

Master's thesis proposal [rev_4.4]

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Abstract

The benefits of Computerized Patient Records (CPRs) are well documented. Yet current dental CPRs inadequately support chairside use as evinced in low adoption rates for operatory computers. If dental professionals have any hope of realizing the advantages CPRs offer, information systems must adapt to their workflow and not *vice versa*. To that end, research suggests tablet devices hold promise as an alternative to traditional desktop PCs' ergonomic shortcomings in the clinical environment. Designing a goal and task specific tablet-based treatment planning interface may help bridge the adoption gap between office and chairside computer use in dentistry. Evaluation can determine if users are faster, more successful, less error prone, or more subjectively satisfied with the tablet application over traditional CPRs.

1 Background

First, I summarize applicable findings from usability and informatics research. Next, I discuss a user model for treatment planning in dentistry. Lastly, I discuss conclusions and potential solutions.

1.1 Adoption Gap

The adoption of Computerized Patient Records (CPRs) by healthcare professionals has long been recognized as a key step in improving patient care [1–5]. Dentists recognized the power of computers assisting with practice administration — such as scheduling and billing — becoming early adopters of computers in-office (Figure 1).

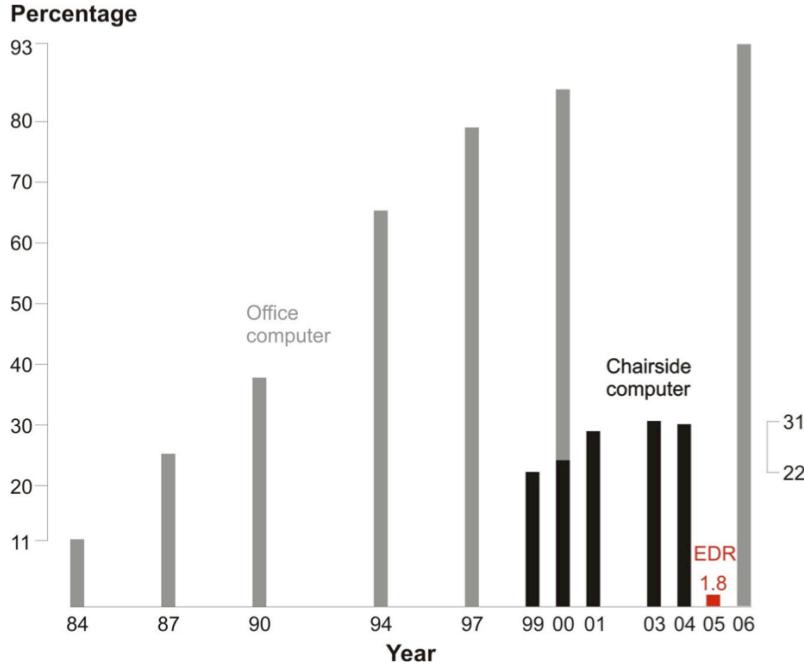


Figure 1: Year of first computer installation for office and chairside use by US dentists [6]. The red bar represents completely paperless practices.

Survey data from 2010, the most recent available, reported 92% of respondents using Practice Management Software (PMS) [7].[†] However, the conclusions of two usability studies on four dental CPRs, which together comprise more than a 70% market share for such systems, suggest poor usability is a barrier to dental CPR adoption for chairside use [8, 9]. The gap between office adoption of computers and the adoption of computers for chairside use is evident in Figure 1.

1.2 Usability

The first of the two cited usability studies employed heuristic evaluation methods [10, 11]. Three expert reviewers examined each of the four CPRs and tabulated violations of Nielsen’s heuristics [12]. Evaluators found 229 violations in total across EagleSoft, Dentrix, PracticeWorks, and SoftDent.

[†]Here I use PMS to refer to software that handles office administration whereas a CPR handles patients’ clinical data. Most CPR software is also PMS but not the other way around.

Consistency and Standards, Match Between System and the Real World (Appendix A.4), and Error Prevention were the most commonly violated heuristics with the distribution of violations roughly equal among the four CPRs inspected. The authors admit their conclusions offered no comparative assessment between the CPRs but the magnitude of violations suggested significant room for usability improvement.

The second usability study compared [13] these same market-leading CPRs by assigning common tasks to five novice users for each of the four systems ($n = 20$). Users were purposively sampled with four full-time dental faculty members, eight practicing dentists, and eight senior dental students from the University of Pittsburgh School of Dental Medicine comprising subjects for the assessment. Two experts coded task completion success and associated usability problems. The authors used Wilcoxon rank-sum tests, Spearman correlation coefficient tests, and Kruskal-Wallis tests to determine the correlation between usability problems and task outcomes. The frequency of observed usability problems correlated positively with the frequency of task failures for all tasks except two ($p < 0.05$): assigning a tooth as missing and recording soft tissue measurements. On average, users correctly completed 43% of the assigned tasks leading to a similar conclusion: the most commonly used dental CPRs suffered from a steep learning curve and have ample room for usability improvement.

The results of these two studies point to inadequate support for chairside use. All four systems included in these studies began life as PMS with clinical functions added later. The abundance of nested menus, tree selections, and drop down lists for clinical and non-clinical functions alike are evidence of this (Appendix A.1). Dentrix, for instance, provides sometimes two or three different input methods for the same function on the same screen (button on a pallet, tree selection, and drop down menu). All four systems evaluated by Thyvalikakath et al. employ screen designs that include nearly all input options at once rather than the options needed for the specific task or goal (Appendix A.3). Interfaces with many options can make finding the function of interest more difficult, increase cognitive load, and slow the user [14]. One could argue complicated interfaces are not universally poor if such an interface is appropriate for the job (for example, an airplane cockpit). But given the evidence, it seems the gulf of execution and evaluation [15] in dental CPRs is unnecessarily wide. Dentrix and Eaglesoft screen design, for example, confused novice users with intermixed controls for entering existing conditions and planned procedures on the same palette. And performing basic tasks, such as marking a tooth as missing, require four to six mouse clicks across a wide swath of screen real estate (Appendix A.2).

Fitts's law [16, 17] predicts the average task completion time, T , as primarily a function of D , the distance from the starting point to the center of the target and W , the width of the target measured along the axis of motion such that $T = a + b \log_2 \left(1 + \frac{D}{W}\right)$ where a and b are experimentally determined constants. Though not measured by Thyvalikakath et al. (2008), one might expect poor task completion time for the surveyed CPRs in light of mousetracking data that illustrated long distances and narrow targets (Appendix A.2). Compounded over the course of an initial exam appointment, this method of data input is time prohibitive for a single user. Meaning, these input design choices are far from efficient for a user that requires efficiency.

Since the information input and retrieval processes were not integrated into the concepts of tasks and workflow, users were required to divide their attention between navigation and task completion. In both usability studies, the authors noted information that would typically appear on a single paper form was spread out over two or more screens in the CPR. The comparative evaluation cited difficulty with tasks that required screen switching as a principle source of user frustration. Evidence suggests these problems are not unique to dental health information technology (HIT) applications [18, 19].

Readers of these two usability studies offered valid criticisms [20]. One such critique centered on the authors' choice of novice users for the evaluation. Critics pointed to the low likelihood of a user being completely unfamiliar with the CPR in a live office setting. Training office staff to use the CPR is routine and thus the steep learning curve cited in the conclusion may not reflect the learning curve faced by actual users. Another critique, from the same citation, questioned the assumption of causality between poor usability and low adoption rates of CPRs by dentists. The author sees private practice dentists' primary concern as one of return on their investment in Information Technology over potential usability issues discovered post purchase. Regarding heuristic evaluation, Nielson and Molich (1990) developed this discount inspection method at a time when it was expensive to gain access to users. Nielson and Molich warn readers of haphazard application of their method and the need for training expert reviewers and ... Heuristic inspection can only determine the extent to which an interface adheres to a set of best practices; to make broader claims about generalizability of results would be problematic.

