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ABSTRACT

This paper describes RaPiD, a computer-aided assistant for the design of dental prostheses called removable partial dentures. The user manipulates icons directly to indicate the desired design solution to a given clinical situation. A developing design is represented as a logic database of components in a design; expert rules are applied as integrity constraints governing valid database transactions/design alterations. RaPiD has two modes of operation: manual mode designed for educational use (at either "student" or "expert" level), and automatic, which is intended for dentists in practice. In automatic mode, the dentist enters key clinical information, after which the system takes over and completes the design. Contravention of design rules is presented to the user in a critiquing style. The critiquing style strategies form the basis for the system's use in undergraduate and graduate dental education. Critiquing strategies used include: (1) a critique is issued only when the user has completed the proposed alteration; (2) a critique is issued immediately upon the user's radical misuse of a tool; (3) critiquing dynamically without negotiation with the user; (4) critiquing requested by the user upon completion of a design session, or at certain other stages in the design process; and (5) optional critiquing, requested by the user who wishes to compare his design with that which would have been produced independently by the system. An assessment of the educational effectiveness is planned. Expanding the range of design rules in RaPiD so that it becomes comprehensive is a current priority, as is the introduction of critiquing strategies (4) and (5), as well as completion of the automatic mode of operation. The extensive use and testing of RaPID, already carried out, show it to be a versatile and robust knowledge-based system. (Contains 14 references.) (Author/MAS)

Critiquing the computer-aided design of dental prostheses

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Abstract: This paper describes RaPiD, an assistant for the design of dental prostheses called removable partial dentures. The user manipulates icons directly to indicate the desired design solution to a given clinical situation. A developing design is represented as a logic database of components in a design; expert rules are applied as integrity constraints governing valid database transactions/design alterations. Contravention of design rules is presented to the user in a critiquing style. The critiquing strategies form the basis for the system's use in undergraduate and graduate dental education.

The education of dental undergraduates includes instruction in the principles of the design of dental prostheses. The design process is a complex and difficult task, and the time available in the dental curriculum to impart the required knowledge is limited. If students were to have open access to a knowledge-based system for the design of prostheses, there could be important educational benefits. Such a system, RaPiD (*R*emovable *P*artial *D*enture design using *a*rtificial *i*ntelligence), is now being developed by specialists in prosthetic dentistry and knowledge-based systems. RaPiD is usable both as a prescription system for dental practitioners and as a teaching system which can be configured for undergraduate and postgraduate use. RaPiD as a prescription system has already been described in the dental and AI literature (Hammond et al, 1993a and 1993b); this paper concentrates on its educational use, in particular on its critiquing strategies which guide a user through a design.

1. Removable partial dentures

A removable partial denture (RPD) is a denture provided for a patient who has some natural teeth remaining. It enables its wearer to chew food effectively, assists speech and helps to stabilise the remaining natural teeth; it may also enhance the patient's appearance. An RPD comprises up to 40 components, the most important of which are as follows. The *saddles* carry the artificial teeth and fit over the area of the gum from which natural teeth are missing. *Rests* are metal extensions which transmit biting forces from saddles to the adjacent natural teeth. *Clasps* are flexible metal clips which grip natural teeth, making a denture secure during function. Finally, a *major connector* is a rigid metal bar or plate which unites the other components into a single prosthesis.

2. The motivation for the development of RaPiD

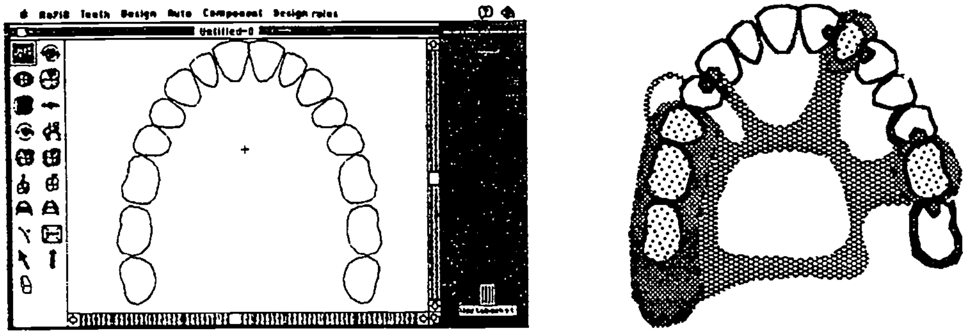
Designing a satisfactory RPD requires clinical training and experience. The dentist should carry out a detailed assessment of the patient and of models of the patient's teeth and then draw a design to be sent to a dental technician as a prescription for the manufacture of the denture. However, general dental practitioners commonly delegate responsibility for design to technicians, whose training is inadequate to assess the clinical factors in a case. The resulting denture may fit poorly, and may even pose a threat to the patient's remaining natural teeth. The reasons for this delegation of responsibility are not entirely clear, although limited design experience may be crucial (Basker et al, 1978 and 1991). One factor which motivated the development of RaPiD was the desire to build an educational tool that could enhance the training of dental students and practitioners. A general dental practitioner in the UK designs, on average, one RPD a month, while in dental schools students may have to produce only five or six RPD designs for patients throughout their undergraduate study (Holt et al, 1993). It is doubtful whether this frequency is sufficient to ensure adequate familiarity with good design principles, whether by students or by graduate dentists. Clearly a knowledge-based system which uses a graphical interface allowing the creation of new designs and alteration of existing ones, which incorporates all the principles governing correct design of RPDs and can detect and critique attempts to violate them, could be a powerful educational tool. The evidence is, then, that a system such as RaPiD will meet a genuine and pressing need.

