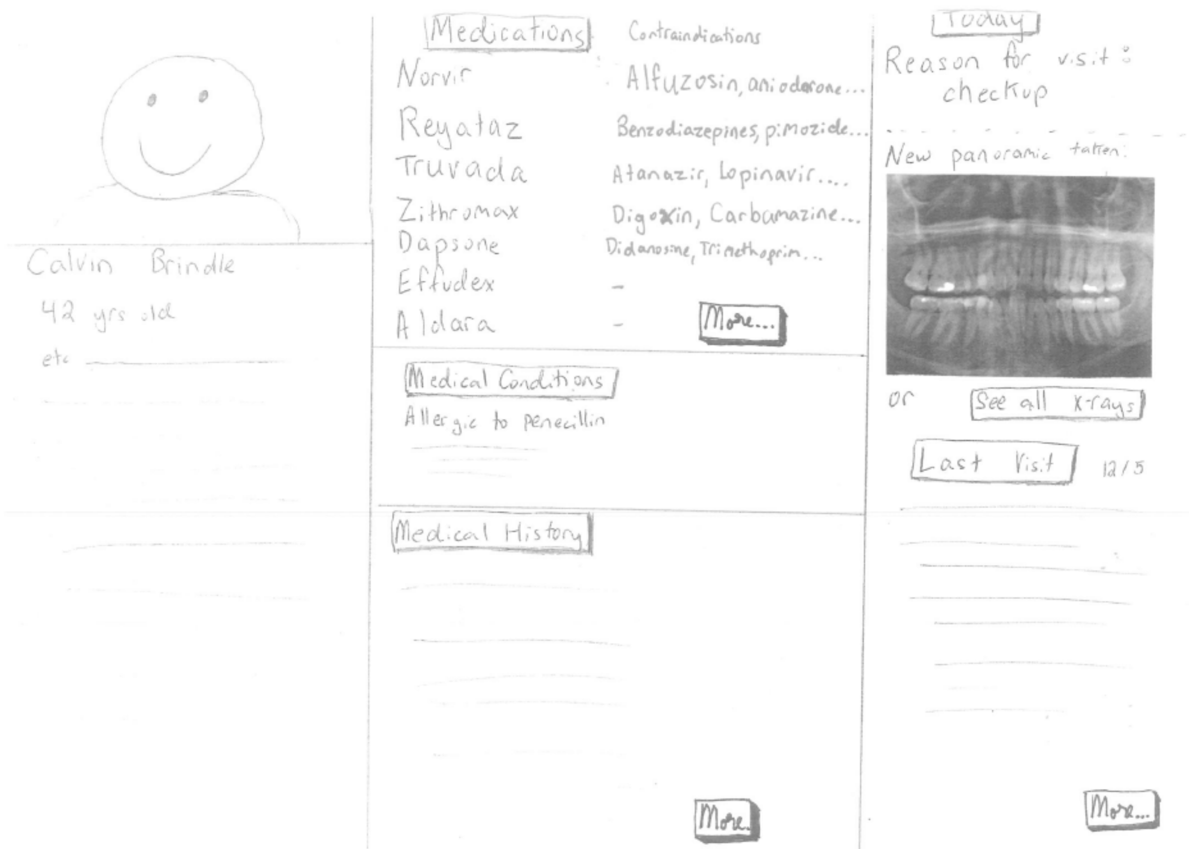
Iteration 2: Touch Based System: Timeline Added as Checkboxes

