COVER STORY

The feasibility of a three-dimensional charting interface for general dentistry

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ABSTRACT

Background. Most current paper- and computer-based formats for patient documentation use a two-dimensional dental chart, a design that originated almost 150 years ago in the United States. No studies have investigated the inclusion of a three-dimensional (3-D) charting interface in a general dental record.

Methods. A multidisciplinary research team with expertise in human-computer interaction, dental informatics and computer science conducted a 14-week project to develop and evaluate a proof of concept for a 3-D dental record. Through several iterations of paper- and computer-based prototypes, the project produced a high-fidelity (hi-fi) prototype that was evaluated by two dentists and two dental students.

Results. The project implemented a prototypical patient record built around a 3-D model of a patient's maxillofacial structures. Novel features include automatic retrieval of images and radiographs; a flexible view of teeth, soft tissue and bone; access to historical patient data through a timeline; and the ability to focus on a single tooth.

Conclusions. Users tests demonstrated acceptance for the basic design of the prototype, but also identified several challenges in developing intuitive, easy-to-use navigation methods and hi-fi representations in a 3-D record.

Clinical Implications. Test participants in this project accepted the preliminary design of a 3-D dental record. Significant further research must be conducted before the concept can be applied and evaluated in clinical practice.

Key Words. Dental informatics; three-dimensional patient records; prototype; user-centered design; evaluation.

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For almost 150 years, the basic method of documenting patient findings and care in general dentistry in the United States has been firmly anchored in two-dimensional (2-D) space. In 1858, Dr. Walter Allport, president of the American Dental Association from 1886 to 1887, "originated the first dental registering ledger with diagrams of the teeth … known as Allport's Registering Dental Ledger"[1] (Figure 1). Today's computer-based dental charts show their provenance in their clear resemblance to this archetype (Figure 2). While we do not know why Dr. Allport designed the dental chart in the way he did, we can see its obvious advantages. It provides a schematic view of the whole dentition that can be assessed with a single glance; findings and procedures are evident from a standard set of notations that use numbers, letters and symbols; and the chart depicts some of the spatial relationships found in a patient's dentition in two dimensions. However, when one considers the reality of the patient's dentition, the chart's disadvantages also are apparent. 2-D charts show only one or more selected projections of the three-dimensional (3-D) situation; they cannot show what is not visible from the outside; and they largely use a one-size-fits-all approach to charting. (For instance, on computer-based charts, all carious lesions are the same size, regardless of the situation in the mouth.)

Given the importance of spatial

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reasoning in medicine in general (M. Keehner, P. Khooshabeh and M. Hegarty, unpublished data, 2007) and dentistry in particular,[2] we decided to investigate how use of a 3-D model for patient records would affect diagnosis and treatment in general dentistry. After all, general dentists face a number of complex 3-D problems on a daily basis, such as determining the extent of carious lesions during restorative care, ascertaining root morphology during endodontic procedures and identifying anatomical structures during surgery. With the exception of casts of the dentition, most general dentists use only 2-D methods, such as charts, photographs and radiographs, to document diagnostic and therapeutic information. Continually having to translate 2-D representations into 3-D and vice versa causes cognitive friction,[3] and it potentially has a negative impact on clinical decision making and treatment. This problem has led to the early recommendation that a 3-D system would more effectively determine the relationship of the dentition to the face for meaningful diagnosis and treatment planning.[4]

In recent years, we have seen the rapid emergence of a variety of clinical software applications that incorporate 3-D imaging. Those applications have been used for diagnosis and treatment planning in orthodontics,[5-9] computer-assisted planning of oral implant surgery,[10] the design and production of fixed restorations,[11] dental education[12,13] and patient education.[14,15] Dentrix Dental Systems (American Fork, Utah) implemented a basic 3-D model in the most recent release of its practice management system, Dentrix G2.[16] Recent technological advances have made it possible to develop such applications in dentistry.[17-20] (Owing to space reasons, we do not elaborate on the details of existing 3-D systems and underlying imaging modalities. Interested readers can find more information on those topics in the literature we have referenced.)