1.3 Attitudes and Use

In a telephone survey of 102 general dentists in the United States, researchers discovered two main sources of user frustration in using dental CPRs: steep learning curves and difficulty entering clinical data [6]. Respondents considered ‘better input methods,’ ‘smaller computers,’ and ‘better user interface design’ as principal areas for improvement. Another important concern included lack of infection control inherent with traditional keyboard and mouse input. These responses track closely with those elicited from British users through a similar survey [21].

Dental practices use their computers primarily for scheduling patients and tracking completed procedures (Figure 2).

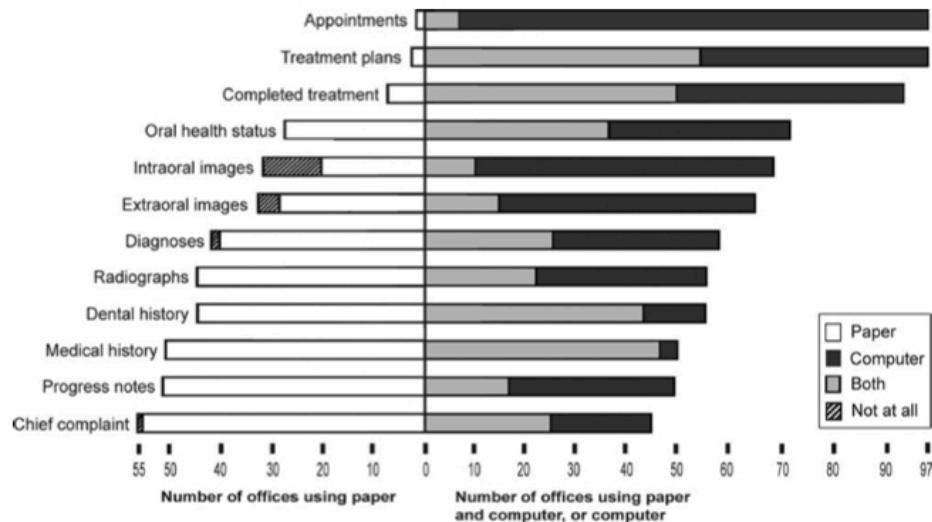


Figure 2: Storage of major clinical information categories on paper/computer, sorted by utilization of computer-based storage in descending order [22].

Because dental CPRs are poorly designed for chairside use, some users accommodate by working around the CPR. Some practices record temporary notes on a patient napkin or tray cover and commit these notes to the electronic record later while others record histories on paper and treatments on the computer. While transcribing notes from paper to the computer is not an inherent problem, such a practice has the potential for error. Storing some information in paper format and some in electronic format (Figure 2), similarly, is not *prima facie* poor practice but requires the consumer

of the information to switch between the paper-based and computer-based records. Fragmentation of data into multiple locations has one inevitable drawback: switching requires cognitive overhead and time. This burden can slow the consumption of information by the clinician or produce transcription errors [23]. The need to work around the CPR is due, in some part, to the difficulty of integrating the necessary hardware into an already cramped dental operatory [24,25] and, in some part, to the time-prohibitive cost of entering data into a poorly designed system. The ergonomics of one dentist, one assistant, and one patient gathering, entering, retrieving, and presenting information are complex (Appendix C). The suggested areas of improvement noted in the Schleyer, et al. (2006) survey highlight the frustration of using software designed without these ergonomics in mind. The task of finding the required information inside the patient record is often criticized as time-intensive and distracting [26]. This is especially concerning given the increased information needs of clinicians in an increasingly time-pressured environment. If we accept the premise that HIT can improve patient care, and there exists a large adoption gap, the necessity of generating and understanding a user model becomes apparent.

1.4 User Model

Recognizing the interplay between usability, practice culture, and operatory configuration, researchers set out to model the workflow of an initial examination and treatment planning appointment through contextual inquiry [27]. During this appointment the dentist documents the patients current condition, the patient-specific goal for oral health, and generates a sequenced plan to proceed from present state to the goal state. This process, with its findings, diagnoses, and resulting plan, must then be discussed with the patient. Depending on the complexity of problems, multiple treatment plans may be required. Of any appointment, this one generates the most clinical artifacts such as radiographs, photographs, hard and soft tissue diagnostic charting, and study models. It follows that the initial exam requires the most data input of these artifacts into the CPR. And artifacts must be quickly retrieved for consumption by the clinician and for discussion with the patient. Following the initial visit and generation of a treatment plan, each subsequent visit requires comparatively little interaction with the CPR. The dentist may check the medical history or reference the planned procedures, for example. Thus the initial appointment requires the most interaction with the CPR for data entry and retrieval, making it an ideal candidate for study.

A thorough initial exam and treatment planning appointment is vital for

not only diagnosing every present condition but communicating the condition, its consequences, and treatment options as well. Generating a treatment plan is analogous to peeling an onion: the dentist starts with the most obvious signs and symptoms and continues examination, testing, and imaging until all signs and symptoms have been mapped to a problem list. The dentist may ascribe diagnoses to items on the problem list and then generate a treatment to address each item. This process is non-deterministic, across patients and dentists, and time-intensive, often requiring two people. Typically one operator will diagnose and call out findings while an auxiliary transcribes the findings into the computerized record. While this task may be handled differently in sequence from one dentist or patient to another, the steps are the same and mappable to common set of terms and abstractions.

Irwin, et al. (2009) observed an auxiliary may not always be available and dental team members used a variety of workarounds in such a situation. For example, hygienists often perform recare examinations without an assistant, noting their preliminary findings on a piece of paper prior to discussion with the dentist. Some clinicians postpone any data entry tasks to a time after the patient has been dismissed. This presents the problem of having to remember what was done and why. Even under ideal circumstances, that is, when an assistant was present, over 60% of the Irwin's observed breakdowns were due to technology. One implicit conclusion from the Irwin model was dentists spend little time entering data with the majority of CPR interaction handled by hygienists and assistants. Schleyer, et al. (2006) reported dentists participating in only 23% of data entry tasks, chief among them being progress notes. Hygienists and assistants handled most other data entry tasks such as diagnoses, oral health status, and histories. Given the larger turnover of non-dentist staff, and the fact non-dentists perform about 75% of data input, learnability of a CPR becomes an important concern. Whether dentists would employ more clinical functions in their CPR given improved interfaces, as Irwin, et al (2009) described, "with the flexibility in sequencing, granularity and comprehensiveness" for data entry remains to be seen. But Irwin conclusions mirror the conclusions from the Schleyer et al. 2006 survey: CPR design must accommodate to the demands of dental workflow.

1.5 Conclusions and Solutions

Several important conclusions can be gleaned from the cited literature. First, dental operatories are small and require careful planning to integrate the CPR's supporting hardware. The suggestion of using smaller computers

from the Schleyer, et al. (2006) survey reveals user frustration with this integration burden. Next, the current paradigm in dental CPR design and ergonomics requires an auxiliary for efficient data entry. Most dentists are consumers of patient information while hygienists and assistants perform most data entry. Following the generation of a treatment plan, subsequent appointments require comparatively little data entry or retrieval. Given the results of the user model study, the highest value targets for CPR improvement are the functions used during the initial visit: namely, diagnoses and treatment planning.