B.4 ITERATION 3: TOUCH BASED SYSTEM

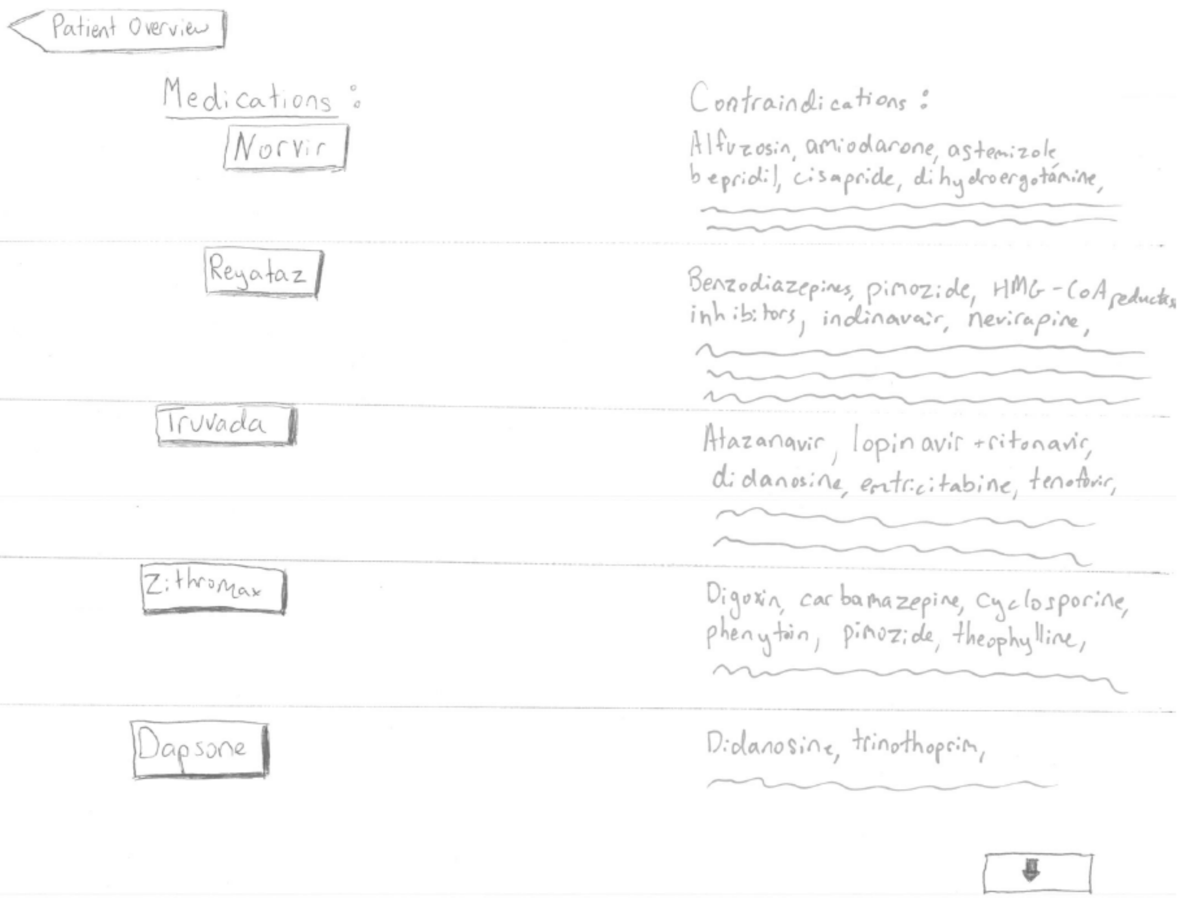


Iteration 3: Touch Based System: Radiographs for One Tooth

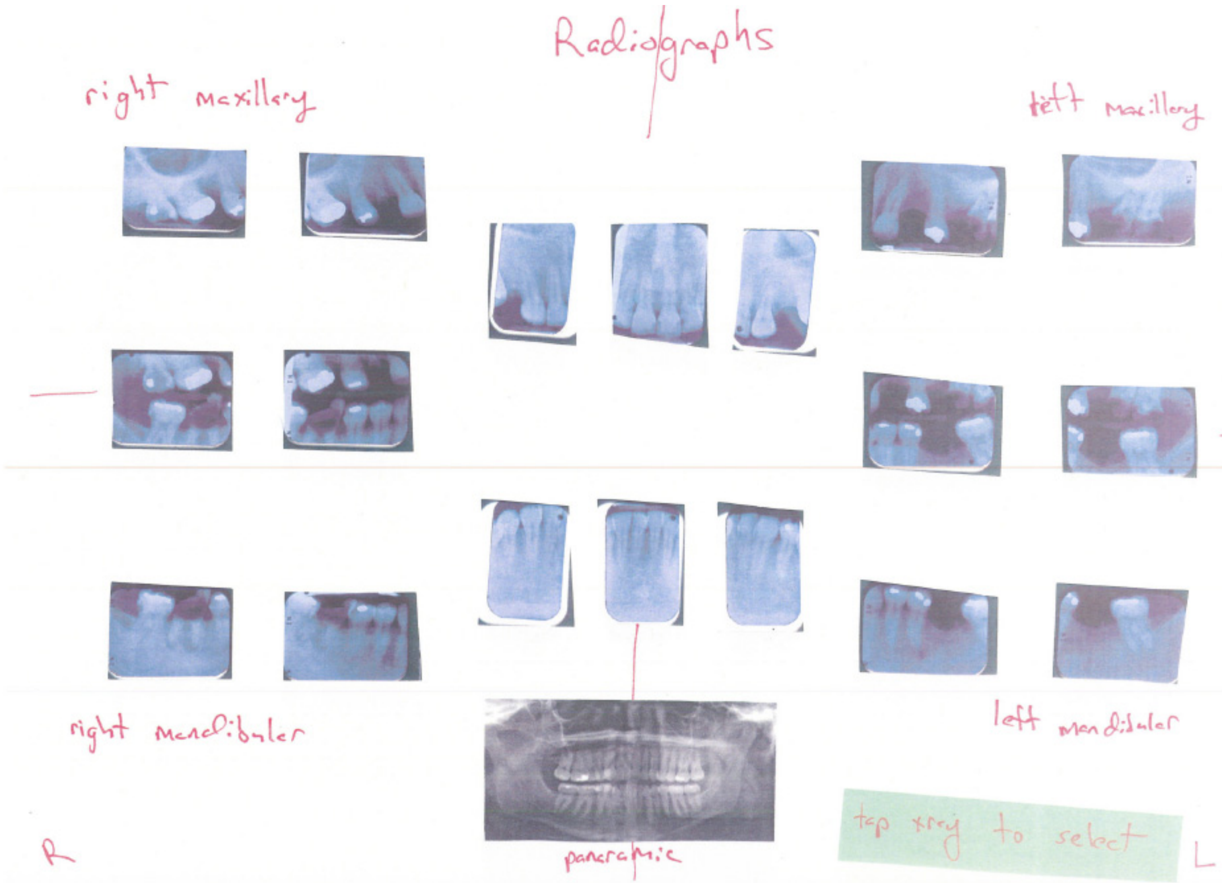
B.5 ITERATION 4: TOUCH BASED SYSTEM



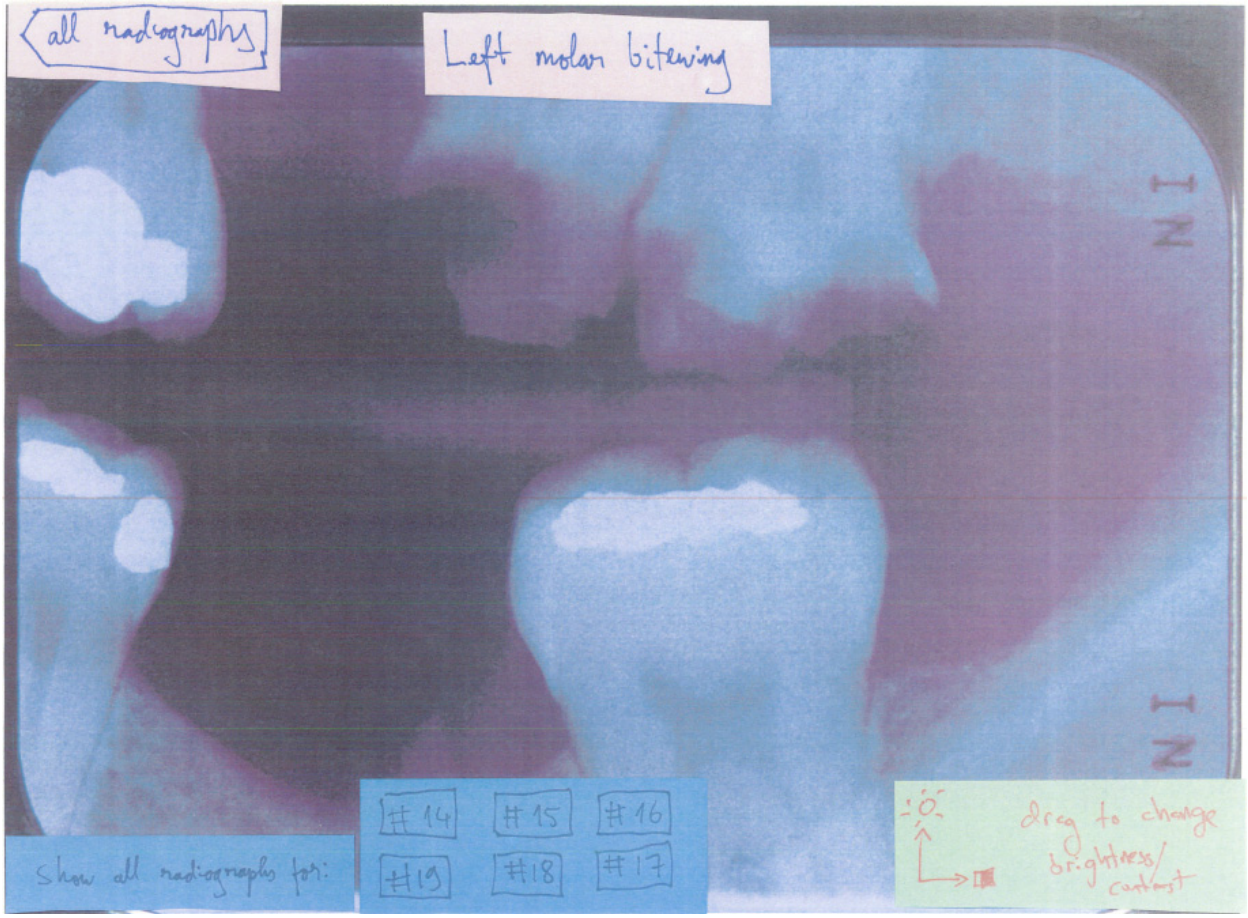
Iteration 4: Touch Based System: Patient Overview Page