Before attempting to study the larger research question of how a 3-D model would affect general dental care, we decided to investigate the feasibility of a 3-D patient record system. In this study, we constructed a basic prototype for such a system and conducted an early evaluation with representative end users. We were interested primarily in how a 3-D model of the patient's dentition could be integrated with other information in a patient's record, how clinicians could interact with the model and what novel functions could be associated with the 3-D model. Clearly, this study

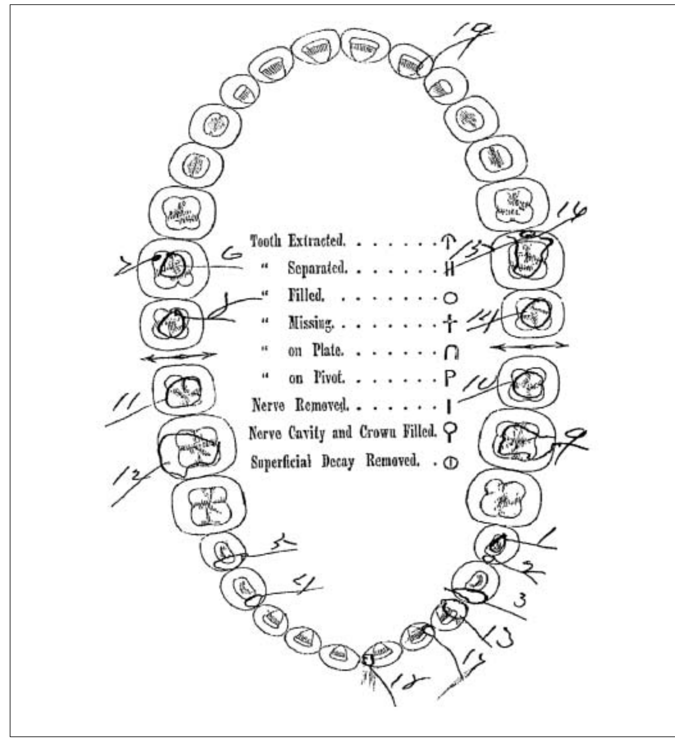

Figure 1. Dental chart developed by Dr. Walter W. Allport, president of the American Dental Association from 1886 to 1887 (reprinted from Allport's Registering Dental Ledger, Philadelphia, The S.S. White Dental Manufacturing Co.; image provided by the American Dental Association Library, Chicago).

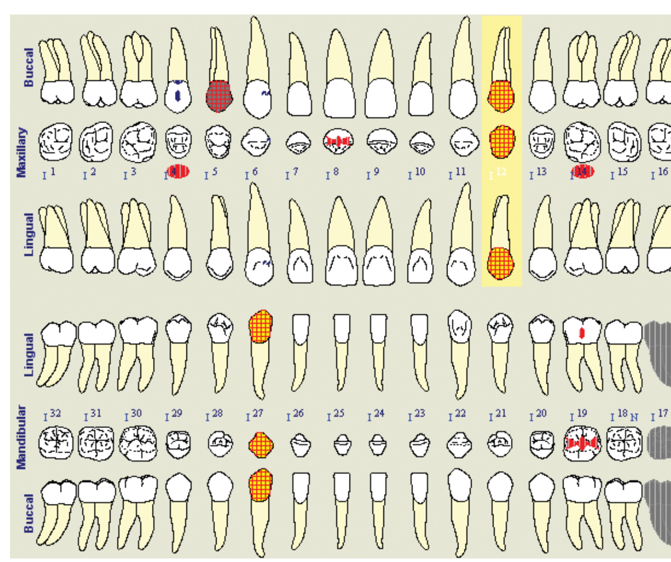

Figure 2. Hard-tissue chart in Patterson Eaglesoft (Patterson Dental Supply, St. Paul, Minn.). Reprinted with permission of Patterson Dental Supply.

ABBREVIATION KEY. 2-D: Two-dimensional. **3-D:** Three-dimensional. **CMU:** Carnegie Mellon University. **HCI:** Human-computer interaction. **Hi-fi:** High-fidelity. **Lo-fi:** Low-fidelity. **PC:** Personal computer.

is only a first step in determining whether 3-D patient records in general dentistry can transcend some of the limitations of today's approach—that is, the paper chart—and thus provide value for clinicians.

MATERIALS, METHODS AND PARTICIPANTS

We used a user-centered design approach (sidebar, "What Is User-Centered Design?", page 1081) to develop the system described in this article. An interdisciplinary team of five undergraduate students in human-computer interaction (HCI), one faculty member and one postdoctoral associate in dental informatics, and one computer science faculty member collaborated on a proof of concept for a 3-D dental record. The students' background included computer science, psychology, design, decision science and information science. We completed the project in 14 weeks as part of an HCI undergraduate project course at Carnegie Mellon University (CMU) in Pittsburgh.

