THE DENTAL CLINICS OF NORTH AMERICA

Dent Clin N Am 46 (2002) 521–538

Clinical decision-making using computers: opportunities and limitations

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"For to err in opinion, though it be not the part of wise men, is at least human." These words from Plutarch (AD 46?–AD c. 120) describe well the current dilemma of too many human errors in medicine, which cause an estimated 44,000 to 98,000 people to be killed each year by mistakes made by doctors, pharmacists, and hospitals. Even with the lowest estimate, the number of people who die from medical human error is more than the number of people killed by traffic deaths, AIDS, or breast cancer, according to the Institute of Medicine (IOM) [1]. The editors say that the problem is not a matter of inconsiderate behavior on the part of people treating patients; it is just basic flaws within the system. The report released by the IOM generated public interest, and the number of deaths were discussed controversially [2,3] and resulted in a white paper about quality improvement in medicine [4]. Bates et al [4] reviewed the use of information technology in medicine and described well some major flaws that lead to medical errors generated by information technology and management issues of health care providers in hospitals and industry. The authors gave general suggestions relevant to many specialties to reduce errors for using information technology and gave specific recommendations on how to implement certain aspects important for overcoming life-threatening conditions.

Fortunately, dentistry is not a "life and death" discipline of health care and will never cause those dramatic figures. Computers are all over the dental office and grow exponentially in their number and frequency of usage; errors occur using these computers and during dental treatment per se. Although dental practice differs from medical practice, we can learn from

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PII: S0011-8532(02)00008-3

the efforts and strategies using information technology in medicine toward the implementation of comparable and tailored systems in dentistry.

Many questions arise here: What exactly is the need for information technology and where in the dental office or clinic can it be used? Which components are necessary? How can one use computers to reduce the error rate? For information technology to be implemented, it must be clear that the return on investment is sufficient.

Answers to these questions are given in this article. The author first describes efforts using information technology at various phases in dental treatment as they represent prerequisites for decision making and prepares recommendations for the further development of computers for clinical dental decision making.

It is beyond the scope of this article to discuss every dental discipline, and the reader might miss other areas of interest. After a thorough literature search and market studies, topics discussed herein are in accordance with areas of heavy use (and need?) of information technology in dentistry.

The best way to begin is to look along the path of a dental patient entering and leaving a dental office. Most of the stages are similar at many dental schools or hospitals and private offices, except for the time spent in each phase related to the availability of sophisticated procedures, equipment, and human experts. Usually the patient enters a private office first before deciding to go or being referred to a larger clinical site, at which the overall time for completion of diagnostics, assessment for treatment plan, pretreatment, and treatment is longer. Depending on the complexity of the case, patients can remain or reenter each stage several times.

The encounters of a dental patient

If one defines "death of a patient" in medicine as the final or absorbing stage of treatment, then a comparable health state occurs in dentistry as the patient becomes and stays edentulous (without any resting teeth but with dentures in general; however, in the endstage patients cannot even use any dentures because of extreme bone atrophy). This can happen for several reasons, for instance, caries or periodontal diseases, radiotherapy, or treatment failure. Human error in dentistry is seldom life threatening to the patient but is detrimental to a particular tooth. Because we have only a limited number of teeth, it is only a matter of time before a patient enters this edentulous phase. Although court cases are frequently settled for the benefit of a patient, replacement of the secondary dentition is critical in many aspects, particularly for esthetics, masticatory efficiency, speech, oral space maintenance, and sociopsychological patterns.

The variation in treatment strategies of modern dentistry also can be the reason why patients face the risk of becoming edentulous at a relative early age. This is supported by demographic studies, which show that the elderly population in the United States (age 85 and over) increased 25-fold from

1900 to 1990, and projections of the total US population show an increase from 1.6% in 2000 to 1.9% for 2010 and 4.6% in 2050 [5]. The average life expectancy was 79.6 years for women and 72.9 years for men in the United States in the year 1999 [5].

An assessment of dissatisfaction with oral health in an older adult population identified the factors associated with dissatisfaction and showed that edentulous patients were more likely to be dissatisfied than dentate subjects. The authors concluded that demographic, clinical, and psychosocial impact variables are associated with oral health [6].