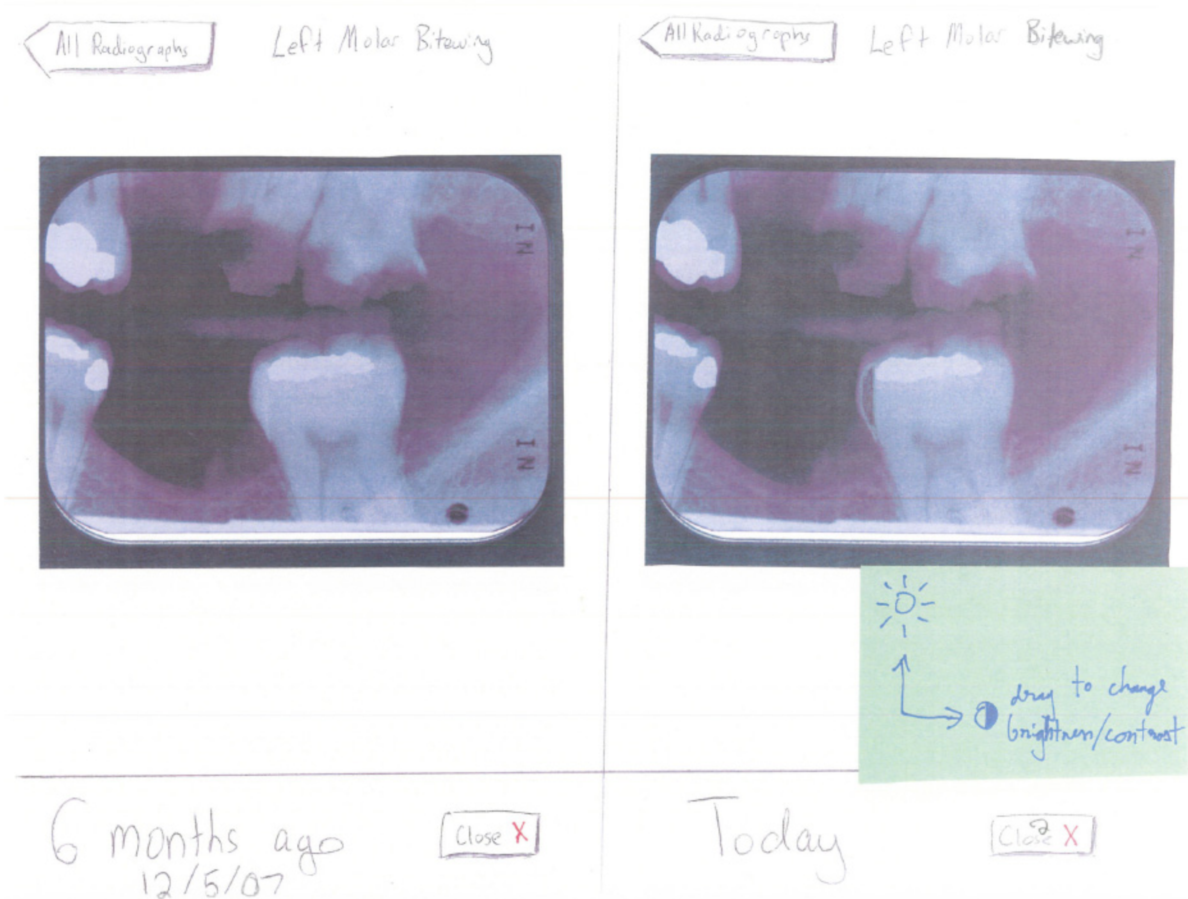
Iteration 4: Touch Based System: Added Medications Page



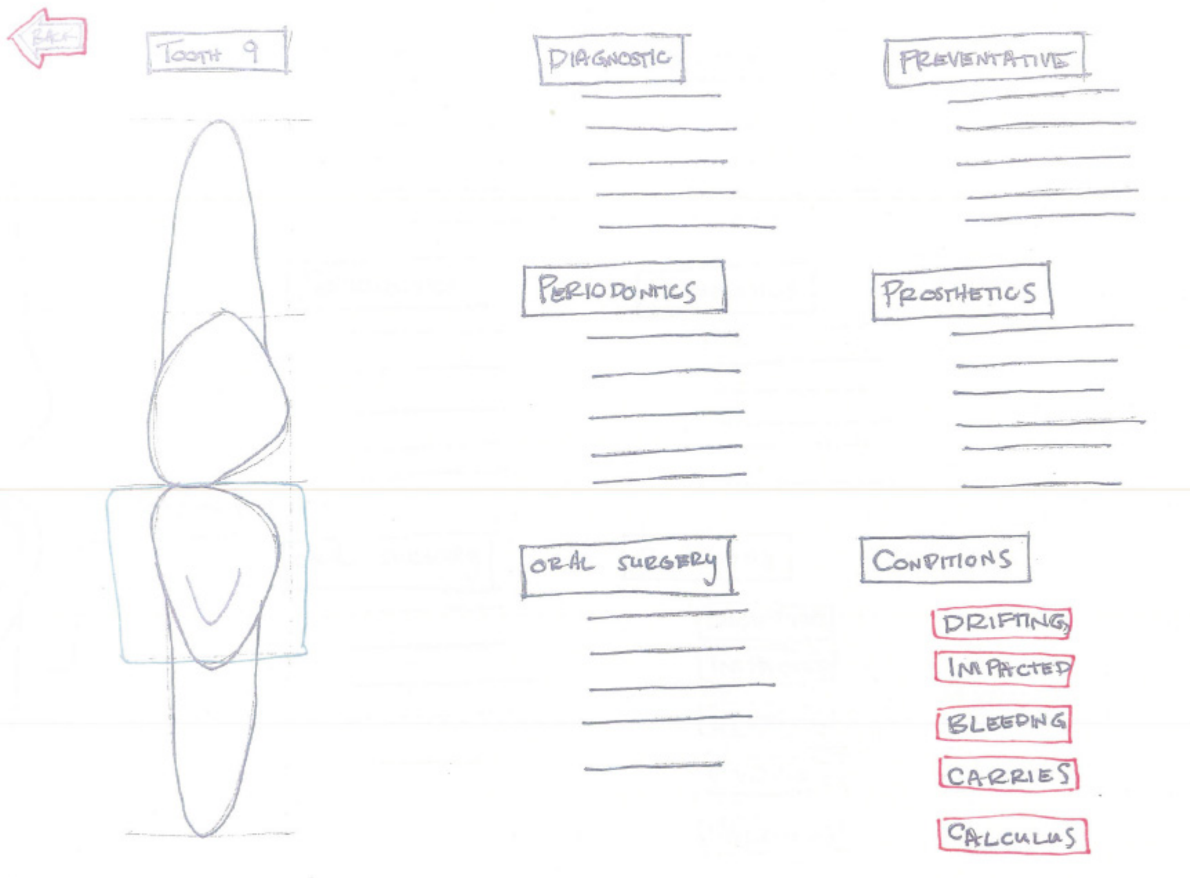
Iteration 4: Touch Based System: Radiographs Layout