3. Levels of operation of the system

RaPiD has two modes of operation, manual and automatic. The manual mode is designed for educational use while the automatic version is intended for dentists in practice. The manual version can be run at two levels of difficulty, "student" and "expert". In "student" mode a user who infringes a design rule is informed of the infringement immediately so that the system controls the user's progression through the design sequence towards an optimal solution. In "expert" mode the designer has a free hand: the design is developed by the user without any interference from the system and without any design infringements being signalled. However, on completion of the design the result is appraised by RaPiD, rules that have been broken are listed and alternative solutions displayed. In automatic mode the dentist enters key clinical information, after which the system takes over and completes the design. In all modes, editing of the final design is possible, and a graphical and textual summary of the result can be printed, as a record for the student, for evaluation, or as an instruction to a technician.

4. Designing with RaPiD

Software development has taken place on Macintosh computers, using an implementation of Prolog, MacProlog (Logic Programming Associates, Ltd, London), which provides powerful object-orientated graphics. A prominent feature of RaPiD is its graphical interface which utilises the window-based environment standard in Macintosh applications. Figure 1(a) depicts a design window at the beginning of a design session, with a palette of tools at the left and the design area, containing a dental arch, in the remainder of the window.



(a) Initial screen showing palette of tools (left) and design window with upper arch of teeth.

(b) A completed design for an upper arch.

Figure 1

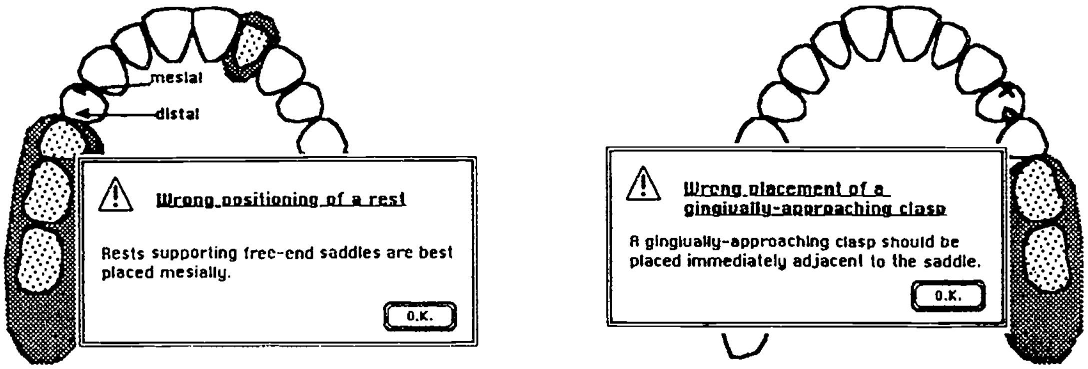
A user begins a design by selecting the "forceps" tool ( ) and then clicking once on teeth icons to be made artificial, whereupon they become shaded. A double-click removes a tooth icon entirely when a tooth is to be missing and not replaced by an artificial tooth. The saddle-placement tool ( ) creates a saddle around the artificial teeth; another tool ( ) places rests on teeth for support of saddles. There are tools also for placing different types of clasps on retaining teeth. The major connector which joins all the components of a denture has to be drawn by the user, employing a mouse. Other tools include one for giving information about individual components, and an editing tool for changing the shape of components. A design can be printed, together with a written summary, for sending to a dental technician for manufacture. Figure 1(b) shows a completed design.