The project extended over five phases: background research, low-fidelity (lo-fi) prototyping and evaluation, high-fidelity (hi-fi) prototyping, user testing and finalization. In answer to the research goals, the team conducted background research with the following aims: understand how dentists and dental auxiliaries use dental records in the clinical context; identify dentists' informational needs for performing clinical tasks; gain insights into the modalities of data entry (who, what, when, how); gain a general understanding of the advantages, disadvantages and potential areas for improvement of paper records and current software packages; and synthesize the findings into a set of design implications for the next phase.

During the background research phase, the CMU students reviewed research papers and the results of recently completed and ongoing evaluation studies of the Center for Dental Informatics at the University of Pittsburgh School of Dental Medicine; examined the functionality and design of several major dental practice management programs and two 3-D applications (Google Earth [Google, Mountain View, Calif.], a mapping application, and SolidWorks [SolidWorks, Concord, Mass.], a 3-D engineering and modeling tool); and conducted observations in four dental offices in the Pittsburgh metropolitan area. (Owing to time constraints and lack of access to programs, we could not include other 3-D applications, such as CEREC [Sirona, Bersheim, Germany], OrthoCAD [Cadent, Carlstadt, N.J.] and Invisalign [Align Technology, Santa Clara, Calif.] in our background research.) The team observed clinicians at work not only to understand the clinical work flow, but also to find "breakdowns"—that is, instances in which technology or other factors created barriers to or inefficiencies in completing clinical tasks. We intended the new design to address these breakdowns, if possible.

After the background research phase, we constrained the scope of the project to increase its feasibility. First, we decided not to implement any data entry functions and instead focused only on information and how it should be displayed. Second, we designed the system to display selected patient information at a limited level of detail. Third, we decided that the prototype would support a limited number of clinical tasks and exclude any administrative functions, such as billing and scheduling. Last, we planned to create a prototype that was refined enough for limited user testing and that would allow us to identify the strengths and weaknesses in our design.

Based on a conceptual design and usage scenarios derived from the background research, we proceeded to develop a series of three lo-fi prototypes on paper. The project team's dental informatics experts (T.K.L.S. and T.P.T.) evaluated and critiqued the first prototype; the second and third prototype were subjected to formal user testing with two and three dentists, respectively. On the basis of the results of the user tests, the research team modified and implemented the third paper prototype as a first version of a hi-fi prototype in Java, Java3-D and JFlashPlayer (all Version 1.5, Sun Microsystems, Santa Clara, Calif.) and Macromedia Flash 8 (Adobe Systems, San Jose, Calif.) on a tablet personal computer (PC) running Windows XP Professional (Microsoft, Redmond, Wash.). The first version of the hi-fi prototype included a stylized, hand-drawn 3-D model of a patient's dentition; intraoral images and radiographs; and selected other clinical information, such as medical alerts, recent progress notes and planned procedures. In the final prototype, we replaced the stylized 3-D model with a high-resolution scan of the maxillofacial portion of a skull.

We recruited two faculty members and two students at the University of Pittsburgh School of Dental Medicine to evaluate the hi-fi prototype.

The participants practiced dentistry three days a week or more and had experience with dental computer systems. Because the objective of the user tests was to evaluate the intuitiveness and understandability of the prototype, we gave the participants no training. We asked them to complete three clinical tasks:

- retrieve clinical information—such as the periodontal status, a hard-tissue–only view of the dentition and radiographs—about the patient;
- identify clinical findings from the data provided;
- diagnose and plan treatment for the condition of tooth no. 12 using the 3-D view.

We conducted the evaluation using a think-aloud protocol, which is part of the standard usability testing methodology.[21] Two observers (M.M. and P.P.) recorded each experiment; in addition, we captured a video of the computer screen and the corresponding audio track using Camtasia Studio Version 2.1.0 (Techsmith, Okemos, Mich.).

The primary objective of the user test was to gather qualitative data about the hi-fi prototype. Since we tested only a proof of concept, we determined that it would be inappropriate to measure more quantitative aspects, such as task completion time and error rate. Rather, qualitative data provided us with a more useful and richer data set, because they showed more clearly the degree to which the users understood the system in the way that the designers intended, as well as which aspects of the system would require additional design work.