Schleyer et al. (2006, 2007) and Irwin et al. (2009) report the common practice of using multiple or duplicate data entry. A user may write something on paper, such as routing slips or preliminary findings, later transcribing this information into the electronic record. Alternatively, one might record the medical history on paper and use the CPR to record planned and completed treatments. This is due, in part, to the fact that dental CPRs cannot capture the variety of data with the flexibility of paper forms [22]. Depending on the survey of paper forms and the CPR used for comparison, CPRs can lack 80–90% of the data elements contained in paper records. Duplicate data entry might also be used to accommodate the non-linear and variable process by which patients are escorted through this initial visit. Therefore, an alternative system needs to allow the user a temporary and mutable data store to enter information before committing the entry to the record. And the clinical vocabulary of the information system must be at least as large as that of the clinician. Efforts are underway to enumerate and control this vocabulary [28–31] but providing the most commonly used data elements and allowing the user to customize the type and sequence of information capture may suffice.

Little research effort has been dedicated to studying mobile devices in dentistry. While many dental-specific mobile applications exist and several vendors are exploring mobile platforms, most literature are case reports. For over a decade, dental clinicians have recognized the potential for hand-held computing devices to address the limitations of traditional PCs [32,33]. Coupling the advantages of mature tablet devices with a novel interface, which incorporates lessons learned though previous research, may hold promise.

2 Tablets and Usability

Tablets offer several advantages over traditional desktop PCs in clinical use. Because CPR access is not universally available in medical exam rooms,

tablets' smaller size and portability were central to their adoption by physicians. Tablets allow the clinician to enter orders, notes, and review information while remaining mobile. Similarly, tablets' smaller footprint and portability could address the ergonomic challenges in dental practice. A tablet is ideal for consuming information, which is the principle concern of the clinician. Tablets can at least match the traditional desktop PC in data entry speed and accuracy with use [34,35]. They can be easily shared between the provider and patient and easily disinfected [36]. Properly designed touch-screen mobile interfaces have demonstrated promise in a variety of medical settings [37–41]. Finally, if users are as capable on a mobile device as a traditional PC, the ergonomic and portability advantages can increase user subjective satisfaction with a mobile system over a conventional desktop [42].

Tablets make ideal devices for which to design interfaces for fast task completion time. Because their screen size is small and users make input choices with their fingers, buttons must be large. Most tablet devices will not discriminate capacitive touch with less than 8–9mm surface area. Further, because tablet screen real estate is limited, one must carefully consider the interface elements and sequence of interactions. This economy of choice requires a tablet-based interface to be well adapted to user tasks and goals. Thus, given a larger button size on a smaller screen, Fitts's law would suggest tablets as a logical platform choice.

Some remain skeptical of the virtues of tablet computers in clinical use [43,44] and, compared to the medical literature, few investigators have studied tablet use by the dental team [45]. Applying the insights from medical informatics research to dental problems presumes exchangeability of the domains. This may not be the case (Table 1). A key difference to note is the small number of diagnoses in dentistry compared to medicine; dentists cover a smaller portion of the body compared to physicians. But for each diagnoses there are a larger number of choices for treatment. One might explain this difference by pointing to the larger role patient preferences play in dental treatment planning [46] or the smaller role of evidence-based practice in dentistry compared to medicine [47]. Another key difference is ergonomic: physicians stand or sit bedside while the dental ergonomic is unique. However, given the success enjoyed by tablets in complex medical settings, I remain optimistic about tablet performance in the dental operatory. Creating a usable and useful interface for the tablet is a separate consideration.

Regarding screen design, Thyvalikakath, et al. (2008) recognized the disconnect between task flow and screen design in dental CPRs ahead of a formal modeling study. Several topical conclusions the 2008 comparative usability study include:

Table 1: Summary comparison of differences across medicinal and dental domains. Because dental patients are usually less sick, the tablet interface needs fewer input controls. Because the number of encounters per day is lower and dental clinicians need to cover a smaller physical area, tablet devices are ideal (instead of say a smartphone). Because the number of diagnoses is small and therapies per diagnoses large, several rule-based functions could help generate treatments from problems saving time.

Feature of practice	Domain	
	<i>Dentistry</i>	<i>Medicine</i>
Patient status	Usually not sick	Usually sick
No. of encounters per day	Few	Many
Average visit length	Long	Short
No. of diagnoses	Few	Many
No. of therapies per diagnoses	Many	Few
No. of initial visit artifacts	Many	Few

- Users should be able to identify their treatment preferences and software should support that approach.
- Data entry and retrieval controls available on screen should correspond with the tasks to be completed. Unrelated or extraneous controls should not be shown. Information that belongs to a specific task context should be shown together or be easily accessible. For instance, hard-tissue and periodontal findings often must be reviewed together to make a clinical decision and should not be separated unnecessarily.
- Data entry and functional controls should be organized and labeled clearly according to input class (findings, planned/completed procedures, notes, pictures, annotations, etc.).

Lastly, the User-Centered Design (UCD) approach to software engineering has demonstrated promise in general [48–51] and HIT specifically [52]. Thyvalikakath, et al. (2007) recognized UCD as a potential solution to the multiple heuristic violations noted during expert review. UCD is a broad term to describe design processes in which end-users influence the software

design. Linking the iterative design process to feedback from users has a proven track record of producing highly usable software. I elaborate on the proposed incorporation of the UCD approach in Section 3.2.

3 Proposed Research

Based on research evidence, tablet devices make a logical hardware choice. However, hypotheses about tablet use in dentistry remain untested. The extent to which tablet devices and touch interfaces can improve data entry and user satisfaction is a question left to evaluation. But first an interactive tablet-based treatment planning prototype is needed.

Research is currently underway to qualify and quantify the data private practice dentists capture in their CPRs. Given the time constraints of clinical practice and poor usability demonstrated by market-leading CPRs, we hypothesize dentists predominantly document completed procedures and few diagnostic findings (Figure 2). This is accepted practice by third-party payers in contrast to medicine. Given the lack of open-domain knowledge of type and quantity of data users store, design choices must rely on literature and best practices. But once completed, the data from this study can help inform system design — ranked list UI elements, for example.

I propose testing two hypotheses: (1) tablet computers, using platform-native UIs, can at least match conventional desktop computers in data entry speed and task completion; (2) users will prefer using a mobile touch screen device over the conventional desktop PC.

3.1 Treatment Planning Prototype

To effectively evaluate the comparative usability of tablets and desktop PCs a measure of functional equivalence across the two systems is required. That is to say the tablet prototype must be able to input and retrieve the same clinical artifacts necessary for treatment planning as a mature software system like Dentrix or EagleSoft. Such artifacts include:

- Patient histories: both medical and dental histories are critical to patient safety and disease management
- Hard tissue: both existing restorations and conditions that would indicate treatment
- Soft tissue: periodontal measures such as clinical attachment level, soft tissue margins, and common periodontal findings (e.g. furcation

location and classification)

- Picture Archival and Communication System: radiographs as well as intraoral and extraoral photographs play an increasingly important role in dental practice. Such artifacts provide not only valuable information to the clinician for decision-making but also aid in communicating that information in a patient-friendly manner.

These are the same class of items required to work through case examples in the seminal textbook on dental treatment planning by Sefanic and Nesbit [53]. Further these artifacts are the same ones used by non-digital dentists (Appendix B) and correspond with the task and user models generated by Irwin et al., thus offering a consensus for high value targets for data input and retrieval. Assuming the four mentioned artifacts are necessary and sufficient to complete a dental treatment plan, and given that such functionality is already present in current CPR vendor offerings, what is the value proposition?

From survey data we know that dental practices value digital functionality related to financial reimbursement. Poor usability demonstrated in evaluation offers a plausible explanation for this and may help explain the practice of keeping some artifacts digital and others on paper. Why would a clinician bother with the many clicks and screen shuffling required to document all of their findings in the digital record if they are paid only for the completed treatments? Indeed many clinicians either use planned treatments as their primary method of documentation or use paper records as a workaround.