5. The use of critiquing

The student of RPD design needs to be made aware of any design errors immediately and to be challenged to modify the design correctly. RaPiD achieves this through a range of critiquing strategies which alert the user to an error, efficiently but as unobtrusively as possible. Three examples will illustrate the use of critiquing.

(i) *Placing rests on supporting teeth.* A saddle which is bounded at both ends by healthy natural teeth is supported by rests placed on the neighbouring teeth. However, with a free-end saddle, one bounded at only one end by natural teeth, this is impossible. Should the one supporting rest be placed on the neighbouring tooth mesially (at the end closer to the front of the mouth) or distally (towards the back)? Prosthetic specialists favour

mesial placement. An attempt to place a rest distally therefore fails and a critiquing message is presented, specifying what is wrong with the proposed alteration and advising correction (Fig. 2(a)). As with other rules, if exceptional clinical circumstances make the rule inappropriate, it can be overridden by means of a function key.
(ii) *Placing a gingivally-approaching clasps.* A gingivally-approaching clasp is a type of clasp which reaches the undercut region of a tooth by passing from the saddle via the gingiva or gum. It is placed by drawing a line connecting the undercut on the gum area of a tooth with a point on the saddle to be clasped. (In Figure 1(b) there is a gingivally-approaching clasp connecting the saddle which carries three artificial teeth with its neighbouring natural tooth.) The clasp which retains a saddle should be placed on the tooth adjoining the saddle. So if a user attempts to draw a clasp starting from any tooth which does not neighbour a saddle, the alteration immediately fails. An error message directs the user to place the clasp on a neighbouring tooth (Figure 2(b)).



(a) Incorrect placement of a rest: the user has attempted to place a rest distally; it should be placed mesially. (Mesial and distal locations not marked in actual design.)

(b) Incorrect placement of a gingivally-approaching clasp: the user has attempted to draw the path of the clasp starting from a tooth (marked with "X") which does not neighbour a saddle.

Figure 2 Critiquing messages

(iii) *Drawing a major connector.* A major connector should be added to a design only if all saddles are adequately supported by rests. In RaPiD, once the user has selected the connector-drawing tool and clicked on a point within a dental arch to commence drawing a connector, a check is made of all the saddles in the arch. If any saddle is inadequately supported, the user is immediately informed, and is required to remedy the deficient support.

Example (i) above follows a somewhat different pattern from (ii) and (iii). In (i), the user indicates a chosen point for placing a rest, and the design check comes into operation. In examples (ii) and (iii), on the other hand, the user's action is more complex and amounts to the completion of a process: in (ii) this is the drawing of a line linking the end-points of a gingivally-approaching clasp, in (iii) the drawing of the outline of a connector. In both (ii) and (iii) a user, having selected a tool, may immediately misuse it in such a way that it would be pointless to continue. RaPiD's intervention does not, then, have to wait for the user to complete the alteration: rather, the operation fails and a critique is issued straight away.

The two types of critiquing strategy considered so far are, then:
(1) *A critique is issued only when the user has completed the proposed alteration*; and
(2) *A critique is issued immediately upon the user's radical misuse of a tool.*
Three additional modes of critiquing can be usefully employed:
(3) *Critiquing dynamically without negotiation with the user.* This amounts to correcting the user's action automatically and dynamically. The user is not given any choice in the matter, nor informed that the attempted modification is being continuously corrected --- although this fact will be obvious from what happens (or fails to happen) in the graphic window. An example concerns the representation in RaPiD of a tooth's drifting along a dental arch following extraction of a neighbouring tooth. There is a tooth-drifting tool which can be employed to drag the icon of a tooth to a new location. But the tooth is movable only along the line of the arch of teeth.
(4) *Critiquing requested by the user upon completion of a design session, or at certain other stages in the design process.* Certain design rules, concerned with the overall balance of a design, are applicable only at the end of a design session, or at any rate when the user has finished placing all the major components of a denture. There are, for instance, rules determining whether a design ensures the retention of a denture during function. These rules involve some complicated geometrical reasoning, centred on the relation of the denture's axis of rotation to

the retaining elements. RaPiD will apply these rules only when the user has developed the design sufficiently.
(5) *Optional critiquing, requested by the user who wishes to compare his design with that which would have been produced independently by the system.* A user may complete a design without contravening any design rule, but it is unlikely that the design will be *identical* to that which the system would produce if operating in automatic mode. The user may, therefore, wish to compare his own design with one produced automatically. The sort of optional critiquing suggested here amounts to listing differences between the two designs. The user's design can then be brought into line with that of RaPiD, if desired. (The fourth and fifth critiquing strategies have yet to be incorporated in the system; their addition will follow development of the automatic mode.)