The development team finalized the hi-fi prototype by implementing additional changes that were based on the results of the user tests. We did not seek outside evaluation of the final prototype again because the design changes were too limited to warrant the expense and effort of an additional user test. In the Results section, we describe the major findings from the background research and the resulting design goals. Because a full description of all the prototype versions is beyond the scope of this article, we describe only the final prototype to help readers understand its design and function. We highlight differences from previous versions where appropriate, as well as findings from the user tests that led to the final design.

TABLE 1

Selected findings from the background research and the corresponding design requirement(s).

BACKGROUND RESEARCH FINDING	DESIGN REQUIREMENT(S)
Many dentists view computers in the clinical environment as intrusive and inefficient and delegate the interaction with the computer to auxiliary personnel	Provide value-added functions for dentists and dental hygienists to encourage them to use the computer; focus on ease of use and simplicity
Infection control issues impede the clinician's ability to interact with the computer during clinical care	Use a hardware interface that can be disinfected easily
Most practice management applications largely replicate the format of paper records	Provide useful functions on the computer that a paper record cannot support
Many practice management applications are aimed primarily at administration, with clinical functions added on	Center prototype design on clinical functionality
Existing three-dimensional (3-D) software implements easy-to-use methods to interact with 3-D models and environments	Determine which interaction methods could be applied in a 3-D dental record
Clinical care involves a number of relatively standardized tasks, such as getting an overview of the patient's status (from either the paper chart or the dental hygienist) and performing all or part of a clinical examination	Design prototype to support those common tasks

This study was approved by the University of Pittsburgh Institutional Review Board.

RESULTS

In developing the prototype, we were guided by several design goals formulated as a result of our background research (Table 1). Our intent was to take a fresh, unbiased look at the design of computer-based dental records that integrate a 3-D model of the patient's dentition; therefore, the principles are general and address only high-level issues, such as efficiency of computer use and infection control requirements. One key intent of our prototype was to develop a system that was centered on the requirements and needs of dentists and dental hygienists and, thus, was more likely to be used by them routinely than is currently the case.[22]

We implemented the prototype on a tablet PC

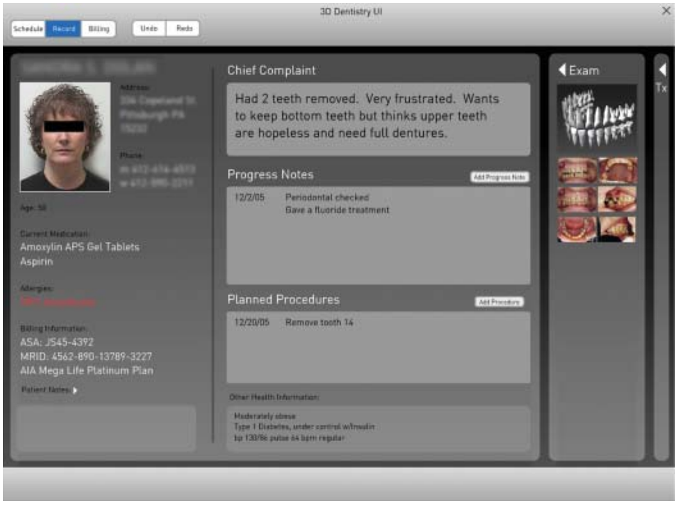

Figure 3. Startup view of the three-dimensional (3-D) dental record prototype. The screen is divided into three panes: patient information summary, clinical examinations and treatment plans. Patient images reprinted with permission of Elsevier from Stefanac and Nesbit.[23] Image of 3-D model published with permission of Brown and Herbranson Imaging, Portola Valley, Calif.

Figure 4. Three-dimensional (3-D) dental record prototype with the Exam pane maximized. The Exam pane shows an actual 3-D model of the patient's dentition and associated radiographs and intraoral photographs. Patient images reprinted with permission of Elsevier from Stefanac and Nesbit.[23] Image of 3-D model published with permission of Brown and Herbranson Imaging, Portola Valley, Calif.

for two reasons. First, we see the tablet PC as a precursor of future computing devices, with high-resolution screens and stylus-/pen-based input that have the physical arrangement or "form factor" of today's clipboard. Those descendants of today's tablet PC will be light, can be carried easily from one operatory to the next (or, more likely, will be available in each operatory) and mimic the paper patient chart in use today.