Patient history and dental record

During the history-taking part of the appointment and after the oral examination, the dentist dictates findings to the dental assistant, who prepares a clinical record. Although the dental assistant is busy with completing the clinical record, he or she also might assist with instruments and positioning in the chair-lamp-tray triad. Speech recognition systems are necessary but are not standardized yet. A study of this technology for clinicians shows that it has advanced considerably in recent years and is a serious contender for replacing the increasingly expensive methods of dictation with human transcription [7]. Many applications are already available for radiology [8], although the technology is still evolving. A comparison of data from 5072 reports generated with a commercially implemented system and 4552 reports produced during the same period 1 year earlier shows that continuous speech recognition markedly improved report turnaround time and proved to be cost effective [9].

Despite this ongoing interest in the medical domain, no dental speech recognition systems known for typical documentation or voice-controlled positioning of chair-lamp-tray systems are available. Research and implementation of information technology on dental-related speech focus on the functional integration of simple and complex human functions that involve the odontostomatognathic functional system [10].

An important general issue that arises with speech technology is audio information retrieval; there are currently no search engines for audio data comparable to "Yahoo!" or "Alta Vista". Because the development of multimedia applications involves audio features, intelligent interfaces for navigating and browsing become necessary [11].

Looking closer at dental clinical records, we know that they are as important as in medicine but differ greatly in the moderate use of pictographic symbols, codes, and colors. Traditional dental records frequently are filled out using colored pens and codes, and the dentist enters intraoral and radiographic findings into the chart by hand. Depending on the specific domain, such as periodontology or prosthodontics, additional symbols and classifications are being used and differ regionally. This also varies because of conventions introduced by different dental schools. Because there is no national or international chart standard, various electronic chart systems are available for dentistry.

The incentives for a computer-based oral health record were developed by a collaboration of seven dental schools in the United States [12,13] and described features and concepts of basic data elements [14]. Currently, this is administered by the American Dental Association (ADA). The development of a multimedia electronic dental record is highly desirable but far from being completed, as described by Lowe for the medical domain [15]. The described system is not transferable on a one-to-one basis to dentistry; there is no equivalent to a dental electronic chart in medicine.

There are, however, several marketed proprietary systems, but only few are available for scientific documentation and publication, such as developed by Benn et al [16,17]. Their system (March/April 2000 version) is described in detail to represent a typical example of a computer-based oral health record. Like all other available systems, it shows good and improvable features.

First, it combines several features at once, for instance, documentation for medical and dental history, pictorial caries charting, including radiographic classifications, periodontal findings, and iconized representation for possible treatment. The authors admit that the new chart may seem complicated to use but it shows an error rate of less 3% after standardized testing with 24 users [18].

This system needs further improvements to reduce the time needed to enter data, click on all findings, or identify the lately entered contents. New computer icons are introduced to represent clinical caries or radiographic classifications, periodontal findings, and dynamic icon composition for implants and endodontic posts. This symbolic specialization might be a good adaptation to dental needs, but the large set of different icons makes it difficult to memorize the specific meaning of an icon, particularly once the chart is printed in black and white. The representation on the screen is filled with many dissimilar icons because a single tooth's finding consists of a minimum of four rows on the monitor and lacks a quick overview and ease of use. More importantly, many icons resemble one another in shape and color, and their total number exceeds the amount of pictorial representation using traditional charts. The details mentioned are more or less valid for all known systems.

Another attempt at computerized reporting of aggregated data and development of telematic applications linked to dental software systems is the ORATEL project [19]. It addresses the issue of quality assurance and provides chair-side decision support and retrospective evaluation of performance for general dental practitioners.

Although further development of these systems is warranted, implementing standard findings known from instructional software design [20–22] and human–computer interaction [23,24] is important. Recently, preliminary concepts on the development of standards for the design of educational software in dentistry [25] were published.

Diagnostics

The actual chair-side sessions, which involve the extraoral and intraoral examination, radiographic, and other imaging modalities, are the most crucial meetings for a patient's future treatment.

A noninvasive method for detection of precancerous and cancerous oral lesions uses computer-assisted analysis of the oral brush biopsy and is termed OralCDx [26]. It can aid in confirming the nature of apparently benign oral lesions and revealing lesions that are precancerous and cancerous more significantly when they are not clinically suspected of being so. Atypical and positive results are still referred for scalpel biopsy and histology to characterize the lesion completely. Given the difficulty in clinically differentiating premalignant and malignant lesions from benign lesions with a similar appearance, OralCDx seems to determine the significance of an oral lesion definitively and detects innocuous-appearing oral cancers at an early and curable stage.