Some examples of the different types of critiquing strategy are set out in Table 1 below. Note that the nature of a critique varies according to the type of error committed. Sometimes the fact that a mistake has been made will be so clear to the user that a simple beep will suffice. At other times a detailed message is necessary. When the third critiquing strategy (automatic, dynamic correction) is being followed, this will be obvious simply from the fact that what the user is trying to bring about fails to tally with what actually happens.

Alteration to design	*Constraint to be applied*	*Critiquing strategy*	*Nature of critique*
Placing rest on tooth	1. Rest is in correct mesial/distal position	1	Detailed message.
	2. Tooth must not already carry a rest in the same position.	1	Beep.
Moving tooth to new position	3. Tooth may be moved only to a point on the arch.	3	No message; correction is automatic and continuous.
Drawing a major connector	4. All saddles in arch are properly supported.	2	Detailed message.
	5. Connector does not cover "forbidden" areas (tongue in lower arch, soft palate in upper).	1	Detailed message.
Testing quality of design so far	6. All design rules appropriate for stage reached are adhered to.	4 and/or 5	Detailed message (or sequence of messages).
Positioning a clasp	7. Tooth is natural.	1	Beep.

Table 1 Some examples of the different kinds of critiquing strategies.

6. The design representation employed in RaPiD

Following a recognised convention, a tooth is identified in terms of the quadrant to which it belongs (quadrants 1 and 2 constituting the upper arch of teeth and quadrants 3 and 4 constituting the lower), and its number (in the range 1-8) within its quadrant. A given tooth may have the status *natural* or *artificial* or *missing*. In RaPiD, the components of a design are represented as a logic database, and the statuses of teeth, in particular, are represented by facts of the general form "tooth_in_db(tooth(Quadrant,Number),Tooth,Status)" --- where the variable *Tooth* is instantiated by the name of the graphical object representing a tooth. For example:

```
tooth_in_db(tooth(1,8),tooth_18,missing)).
tooth_in_db(tooth(1,7),tooth_17,artificial)).
```

The existence of components is represented in the database by facts such as "rest_in_db(rest1)", "saddle_in_db(saddle1,[tooth(1,5),tooth(1,6)])", "connector_in_db(upper,connector2,multibar,metal)". These facts state, respectively, that rest1 is a rest, that saddle1 is a saddle carrying artificial teeth 5 and 6 in quadrant 1, and that connector2 is a metal multi-bar connector in the upper arch. There are also facts recording the relationships of components to one another: for example, "clasp_retains_saddle(clasp1,saddle3)".

A user's manipulation of the iconic representation of a design is interpreted as an alteration or update of the design database. If, for example, the incisor tooth (1,1) is to be represented as artificial, the fact "tooth_in_db(tooth(1,1),tooth_11,natural)" is removed from the database and is replaced by the fact "tooth_in_db(tooth(1,1),tooth_11,artificial)". Other design alterations present a more complex picture. If, for instance, a user attempts to place a rest on a tooth, the system surveys the state of the database and determines whether a rest in that position would have the function of supporting a saddle, or some other function such as ensuring the overall stability of the denture. In either case a fact of the form "rest_on_tooth_in_db(Rest,Tooth)" will be added to the database, whereas in the first case only, an additional fact of the form "rest_supports_saddle_in_db(Rest,Tooth,Saddle)" will also be added.

A RaPiD design is in the form of a deductive database and can be thought of as a set of clauses comprising both the facts relating to a given case and the design rules applicable to any case. Facts about the individual case are always atoms, while rules are expressed as extended Horn clauses (Kowalski, 1979), of the form

$$A \leftarrow W$$

where A is an atom and W is any expression (atomic, negative or conjunctive) of first-order logic. We could, for example, express as follows the rule that a rest supporting a free-end saddle should be placed on a tooth mesially:

```
rest_on_tooth(Rest,Tooth,mesial) ←
    saddle_in_db(Saddle,Artificial_teeth_on_saddle),
    tooth_associated_with_saddle(Tooth,Artificial_teeth_on_saddle),
    type_of_saddle(Saddle,Artificial_teeth_on_saddle,free_end).
```