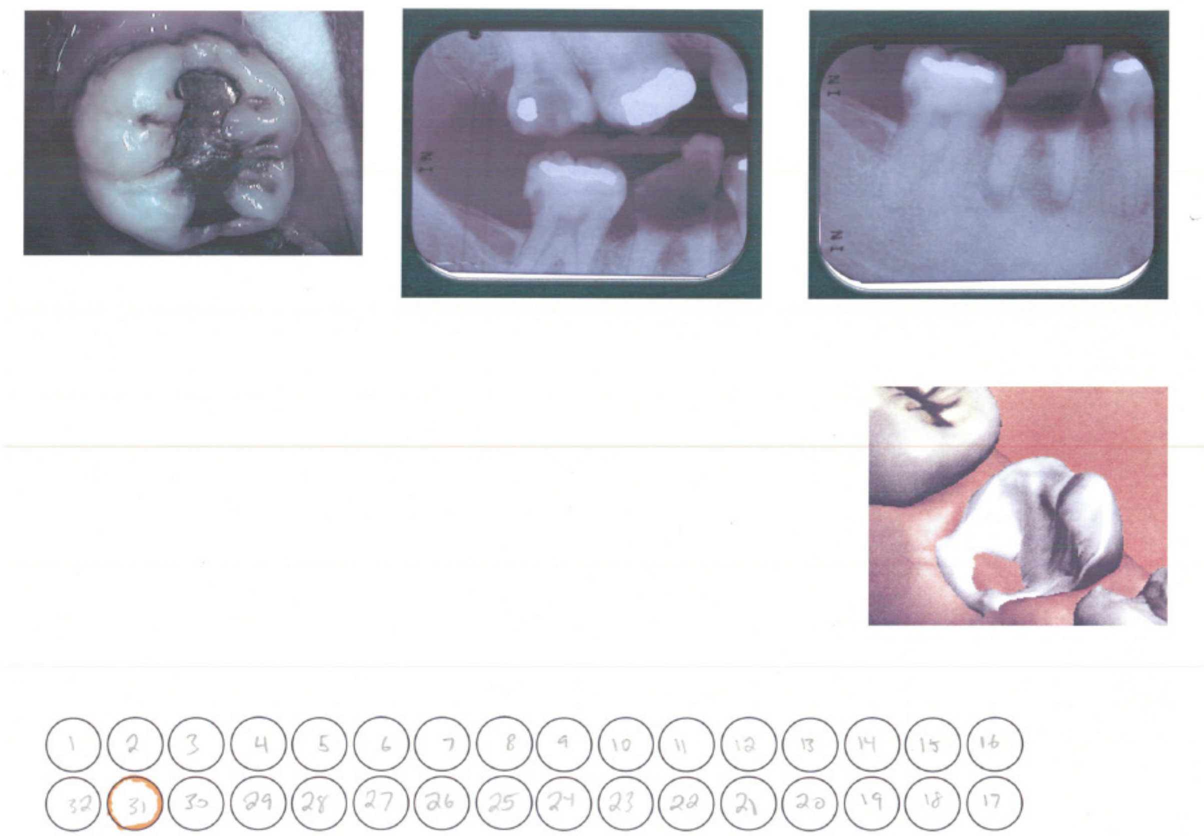
Iteration 4: Touch Based System: Page Showing Radiographs for Specific Teeth



Iteration 4: Touch Based System: Screen Comparing Radiographs From Different Dates



Iteration 4: Touch Based System: Screen Showing the Single Tooth View Page



Iteration 4: Touch Based System: Screen Showing the Single Tooth View Page Displaying Radiographs, Intraoral Photos and the Corresponding Three Dimensional Model of the Tooth

B.6 CHANGES MADE DURING ITERATIVE DESIGN PROCESS

The following changes were made during the three iterations with the paper prototypes and the high-fidelity prototype.

Iteration 1 → Iteration 2

1. The voice based system was downsized and integrated with the touch screen system.
2. All double tapping was removed, because the users could not understand the difference between single and double taps.
3. The timeline, which was previously activated by double-tapping, was implemented using checkboxes.
4. Voice/touch input was added for the hard tissue and the periodontal chart.
5. Medical contraindications were added and the medications page was expanded.
6. The screen 'show all the radiographs' was added to provide a quick view of all the radiographs.

Iteration 2 → Iteration 3

1. The timeline was simplified to "compare today's photo/ radiographs with previous photos/radiographs". It is now a way to obtain patient overview information from a previous visit.
2. Complex comparisons were eliminated; only simple ones are now available.
3. Annotations are only done using a stylus. They are now offered in two forms: one for dentists and the other for patient education.
4. "Show all radiographs for" become the global shortcut to the view by tooth screen.
5. Left and right arrows were added to quickly switch between X-rays and photos.
6. The 3D explorer interface was added.
7. The notes entry system and the voice/touch input were removed (beyond the project's scope).