If a system were designed with goals and tasks in mind, however, it is feasible that a small number of rules could unambiguously and programmatically render diagnoses from problems—generating knowledge from data and saving the operator valuable chair-time in the process. These rule-based functions are a necessary first step to improving patient care by changing the work flow process from “what treatment should address the problem?” to “why is there pathology present?” Doing so allows a potentially valuable hook into decision making process with which to provide clinical decision support.

In order for the prototype to be interactive, The functional specification includes:

- The ability to document the most common diagnostic findings in a clinically linear fashion (find all sites affected with diagnostic condition, move on to the next condition)

- The ability to automatically generate diagnoses from the documented findings
- The ability to automatically map a list of treatments, based on provider preferences, from the list of problems and diagnoses
- The ability to bin and sequence the list of treatments to form one or several treatment plans

Following the generation of a treatment plan (or plans), the provider next discusses the findings with the patient. The ability to summarize findings for the providers use in treatment planning is as important as communicating these findings to the patient. Using the treatment plan “patient view” to facilitate this discussion could help drive treatment plan acceptance. This feature would undoubtedly be beneficial but may fall outside the scope of this project. The “patient view” function is but one example of the many functions available to users once patient data is present in the CPR. However, addressing the problem of cumbersome data entry is a necessary prerequisite to reaping the benefits of computerized records.

3.2 Evaluation

Dsesigning a novel tablet interface lends itself well to the evaluation process. Were I to evaluate only the interfaces, there would no advantage to use of a smaller device. Subjects could just as easily evaluate the novel interface on a desktop PC alongside a conventional CPR. Therefore, I propose a two stage evaluation using fractional factorial design. For the vector of participants of length n , each participant p is tasked with entering one of two comparably difficult patient cases $c_{1,2}$ into the conventional CPR and tablet system. If Bob were assigned to enter c_1 into Dentrix, he would then enter c_2 into the tablet system. For the next participant, Alice, the case assignment switches (see example results below). The design is fractional factorial because not every combination of cases and methods will be administered for each subject in order to avoid learning effects from entering the same patient case twice. This experiment design is well suited to comparing the relative efficiency of data entry across the tablet and conventional CPR because of within-subjects comparison. Each user must use both methods of data input and thus acts as their own control when comparing to an alternative. After gathering the data, I can retrospectively examine the impact of case selection on task completion time. Significant effort will be made to select two patient

cases of equal difficulty and comprehensiveness in order to minimize the case effect.

A second evaluation, using the same design but different setting, can determine the relative ergonomic advantages to a tablet device. Subjects will sit in a dental operatory and receive paper artifacts to enter each system. Using video recording, I can measure subject motion over time and determine the relative efficiency of each device in the physical environment.

Table 2: Proposed within-subjects evaluation design using a tablet-based prototype and conventional CPR for comparison

Evaluation	Users	Setting	Design
A	Naïve with 30 minutes of training	Lab-based	Users sit at a desk in ‘clean room’ enter one task set per system; tests interface with time
B	Naïve with 30 minutes of training	Clinical	Users sit in a clinical environment enter one task set per system; tests interface & ergonomic with time & motion

Evaluation of the tablet application requires comparing it to an alternative. Two logical points of comparison are the most popular CPRs in private practice: Dentrix and EagleSoft. Vendors have granted access to these CPRs to the CDI and using them for the purposes of evaluation should present no challenges.

Similar to Thyvalikakath, et al. (2008), summative measures like task completion success rates provide a valuable evaluation metric. Task completion time (if successful) and subjective user satisfaction are also useful [54]. Task completion time can be simply measured with a stop watch by an observer. Subjective user satisfaction could be measured through a survey administered after each user completes the task set on each system. By using within-subjects comparison the effect of user familiarity with tablet devices and the traditional CPR can be minimized.

One important tradeoff to consider is fidelity to real-world use versus ease of evaluation. Setting up a mock clinic with myself (or someone else) acting as a patient would provide a more realistic environment but may bias

the evaluation if the primary investigator serves also as the mock patient. Alternatively, several naïve users could complete a common task set using the tablet application and an alternative.

As previously described, the UCD approach to development is ideally suited to the proposed research. The University of Pittsburgh's Center for Dental Informatics and School of Dental Medicine can provide ready access to potential participants for design feedback ahead of the formal evaluation. The purpose of this feedback is to confirm the design specification and to maximize application usability. Depending on the results of this feedback, one or more rounds of iteration may be necessary.

3.2.1 Instruments

- Task completion success

Logical summative measure for overall usability

Measured by determination of user completing the task within a specified time range (say 10 minutes), regardless of accuracy of the input.

- Task completion time if successful

Useful metric because of quantitative nature allowing statistical model inspection of the relative effects of the method, case, and subject on the task completion time

Measured with a stop watch by observer

- Subjective user satisfaction

One of the only means of measuring user preferences across data input methods

Measured through survey of users with calibrated instrument

- Error rate

Also quantitative measure, if secondary to task completion time, useful for gauging effectiveness of user input rather than speed

Measured through match of paper artifacts to electronic records

3.2.2 Power Analysis

Little consensus exists on the appropriate sample size for usability evaluations [55–58]. While some researchers in the HCI domain acknowledge

parameter settings for a power analysis are little more than a best guess, the experiment design makes use of quantitative measurements. Because of this, we can use generalized linear models to simulate the data and determine power accordingly. Thyvalikakath et al. (2008) argue:

“We chose five participants per group because this number is considered adequate for usability testing as evidenced in the usability engineering literature Thyvalikakath [13].”

Nielsen offers no guidance on sample size in the cited article, however.

Virzi (1992), Nielsen and Landauer (1993), and Lewis (1994) have published influential articles on the topic of sample size in usability testing. In these articles, the authors presented a mathematical model of problem discovery rates in usability testing. Using the problem discovery rate model, they showed that it was possible to determine the sample size needed to uncover a given proportion of problems in an interface during one test. The authors presented empirical evidence for the models and made several important claims:

- Most usability problems are detected with the first three to five subjects.
- Running additional subjects during the same test is unlikely to reveal new information.
- Return on investment (ROI) in usability testing is maximized when testing with small groups using an iterative test-and-design methodology.

Nielsen and Landauer (1993) extended Virzis (1992) original findings and reported case studies that supported their claims for needing only small samples for usability tests. They and Lewis (1994) identified important assumptions about the use of the formula for estimating problem discovery rates.