This deductive-database approach provides (1) a clear, unambiguous description of the components in a design and of their relationship to one another, (2) improved modularity for grouping design rules, and (3) a logically sound procedure for checking database updates. (For general theoretical accounts of the nature of a deductive database, see Sergot, 1991 and Das, 1992.) To test whether a design modification is acceptable, we check the proposed change against the design rules, expressed as integrity constraints, conditions which the database is required to satisfy. Many of the integrity constraints used in RaPiD are dynamic, that is, constraints governing the transition from one state of the database to another during an attempted update. As such they are applied as *preconditions* for allowing a proposed modification to succeed. If an attempted modification satisfies all its preconditions, it is accepted and the database is updated. If the input fails to satisfy even one of its preconditions it is rejected and the database remains as it was. For instance, it is a precondition for placing a rest on a tooth that the tooth is a natural one; it is a precondition of placing a saddle on an edentulous area that that area is not already covered by a saddle. Given a full range of *precondition* clauses, encompassing all the various types of input, we rely on a procedure *assimilate* in the style of Kowalski and Sergot (Kowalski, 1979; Sergot, 1991) to handle the incorporation of attempted alterations. If the preconditions for an alteration are satisfied, an *update* procedure is used to incorporate the alteration in the database; if one of the preconditions is not satisfied, the alteration will not succeed and the nature of the failed precondition will determine whether a message should be presented to the user, or whether there should be some other response such as a beep.

7. Evaluation of the system

RaPiD's user-interface and its graphical capabilities have been extensively tested by the project team and also evaluated by a consultant dental prosthetist, a panel of dental practitioners and a number of dental technicians. Their comments have been recorded and relevant improvements incorporated into the software. This process of evaluation by users of RaPiD as a graphical tool is continuing and will recruit teachers and students in other UK dental schools and postgraduate centres. In addition, an assessment of the graphical quality of the designs produced by RaPiD has been completed. A series of designs produced manually by students under staff supervision was obtained. Each design was reproduced using RaPiD, and both versions were returned together with a questionnaire to the originating dental staff for comparative assessment. The results for the RaPiD versions of the design were highly favourable (Hammond et al, 1993b).

The design rules which are being incorporated into RaPiD are based, not on local preference, but on an extensive survey (now complete) of the literature. A detailed questionnaire has also been circulated to prosthetic specialists at all UK dental schools, aimed at gauging levels of acceptance of various design rules. The responses to this questionnaire of 10 specialists at the School of Dentistry in Birmingham have been recorded and analysed. The questionnaire is to be distributed to co-operating schools abroad.

An assessment of the educational effectiveness of RaPiD is planned, and will be undertaken in two stages:

(a) A project, undertaken in co-operation with the Faculty of Education, University of Birmingham, to measure any improvement in students' grasp of the design rules, and their ability to design a denture in accordance with the rules, resulting from the use of RaPiD. The project involves working with two groups of students in the Dental School who have completed their basic course in RPD design. One group will use a version ("expert" mode) of RaPiD in which the design rules are not applied to restrict users' actions in any way, although their achievement will be recorded through an error log of design rules contravened during the design process and by a design quality index of the finished design: the latter index is a measure of the compliance of the finished design with the established design rules. The other group will use RaPiD in "student" mode with design rules operative so that students are guided to an optimal solution; again an error log and quality design index will be obtained.

(b) 100 consecutive hand-drawn RPD designs for patients, produced by students without RaPiD's assistance, have been collected. The compliance of these designs with the design rules is to be measured to produce a design quality index. The full "student" version of the system, once it has been completed, will be used to produce all designs by students. A post-RaPiD design quality index will then be obtained and compared with the pre-RaPiD index to indicate the level of improvement within the school as a whole achieved by introducing the system.

8. Related work

Systems for RPD design have been described by Maeda et al. (1985 and 1987) Wicks and Pennell (1990) and Beaumont (Beaumont & Bianco, 1989; Beaumont, 1989). For some critical remarks about these systems, see Hammond et al, 1993b. The *Kontest* system (Jakstat et al, 1991) is concerned with undergraduate education; its effectiveness is, however, restricted because much data must at present be input at the keyboard. It has not been possible to appraise the *Stelligraphe* system (J. Gaillard, Appolline Productions, Sainte-Usage, Louhans, France), now in commercial use, because public-domain descriptions of the software are not yet available.

9. Future work; concluding remarks

Expanding the range of design rules in RaPiD so that it becomes comprehensive is a current priority, as is the introduction of critiquing strategies (4) and (5) (see section 5 above), as well as completion of the automatic mode of operation. The programme of evaluation of all aspects of RaPiD is now being actively pursued. The extensive use and testing of RaPiD already carried out show it to be a versatile and robust knowledge-based system whose benefits in dental education will be widespread.

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