8. Today's date was added on every page because users want precise information on when the X-rays and photos were taken.

Iteration 3 → Iteration 4

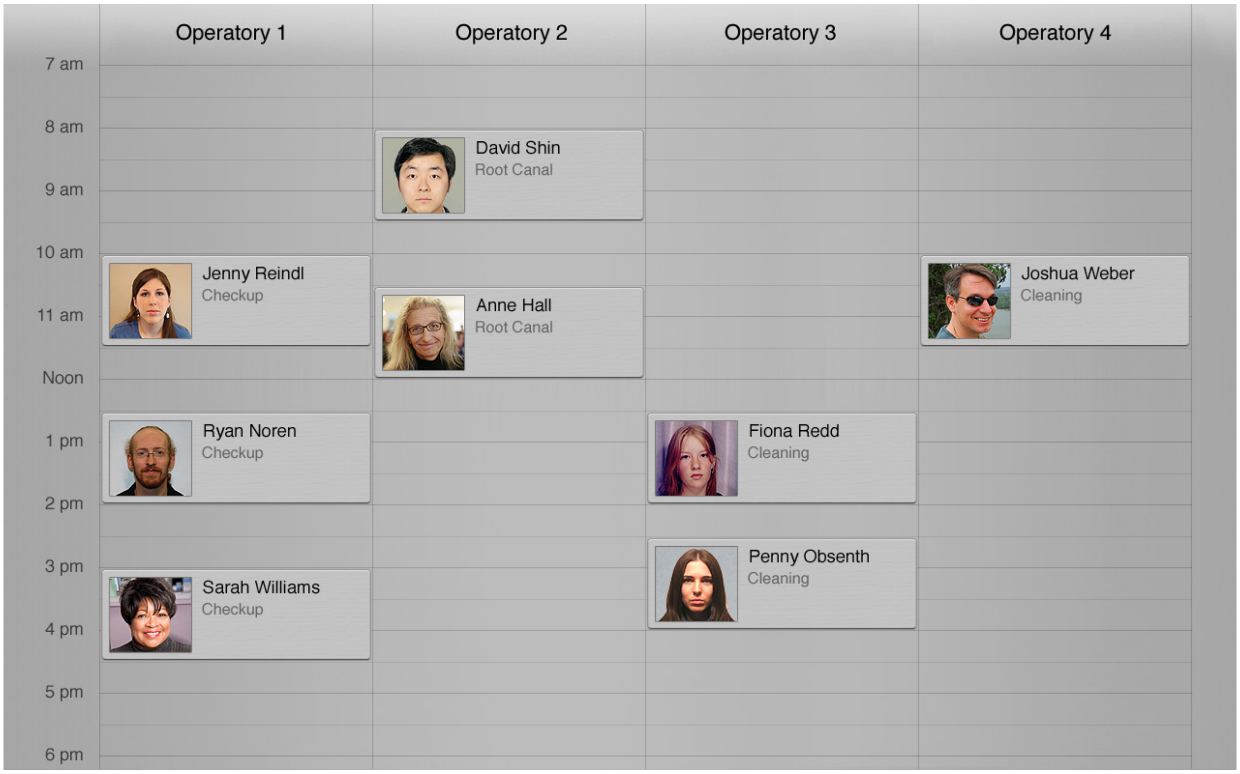
Very few changes were made in this third prototype iteration.

1. Several users wanted more medication information. Therefore, a medication information page was added with more details on the patient's medications.
2. Based on the users' feedback to make it more prominent, the patient's allergies that were shown in the lower left corner were moved to the center of the screen.
3. The ability to click on a tooth in the hard tissue and the periodontal chart was added in order to redirect the user to the related view by tooth page. Prior to implementing this feature, users were already clicking on the teeth to access the view by tooth page.
4. Small text changes were made. For instance, 'notes' was changed to 'progress notes' and the 'calendar' view was changed to 'today's schedule'.