After discussion with Dr. Roger Day, we arrived at two methods for determining the needed sample size to ensure adequate statistical power for the analysis of results. The first method assumes task completion times will be normally distributed and simulates times with the R command `rnorm()` using the parameters: `n_hypoth <- rnorm(n=20, mean=17.45, sd=5.13)` and `a_hypoth <- rnorm(n=20, mean=14.83, sd=4.35)`. After construction of the `data.frame`, we have:

```
> head(study_frame)
  Person Method Case          Time
1      1       A   1 13.2527887567932
2      1       B   2 12.7749906535696
3      2       A   2 21.2468856794146
4      2       B   1 19.2013917780723
5      3       A   1 13.2942597949759
6      3       B   2 8.16402213811822
```

With the simulated data we can now perform the power analysis. First, I generated a generalized linear model using the Method (tablet or conventional CPR), Case (1 or 2), and Person to predict task completion time:

```
> model <- glm(as.numeric(Time) ~ Method + Case + Person,
               data=study_frame)
> summary(model)
```

Deviance Residuals:

Min	1Q	Median	3Q	Max
-16.600	-3.275	0.000	3.275	16.600

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	8.100	7.924	1.022	0.32023
MethodB	-4.800	3.379	-1.421	0.17252
Case2	1.600	3.379	0.474	0.64153
Person10	14.000	10.685	1.310	0.20658
Person11	14.500	10.685	1.357	0.19154
Person12	12.500	10.685	1.170	0.25731
Person13	1.000	10.685	0.094	0.92647
Person14	22.000	10.685	2.059	0.05427 .
Person15	27.000	10.685	2.527	0.02109 *
Person16	7.000	10.685	0.655	0.52067
Person17	18.000	10.685	1.685	0.10932
Person18	7.000	10.685	0.655	0.52067
Person19	-4.000	10.685	-0.374	0.71251
Person2	21.000	10.685	1.965	0.06499 .
Person20	16.500	10.685	1.544	0.13993
Person3	16.500	10.685	1.544	0.13993
Person4	11.000	10.685	1.029	0.31688

```

Person5      31.000    10.685    2.901  0.00952 **
Person6      15.500    10.685    1.451  0.16408
Person7      24.000    10.685    2.246  0.03748 *
Person8      14.500    10.685    1.357  0.19154
Person9      11.000    10.685    1.029  0.31688
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1

(Dispersion parameter for gaussian family taken to be 114.1667)

Null deviance: 5330  on 39  degrees of freedom
Residual deviance: 2055  on 18  degrees of freedom
AIC: 317.08

Number of Fisher Scoring iterations: 2

> study_aov <- aov(as.numeric(Time) ~ Method + Case + Person,
+                     study_frame)
> summary(study_aov)

```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Method	1	230.4	230.4	2.018	0.173
Case	1	25.6	25.6	0.224	0.642
Person	19	3019.0	158.9	1.392	0.244
Residuals	18	2055.0	114.2		

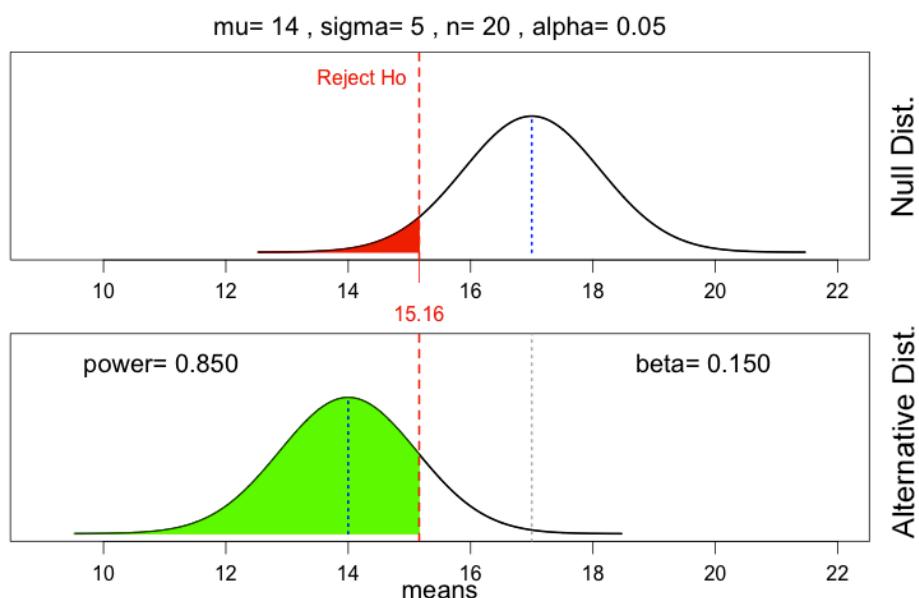


Figure 3: Plot of null and alternative distributions; the rejection region and the power region are highlighted allowing manipulation of the effect size, standard deviation, sample size, and alpha to determine the effect on power [59].

4 Proposed Timeline

<p>April Initial proposal May Begin development</p> <p>June Begin contextual inquiry</p> <p>August Complete contextual inquiry August Model building</p> <p>September Screen design and wireframe revision</p> <p>September Complete preliminary expert review</p> <p>September Complete proposal October Begin principal development</p> <p>October Second round of expert review</p> <p>December Third round of expert review</p> <p>January Complete interactive prototype</p>	<ul style="list-style-type: none">• April Begin thesis•••• August Begin sketches and paper prototypes• September Preliminary expert review•• September Complete functional specification• November Begin design iteration• December Design polish• January Begin evaluation
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Appendix A CPR Screenshots

Appendix A.1 Dentrix

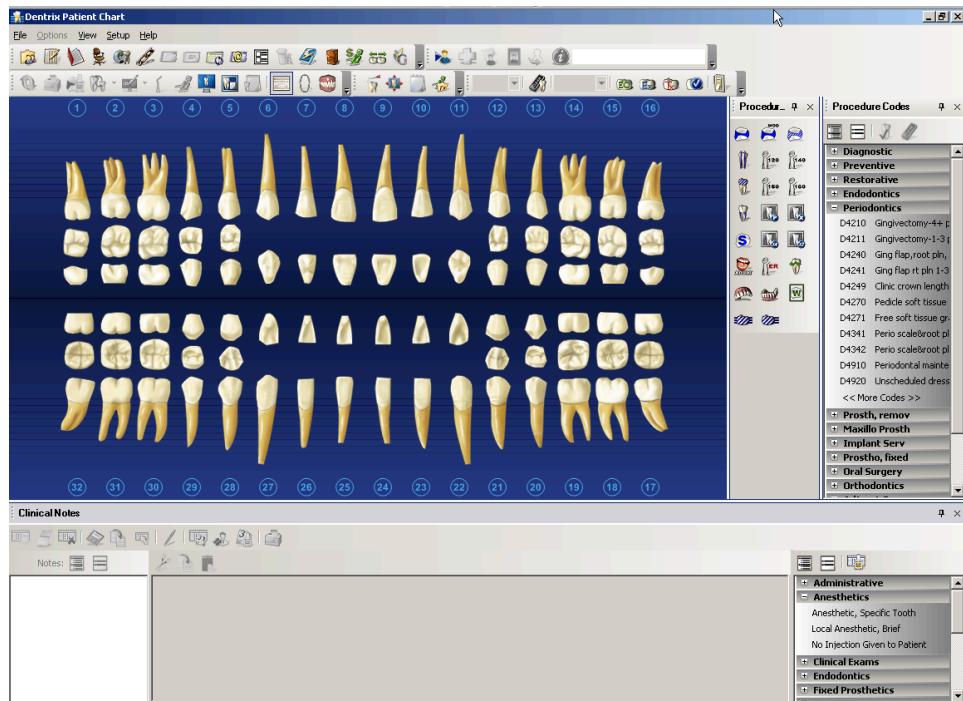


Figure 4: Screenshot of Dentrix's G4 user interface.