Second, medical-grade versions of the tablet PC can be disinfected and thus are suitable for the dental operatory environment. However, users also can interact with the prototype using a standard desktop computer with a keyboard and mouse.

Integration of the 3-D model with existing patient information. Figure 3 shows the main screen of our final prototype (featuring a case described in Stefanac and Nesbit[23]). It uses a three-pane design that provides access to the patient information summary, data from clinical examinations and treatment plans. (The Treatment Plan pane, intended for viewing and entering treatment plans, was outside the scope of implementation of the prototype and is not discussed further in this article.) On startup, the application displays the Patient Information Summary. The goal of this view is to provide the clinician with an overview of the patient's status. The left portion of the screen displays the patient's picture and general information, such as current medications and medical alerts. Personal notes at the bottom can be hidden from the patient. The center of the screen shows additional clinical information, such as the chief complaint, progress notes, planned procedures and medical conditions.

To display clinical examination data, the user clicks on the Exam pane. This action shrinks the size of the Patient Information Summary pane and reduces the amount of information it displays to provide some context for the clinical information displayed in the now expanded Exam pane. Figure 4 shows this view, which is dominated by a 3-D model of the patient's dentition and associated radiographs and intraoral photographs.

Interaction with the 3-D model. The controls on top and to the left of the 3-D model help the user navigate and annotate the 3-D model. The rightmost six controls at the top activate views of the dentition that correspond to standard views in clinical photography. The slider on the left zooms the 3-D model in and out; the user can rotate the model by clicking and dragging it. During the user tests, participants showed interest in the ability to interact with the 3-D model. One participant commented how useful it was to be able to view the dentition from any angle and to be able to zoom in and out at will.

The users interacted with the prototype, including the 3-D model, by means of a stylus. The stylus allows the screen design to be more