APPENDIX C

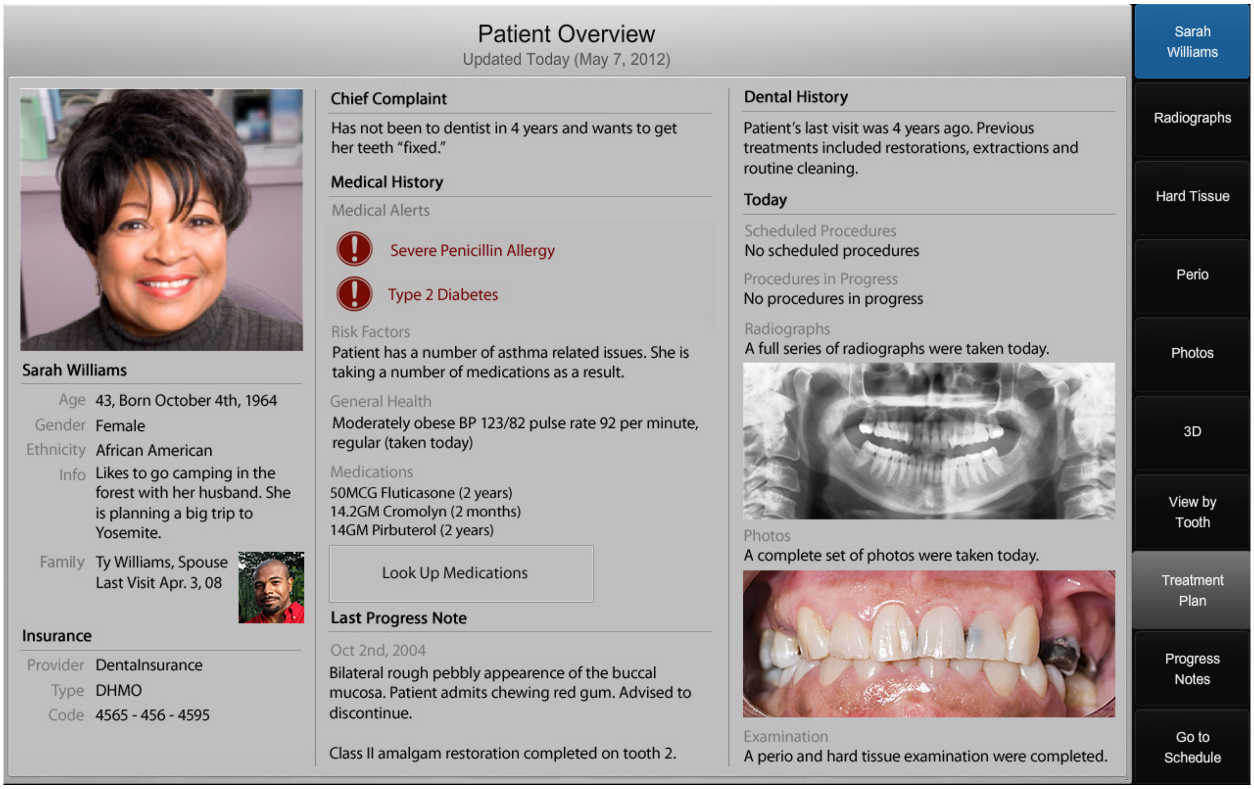
SCREENSHOTS OF THE DMD PROTOTYPE

Switch patient screen



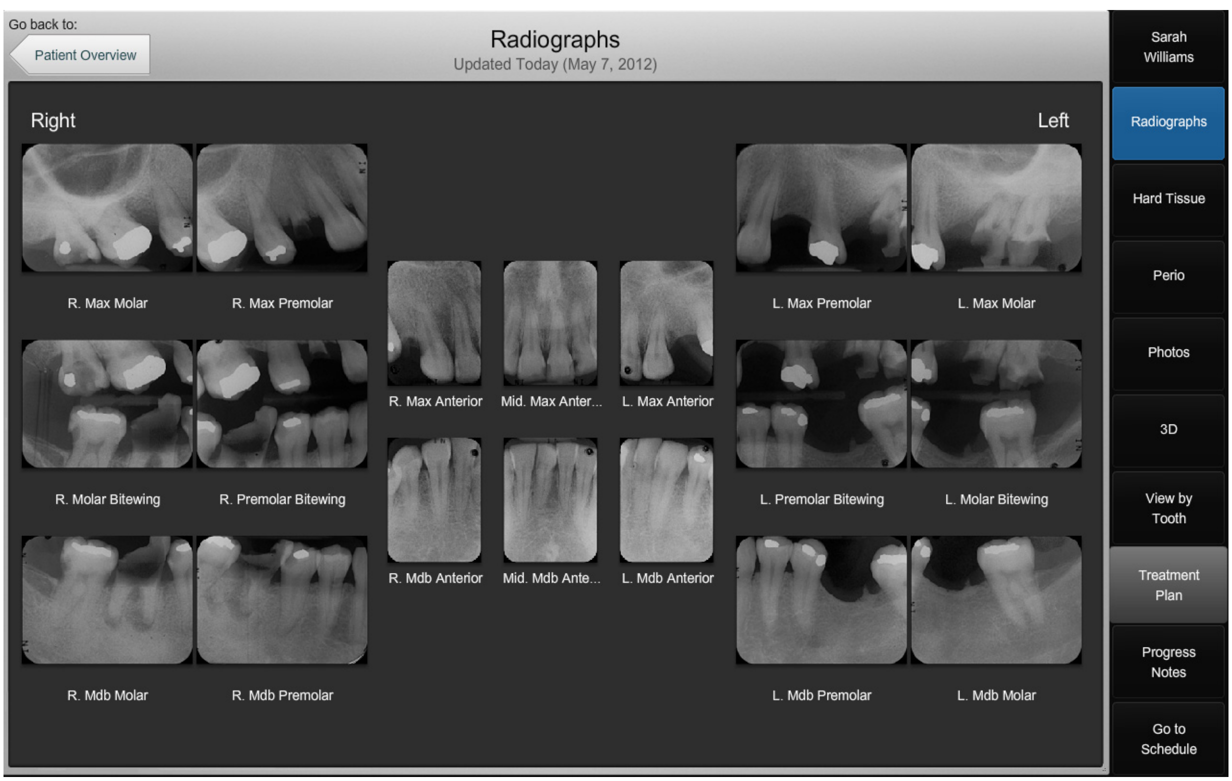
Goal	Let dentist easily switch between patients; identify who is in which operatory at what time, and what each patient is there for.
Design	This is a schedule, which lets dentists switch between patients. Patients are organized by operatory. Patients' names and faces are shown, along with their reason for visit and time of appointment.
Rationale	Many current dental software systems have similar screens. We found similar analogue schedules at dentists' offices during our contextual inquiries. While administration is out of our scope, the schedule is part of the dentist's workflow. Several users noted that they liked having pictures as a reminder of who the patient is.

Patient Overview Page



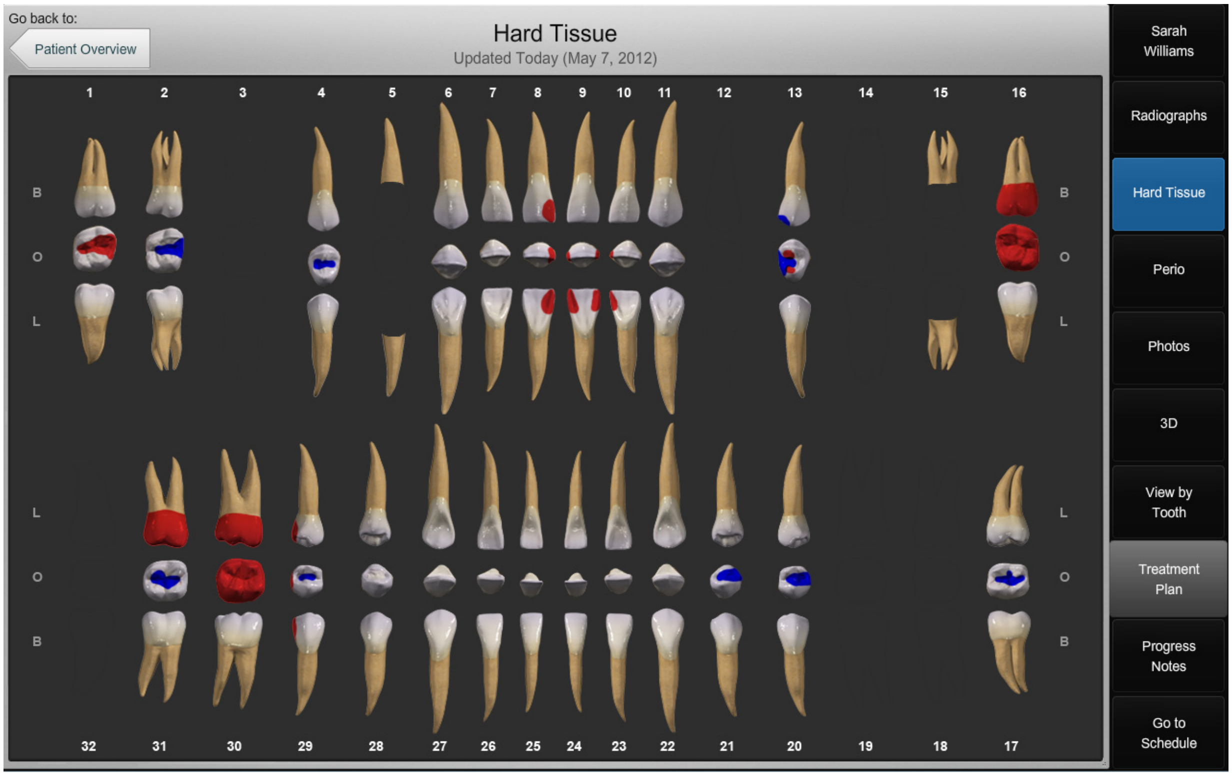
Goal	Give dentists one location for all of the background information they might need before beginning to plan a treatment
Design	This page presents basic information about a patient- their name, vitals, picture, basic demographics, reason for visit, insurance, allergies, medications, chief complaint, planned procedures, and medical and dental history. Further details about medications can be found by pressing the 'Look up medications' button. A small image of all radiographs taken that day is shown; if a panoramic is available, that will be shown instead. An extraoral photo is also shown.
Rationale	The cognitive task analysis data (CTA; Appendix E) inspired us to create a patient overview page, which is the first thing a dentist sees after choosing a patient. While there were many differences in how dentists accessed data in the CTAs, most looked at medical and dental history first. Users responded very positively about this page. Many users tried to click on parts of this page, such as the insurance information or medical alerts, to get more information. One possible future direction for this page may be to include a way to access more information for each field. In our case, this actually shows all of the data we had, but for other patients, more information might be available.