Appendix A.2 Mouse tracking of users trying to perform a common task in Dentrix

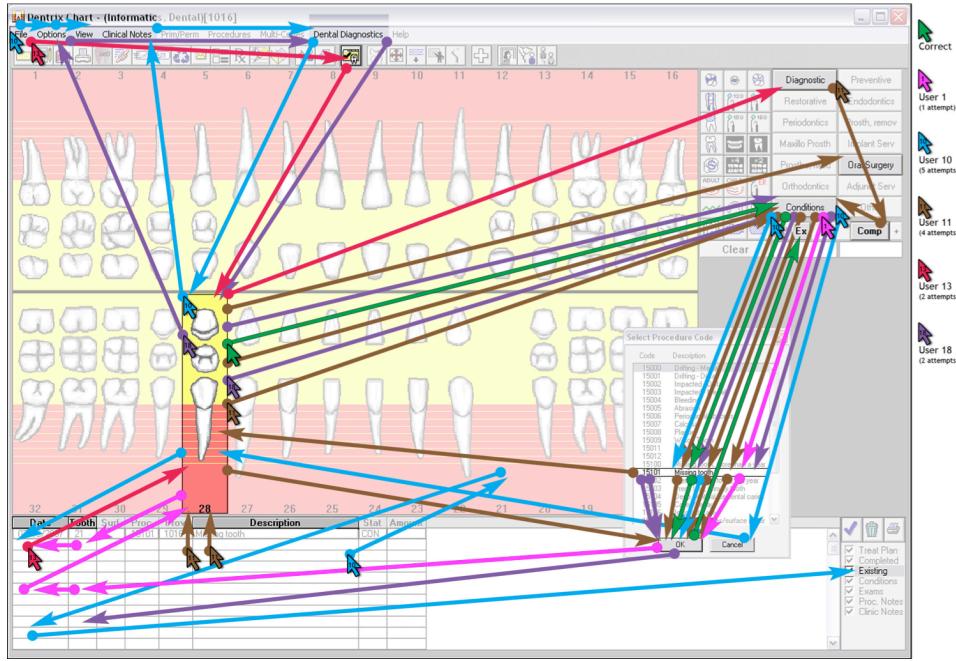


Figure 5: Screenshot showing a users actions while trying to record tooth no. 28 as missing while using the Dentrix v11. The correct sequence consists of the following left mouse clicks: tooth no. 28, Conditions, Missing tooth, OK and EX [9].

Appendix A.3 EagleSoft

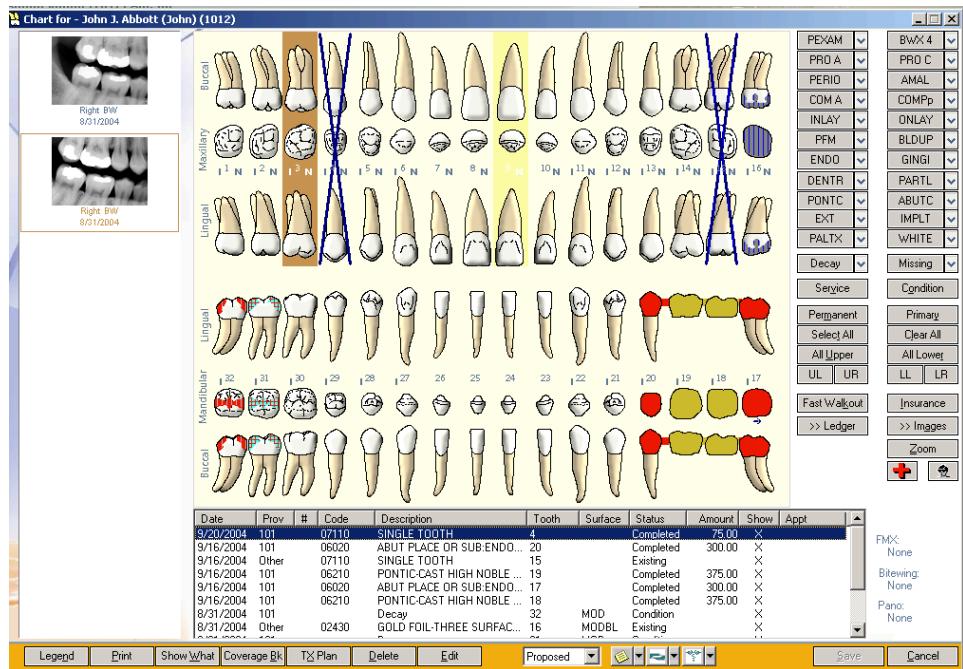


Figure 6: Screenshot of EagleSoft's v16.0 user interface.

Appendix A.4 Screen controls

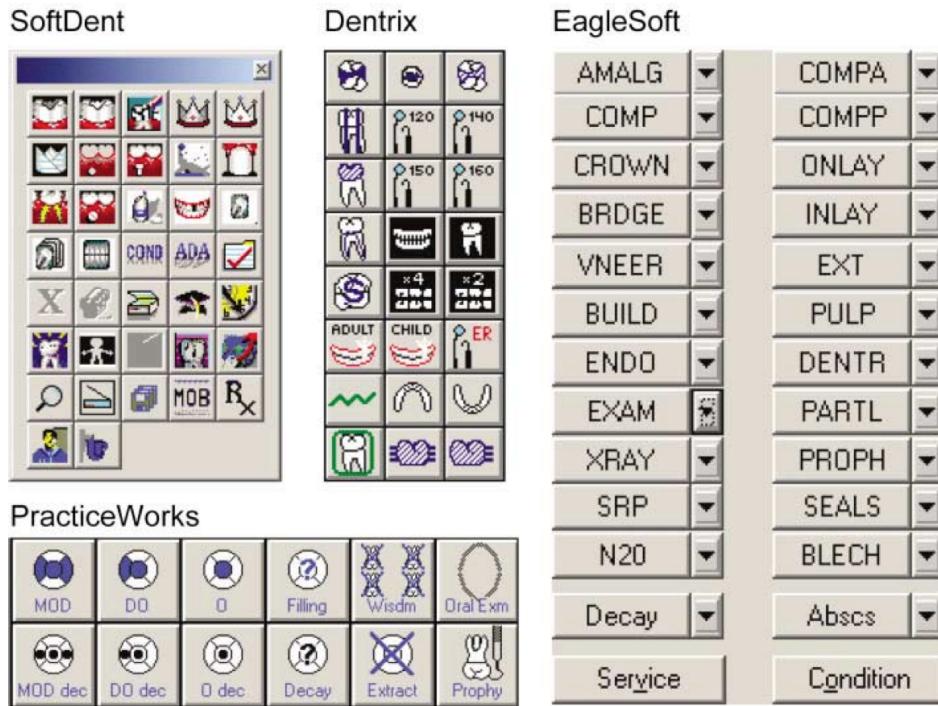


Figure 7: Charting icons for hard-tissue findings and procedures in Dentrix v 10.0.36.0, EagleSoft v 10.0, SoftDent v 10.0.2, and PracticeWorks v 5.0.2 [8]. Expert review found heuristics such as Consistency and Standards and Match Between System and the Real World were often violated by hard tissue controls. One expert found PracticeWorks icons to be ambiguous. One common theme was the lack of reliance on operating system convention to help the user with recognition rather than recall.