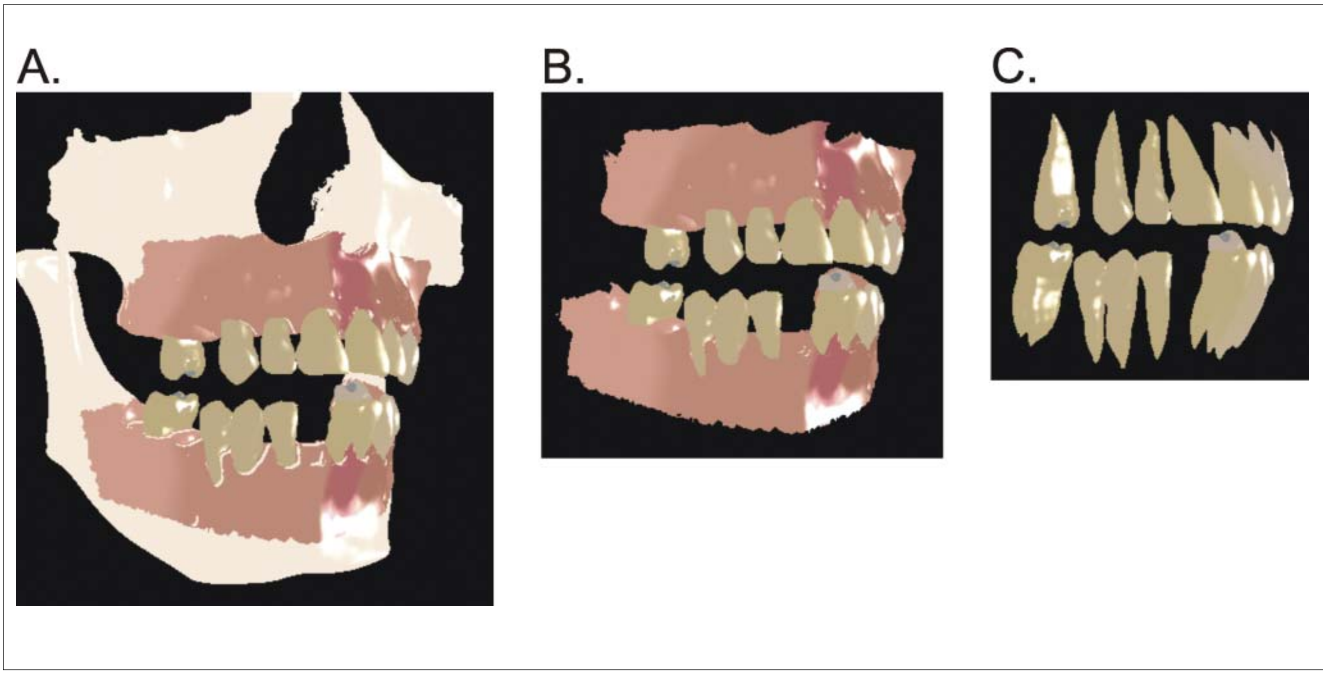

Figure 5. Selected views of the dentition in the three-dimensional (3-D) model. **A.** Bone, soft tissue and teeth. **B.** Soft tissue and teeth. **C.** Teeth. Image of 3-D model published with permission of Brown and Herbranson Imaging, Portola Valley, Calif.

detailed and dense, since it has a greater precision in pointing than does the finger one typically uses with a touch screen. In addition, a stylus resembles many of the hand instruments used during clinical care and, thus, does not require the clinician to use different psychomotor functions when using the computer.

Clinically relevant functions associated with the 3-D model. The Exam Pane implements four navigation and display functions, several of which are driven by interacting directly with the 3-D model.

Automatic image/radiograph retrieval. Most practice management systems require an explicit user action to retrieve clinical images or radiographs associated with an area of interest. For instance, the user typically selects the image of a particular tooth to display one or more corresponding radiographs. Our prototype eliminates this inefficiency by automatically displaying the corresponding radiographs and clinical images when the user rotates the 3-D model. For instance, when the user looks at the frontal view of the model, the software displays radiographs that show all or a portion of the anterior sextant. Similarly, rotating the model to the right displays the images and radiographs for the right sextants.

Flexible teeth, soft tissue and bone view. The user can display the patient's teeth, soft tissue and bone individually or in any combination (Figure 5 shows sample views). For instance, endodontists can examine a tooth's root morphology in detail, and periodontists can do the same with alveolar bone. In addition, the user can display completed and planned procedures.

Access to historical patient data through a timeline. A Patient Timeline control (lower right portion of Figure 4) allows the clinician to move through clinical examinations in chronological fashion. Moving the slider to the left (into the past) displays the patient's status at selected times, so that the clinician easily can review when certain events occurred. When the user releases the slider, it automatically returns to the current date so that outdated information does not appear on the screen inadvertently.

Focus on a single tooth. By right-clicking on a tooth in the 3-D model, the user can bring the particular tooth into focus. In our prototype, the model is repositioned to display the selected tooth in the center of the screen, and the other structures become transparent. Additionally, the tooth becomes the center point for the model's rotation. An enhanced prototype we are planning will display data pertaining to the particular tooth.

The prototype implements additional functions, such as maximizing clinical images and dis-

TABLE 2

Result of the user tests with the almost-final prototype.*

TASK (DIFFICULTY)	OUTCOME†			
	User 1	User 2	User 3	User 4
1. Obtain Selected Patient Information (Easy)	**○**	**○**	**○**	**○**
Patient name	●	●	●	●
Periodontal status	○	○	○	○
Clinical examination	○	○	○	○
Warnings about the patient	●	○	●	○
Personal information	●	○	●	○
Radiographs	●	○	○	●
2. Obtain Additional Clinical Findings (Medium)	●	●	●	●
3. Select Tooth No. 12 and Determine Any Necessary Treatment (Hard)	○	○	○	○

* Participants were asked to complete two information retrieval tasks (1 and 2) and one information retrieval/decision-making task (3).
† Task outcome: ● = successful completion; **○** = partial completion; ○ = failure to complete.

playing a 2-D intraoral chart. However, owing to space constraints, we will not describe these features in this article.

Selected results from user tests. Table 2 shows the results of the user tests with the almost-final prototype, which resembled the system described above very closely. (We describe relevant differences in the text below.) Although all users retrieved at least one selected patient information item in task 1, their success in doing so varied. No test participant was successful in retrieving all information items. All test participants successfully completed task 2, obtaining additional clinical findings. None of the participants completed the diagnosis and treatment plan called for in task 3.