Photos and Radiographs Layout Page



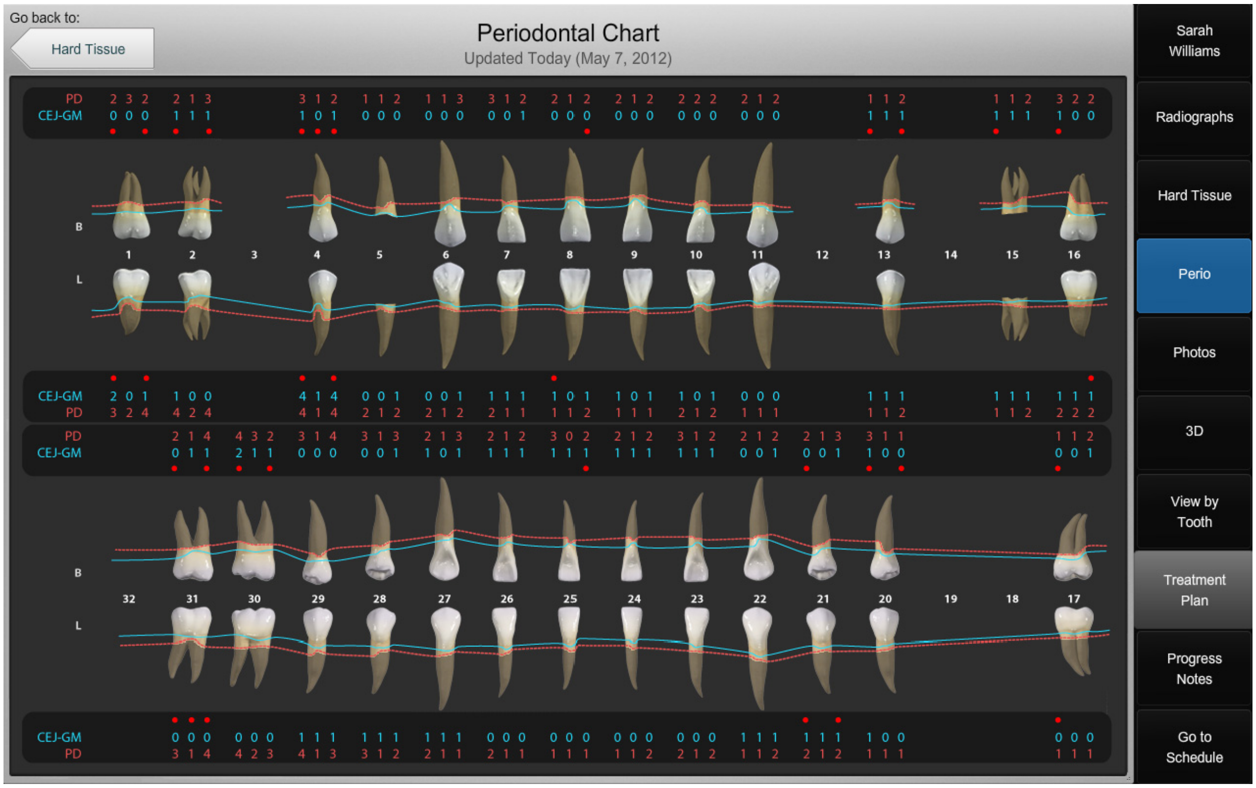
Goal	Give users an understandable overview of the radiographs or photos
Design	We used the standard dental radiograph layout on the main radiograph screen. Users can choose a radiograph by simply pressing on the one they choose. The photo page is laid out with several extra-oral photos in the center, and intra-oral photos around the edges. Each thumbnail can be clicked to show a larger version of the image.
Rationale	Choosing the layout for radiographs was fairly simple, since there's a known standard. However, there is one main difference between dentists using this layout: some have the right and left sides swapped from the way we show it. We use the radiographic standard. Perhaps some preference could be added to our program to allow users to swap the sides. The current layout was created to mimic the upper and lower arches of the teeth.

Hard Tissue Chart



Goal	Give dentists an overall view of teeth conditions, pathologies, and previous treatments
Design	Clicking on a tooth takes the user to the relevant 'View by Tooth' page.
Rationale	No changes were made except the tooth shapes were made more realistic and the user are able to jump to the relevant 'view by tooth' page by clicking on a tooth.