Appendix A.5 Tablet prototype

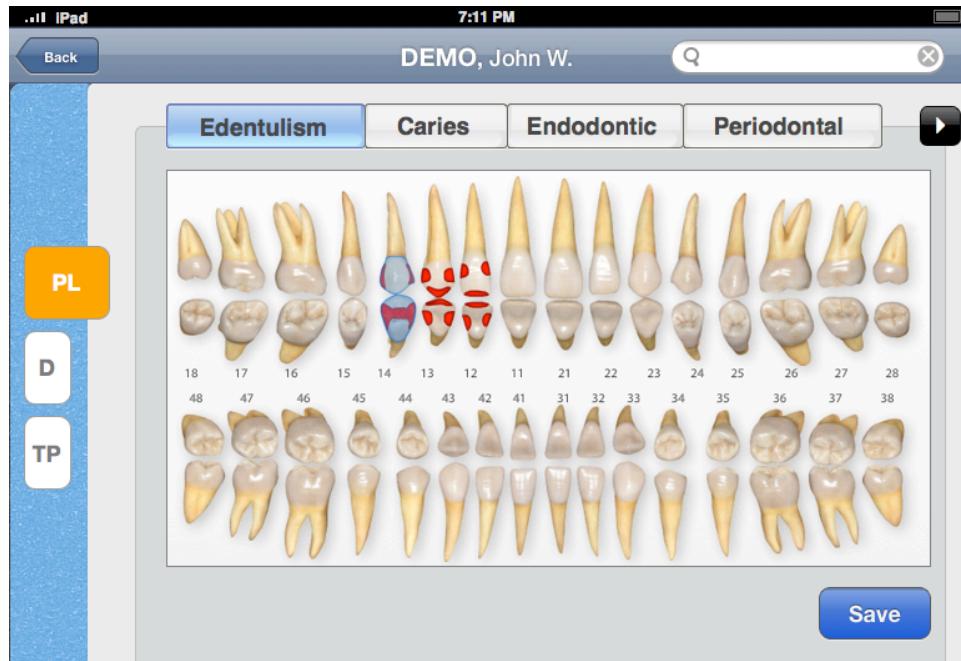


Figure 8: Mockup for tablet-based prototype. Much of the design inspiration comes from the two usability studies of dental CPRs. Button controls large enough for fingers and taken from the `StdUILibrary` within Xcode. Many other conventions like tap to select and swipe-based navigation also leverage user familiarity with iOS devices. Navigation along the top is couched in the concept of the initial exam and allows users to customize the content and sequence of data capture. And the ability to programmatically render diagnoses and treatments based on problems identified allow more efficient data entry.

Appendix B Artifact Model

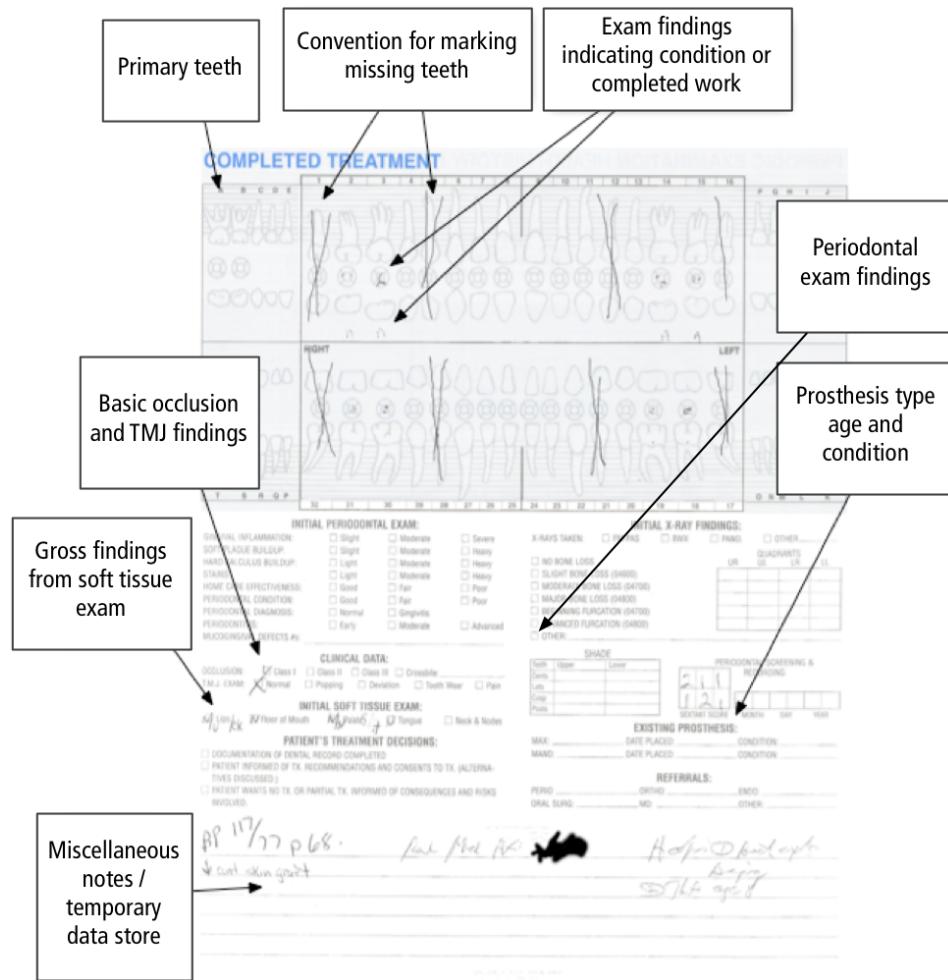


Figure 9: Artifact model generated from common paper-based treatment planning forms

Appendix C Physical Models

Appendix C.1 Rear-delivery

01 Rear-delivery physical model

Right-handed operator

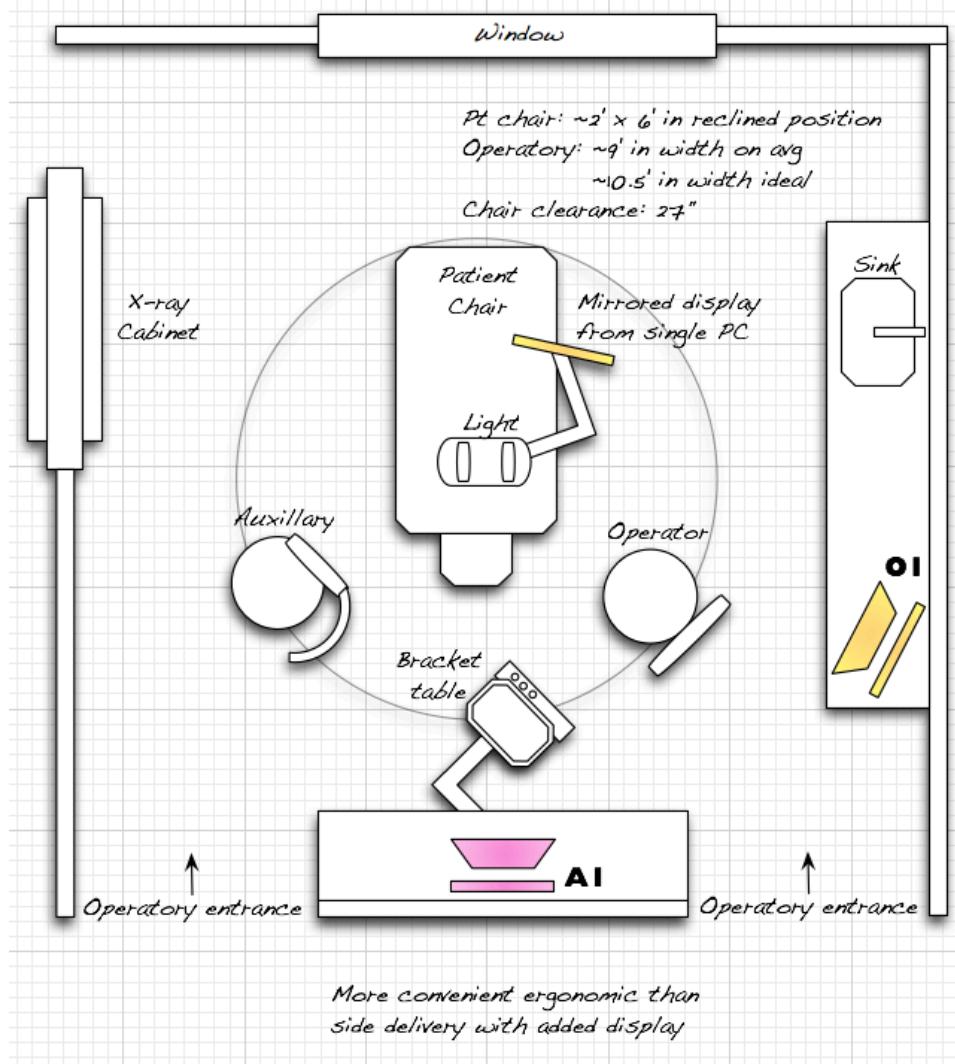


Figure 10: Rear-delivery physical model for a right-handed operator.