The usability tests identified several problems with our interface. The version we tested required the user to click on a “zoom” button that activated zooming, and then to click and drag the 3-D model to zoom in and out. Rotation functioned in a similar fashion, by means of a “rotate” button. Users had difficulty with this design, and, as a result, we implemented the slider for zooming (described above) and allowed the user to rotate the model simply by clicking and dragging it. Three of four users were confused by the concept of centering and rotating the 3-D model around a selected tooth. At the time, the prototype did not make the structures surrounding the selected tooth transparent, which was the most likely cause of this confusion. We implemented transparency of surrounding structures in the final version. Users also complained about the 3-D model’s lack of realism, because the first hi-fi prototype rendered the teeth and soft tissues in a stylized fashion. This lack of realism prevented our users from completing task 3, and it made performing task 2 more difficult than necessary. Therefore, in the final version we implemented a complete, high-resolution model of the maxilla and mandible, including bone, scanned from a dry skull. We also modified the 3-D model to approximate the findings on the clinical photographs and radiographs of the test patient. Users made several suggestions that we incorporated into the final prototype, such as using miniature radiographs and images instead of abstract icons to label some buttons, adding more standardized views of the 3-D model (such as occlusal views of each arch) and increasing the size of the 3-D model.

During the tests, several users commented on the value of selected features of the program, such as the automatic display of corresponding clinical photographs and radiographs when the 3-D model was manipulated, the ability to view the patient’s dentition from any angle and the easy access to historical clinical data. Users also said they appreciated the exclusively clinical focus of our application.

DISCUSSION

In this research project, we developed a prototype of a 3-D computer-based dental record for general dentistry and conducted an initial evaluation of it with dentists and dental students. While the prototype included only limited functionality, our evaluation demonstrated that the test participants conceptually understood and welcomed the program's addition of a 3-D model of the patient's dentition and the associated features. The user tests showed that participants were able to complete several information retrieval tasks relatively easily, but the test results also highlighted the challenges of designing a powerful and easy-to-use 3-D dental record. While our approach to designing the interaction with the 3-D model seemed appropriate for the users, we identified several usability issues that we addressed in the final prototype. The major problems that users found centered on aspects of interacting with the 3-D model, the insufficient realism of the earlier 3-D model of the dentition and the lack of intuitiveness of novel features, such as selecting a tooth on the 3-D model.

The development and evaluation of the prototype were subject to several limitations. Since the design of computer-based dental records is a large and complex undertaking, we limited the scope of this project significantly to produce a workable prototype within our resource constraints. We did not design a detailed interface for many important clinical information categories, such as the medical history, progress notes and treatment plans. As evidenced by current practice management systems, the multitude of data types and program functions, as well as the volume of data, create difficult and challenging design problems that are not overcome easily.[24] The lack of refinement of the 3-D model clearly affected the sense of realism that test participants experienced and made it impossible for them to complete higher-order clinical tasks. An evaluation with a larger set of representative end users most likely would have resulted in a richer understanding of strengths and weaknesses of the user interface and produced more design suggestions. While Nielsen and Landauer[25] considered between three and five users to be typically sufficient to identify more than 60 percent of the usability problems in a system, Shneiderman and Plaisant[26] pointed out that this low range is controversial. Since the primary purpose of this study was to establish the feasibility of a 3-D record system and not strictly to validate our particular design, we considered the number of test participants to be adequate. A relatively small team of core developers (five people) and a constrained project time frame (14 weeks) limited our ability to refine this project further.

Our prototype opens a wide perspective for further research. First, additional development should make the feature set more robust. For instance, while our prototype implemented one approach to interacting with a 3-D model (several standard views combined with the ability to rotate and zoom freely), other alternatives are possible. In addition, further studies should determine which degree of realism of the 3-D model (for instance, with respect to resolution, coloring and shading) is necessary to support diagnostic and therapeutic decision making. Finally, a more mature system should be compared with existing practice management software on a number of performance parameters, such as learnability, ease of use and error rate.

CONCLUSION

Users who tested our prototype of a 3-D charting interface for a general dental record accepted the prototype's basic design, but they also identified several challenges in developing intuitive, easy-to-use navigation methods and hi-fi representations in a 3-D record. Significant further research must be conducted before the concept can be applied and evaluated in clinical practice. ■

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Readers interested in the National Center for Research Resources (NCRR) project Re-engineering the Clinical Research Enterprise can find information on the World Wide Web at "http://nihroadmap. nih.gov/ clinicalresearch/overview-translational.asp".

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What is user-centered design?