Periodontal Chart

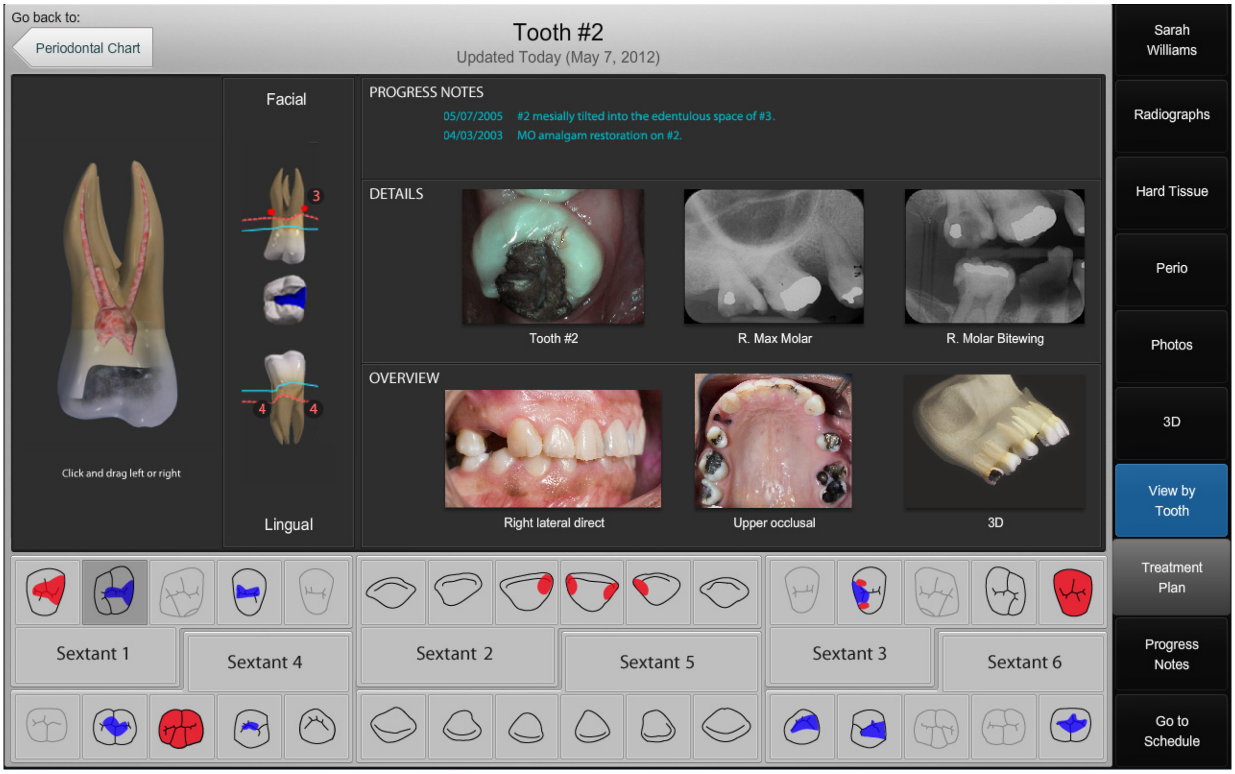


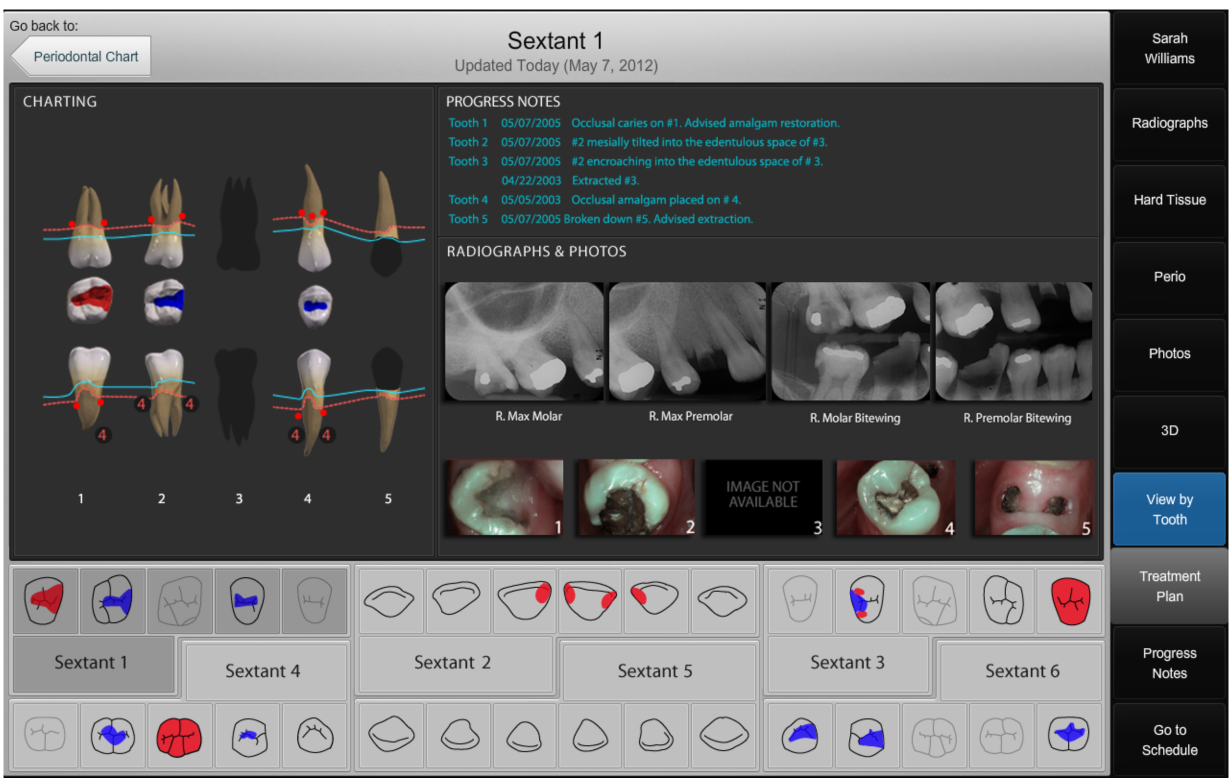
Goal Show dentists the periodontal measurement for the current patient

Design Measurements are shown for the pocket depth (PD) and the cemento-enamel junction (CEJ)/gingival margin (GM). A line representing both the pocket depth and the calculated attachment loss (CAL) is shown on each tooth.

Rationale During cognitive task analysis study and usability testing clinical attachment loss were considered the most important findings to determine the periodontal status of the patient.

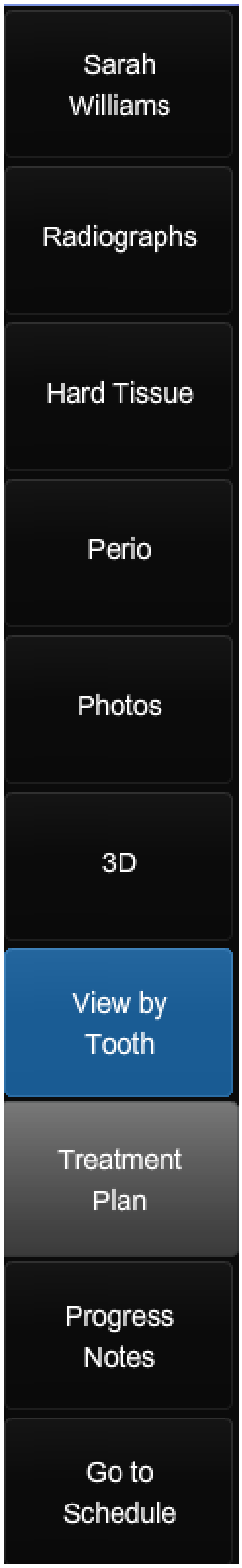
View by Tooth Page (Single Tooth View)





Goal	Give dentists one location to view relevant information about a single tooth or section of the mouth.
Design	Photos, 3D images, radiographs, soft and hard tissue chart data, and relevant notes about a single tooth are presented on one page. Any of these can be expanded by clicking on the image. Switching between teeth is simple, using the tooth selector at the bottom. Each tooth in the tooth selector contains information about the condition of the tooth from the hard tissue chart. Shortcuts to this page are available in photos and radiographs. Teeth shown in a particular image have buttons to the side so that a user may jump directly to all of the information about that tooth. On the hard and periodontal tissue chart, a tooth can be clicked on to jump to the relevant single tooth view. There is also an option to choose to see information for an entire section of the mouth. The mouth is divided into its sextants. Each tooth's information is separated into three sections: hard and soft tissue, detail, and overview.
Rationale	Dentists frequently compare multiple types of information. The single tooth view helps them accomplish this goal without a lot of searching or flipping between tabs. All relevant data for a tooth are found in one location.

Tabs for Navigation



Goal	Enable users to view any page with a single click
Design	A series of tabs along the right side of the screen
Rationale	Tabs are a simple intuitive navigation system that allows users to quickly access any type of information available. As the cognitive task analysis data showed, dentists frequently switch between different information sources. For instance, they frequently switched between radiographs and images and hard tissue chart and periodontal chart or radiographs.

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