Appendix C.2 Side-delivery

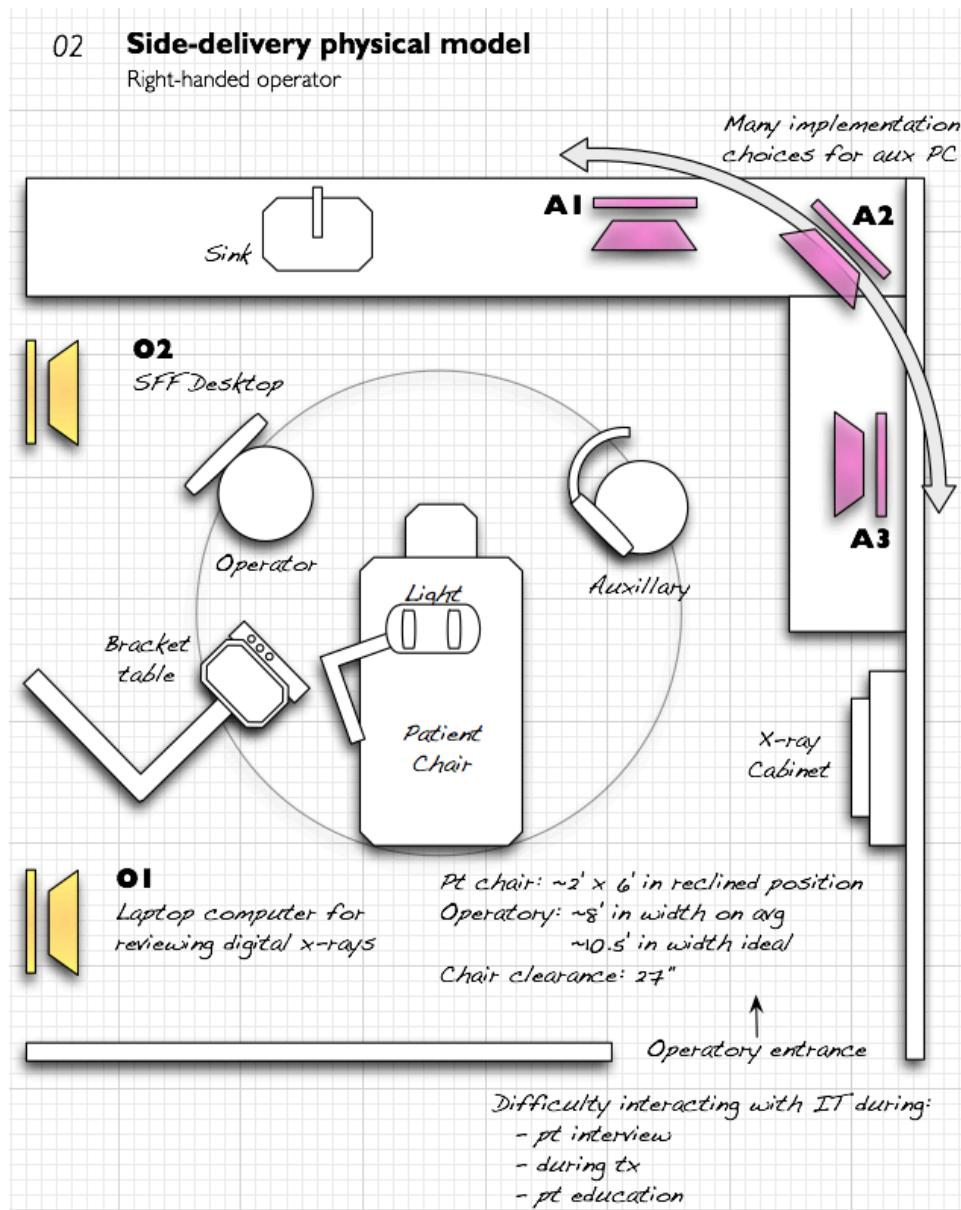


Figure 11: Side-delivery physical model for a right-handed operator.

Appendix C.3 Chair-delivery

03 Chair-delivery physical model

Right-handed operator

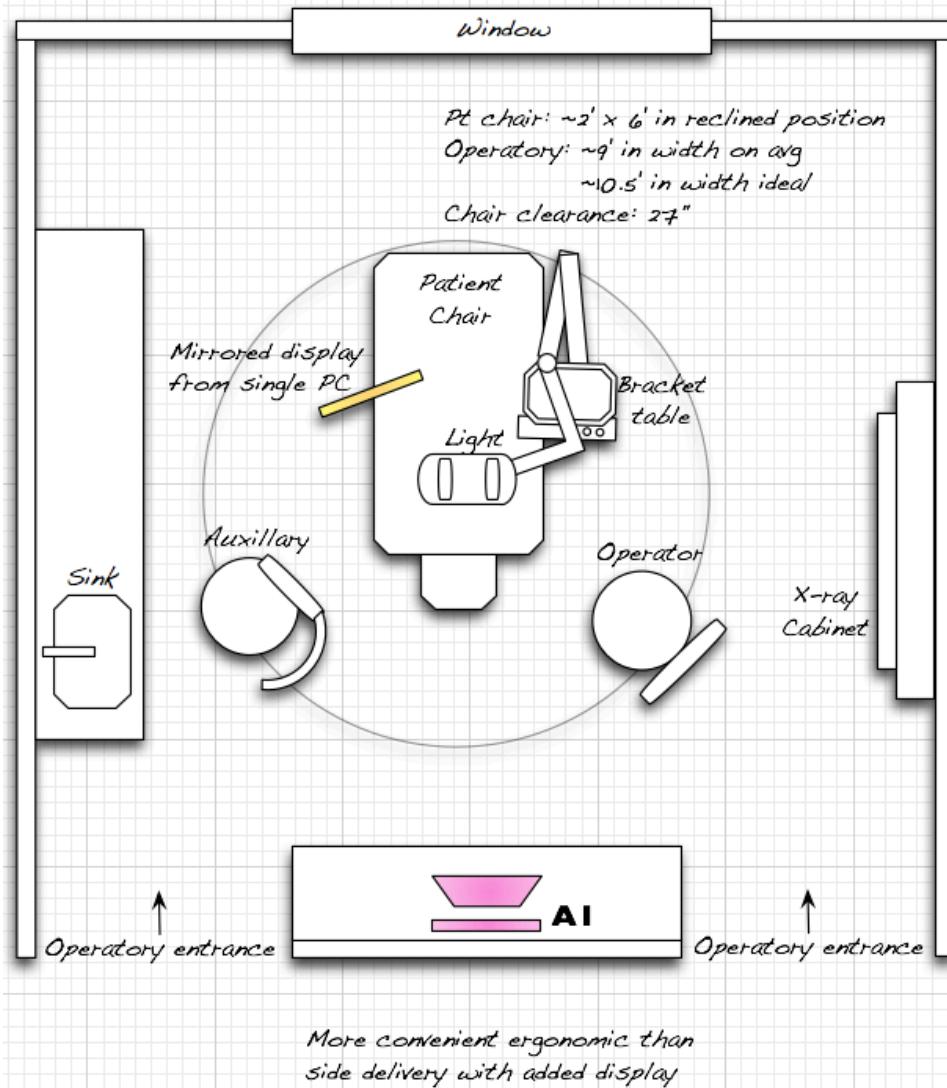


Figure 12: Chair-delivery physical model for a right-handed operator.