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User-centered design (UCD) is an approach to designing computer systems and software applications that focuses on the user's needs, wants and abilities as central elements of the design process. UCD does not assume that technologists and developers "know better," but that users implicitly can guide a design process toward a product that is intuitive, easy to use and useful.[1,2] Developers can harness the powerful, but often unarticulated, insights of their target users with a few simple strategies: watch users work in their daily environment, involve users early and often in the design process and learn from the interaction of users with prototypes and other design artifacts.

The philosophy of UCD was born of the realization that traditional design processes often lead to less-than-optimal results. The remote control has become the archetype for the result of such design processes: hard to use, complex and intimidating.[3] Despite the thousands of engineering hours spent on the development of most remote controls, many of these devices make it difficult and frustrating for most users to perform very basic and simple tasks. UCD emerged as a reaction to this kind of technology- and feature-driven design, focusing instead on the actual needs of the people who will use a system.

> **The philosophy of user-centered design was born of the realization that traditional design processes often lead to less-than-optimal results.**

UCD developers try to optimize the user interface around how people can, want or need to work. Doing so requires a deep understanding of the work practice, terminology and organization of the people who will be using the system, as well as getting feedback from users while the product is being refined, rather than when the product is "finished" and it is too late to incorporate major changes. To achieve this goal, a UCD team must have expertise in multiple fields, such as human-computer interaction, design, information science and computer science.

THE PHASES OF USER-CENTERED DESIGN

A UCD project typically involves five phases:
- analysis of users' needs;
- creation of a conceptual design;
- creation of a detailed interface design, a low-fidelity (lo-fi) prototype;
- design of a high-fidelity (hi-fi) prototype;
- implementation.[4]

We describe these phases briefly below.

Analysis of user needs/requirements. The user-needs analysis helps the team understand how the users work, what their needs are and how technology could help fulfill those needs. In addition, the team establishes goals for usability in this phase. During the user-needs analysis phase, the team uses methods such as contextual inquiry; user profiling and task analysis; and surveys, interviews and focus groups. During contextual inquiry, team members observe users in their normal work environment to gain an understanding of who performs which tasks, what detailed series of steps make up each task, and where users encounter barriers and/or problems in carrying out tasks efficiently and effectively. During user profiling and task analysis, team members document the users' work flow and break it down into separate tasks, and they conduct surveys, interviews and focus groups to gain general insights into the user's domain or work.

ABBREVIATION KEY. Hi-fi: High-fidelity. **Low-fi:** Low-fidelity. **UCD:** User-centered design.

Creation of conceptual design. During conceptual design, the team members develop a high-level concept of how a new system could support users in doing their jobs. During this phase, team members create "personae," prototypical users of the proposed system who behave as would real users (for instance, "Dan, periodontist with little computer experience beyond sending e-mail"). The developers create storyboards or paper sketches of the application to support typical tasks that the personae might want to perform. Representative users then evaluate those designs and sketches.

Creation of detailed interface design. The team then develops detailed interface designs, which are lo-fi prototypes, on the basis of the results of the conceptual design. In this phase, the team creates initial drafts of the user interface design on paper. Paper prototypes are useful at this stage, because, as compared with programming, they are relatively inexpensive and require little effort for modification. The design team tests these prototypes with users in their workplace or in a laboratory, simulating the tasks the users would perform using the proposed system. In our project,[5] we used several paper prototypes that we could redesign on the fly (by moving user interface components printed on removable adhesive notes). In this manner, we were able to make immediate adjustments if a user test uncovered a problem.

Design of a hi-fi prototype. Using the results of developing the lo-fi prototype, the team designs a hi-fi prototype. This prototype has relatively comprehensive functionality and is fully interactive. While the lo-fi prototype primarily focuses on the layout and visuals of an interface, the hi-fi prototype adds the navigation and flow.[4] Again, the team conducts usability evaluations during this stage and makes appropriate modifications to finalize the interface and interaction design.

Implementation. The implementation phase (which our project[5] did not include) begins once the team finalizes the interface design through iterative usability evaluations. In this phase, usability tests with actual users serve as a check of whether the usability goals established in the user-needs analysis phase have been achieved. In addition, the team obtains qualitative feedback from the users via surveys and interviews.

CONCLUSION

User-centered design is a method that has been shown to produce more useful and usable systems than other approaches.[1] As a result, the methodology is becoming widely used in design and development projects. ■

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