Caries detection is another major preventive task of a dentist. A newly developed system called Logicon Caries Detector program (Logicon Inc, Northrop Grumman Information Technology, Herndon, VA) is designed to assist dentists in the detection and characterization of proximal caries. An evaluation of the program showed that the automated caries detection program was not consistent and provided different opinions on the caries status in a surface. The interobserver agreement in caries diagnosis also did not improve using the program [27].

The process of taking impressions is an everyday task and sometimes can be difficult for dentists and patients. Noncontact impression techniques that use video scanning of the oral cavity are under development [28,29]. Video techniques generally are widely used in dentistry, including dental education and training [30–32], teleradiology [33], prediction of orthodontic treatment [34–37], and diagnosis and treatment planning [38], most of which represent stand-alone computer systems.

The collection of clinical data and findings using computer technology is mostly undertaken in oral radiology [39,40] and with dental imaging techniques [41,42]. Technology advances quickly, and systems reviewed in 1993 for panoramic radiography [43], including common errors in patient positioning, their effect on the radiographic image, and how to correct the errors, have improved significantly.

The comparison between extraoral and panoramic systems [44] demonstrates the newest technologies available in dental radiographic hardware, such as charge-coupled devices, charge-injection devices, complementary metal oxide semiconductors, thin-film transistors, and photostimulable phosphors. The corresponding software goes beyond the scope of pure displaying radiographic images. For instance, the application of a 4-gray level isodensity filter to the air surrounding the face of a cephalometric image clearly depicts the soft tissue profile of the patient, which is useful in the treatment of orthodontic and maxillofacial prosthetic cases.

Three-dimensional imaging was carried out from the beginning of computed tomography (CT) in the presurgical evaluation of dental implant sites and implemented in the Sim/Plant software (Columbia Scientific, Columbia, MD). More advanced procedures include the use of stereolithographic methods to build three-dimensional plastic models for diagnosis and therapy planning of oral and maxillofacial disorders and surgery [45,46]. These three-dimensional methods are not limited to MRI alone [47,48]. Current studies are investigating the combination of other techniques, such as videofluorography [49], spiral CT [50,51], and the accuracy of two-dimensional/three-dimensional CT data [52].

For many years, distortions and artifacts in CT data caused by a patient's metallic restorations were a hurdle in three-dimensional image reconstruction that was needed in the diagnosis and treatment of dental implants, impacted teeth, and temporomandibular joint disorders. Befu et al [53] performed special algorithms for noise reduction by moving an average of 8 voxel intervals to two-dimensional images and other edge detection methods. The three-dimensional image was finally obtained from multidirectional interpolation [53]—free and clear of those artifacts. Their clinical model of limited cone-beam x-ray CT for dental use is called "3DX multi-image micro CT" and is currently available only in Japan (J. Morita Mfg Co, Kyoto, Japan).

A stereoradiographic system termed "tuned aperture computed tomography" (TACT), which is a method to produce three-dimensional images from a series of two-dimensional images [54,55], has been licensed by Instrumentarium Imaging (Tuusala, Finland). The use of TACT for dental applications is currently in progress for diagnostic efficacy in primary caries detection [56], diagnosis of external root resorption [57], the accuracy of depth discrimination [55], assessment of bone defects at implant sites [58], and determination of the orientation of a tooth root or titanium dental implant to an inferior alveolar canal in three dimensions [59].

Besides these image specific hardware improvements, software modalities concentrate on automatic densitometric image analysis, termed CADIA, in periodontal radiographs [60] and digital subtraction methods to quantify alveolar bone density changes caused by periodontal surgery. To make subtraction radiography more accessible to researchers and practitioners, a method has been developed to align dental radiographs automatically for digital subtraction radiography [61]. A series of applications of computer-assisted interpretation in radiographic diagnosis [62] and accuracy [63,64] are being developed constantly. Examples include automatic interpretation of periapical bone lesions [65], data handling capabilities merged with algorithms to ideally produce diagnostic outcomes of equal or greater accuracy than those made by accepted experts [41], and the automated detection of caries [66], which measures bone loss to adjacent dental implants [67].

Digital radiographic and imaging modalities offer many advantages that may sometimes be in the patient's best interest, including fast transmission to consulting dentists, insurance companies, and after-hours interpretation. Once scanning of radiographs becomes unnecessary, all data in digital format also will be transmitted more frequently, making teledentistry and teleradiology standard [68–71]. The side effect of using teleradiology systems is the change of work practices in terms of collaboration, reorganization of work, and education [72].

A recent development in the diagnostic field is the virtual articulator for the analysis of dysfunctions and the dysmorphology of dental occlusion. Results of a three-dimensional scan of a single tooth and complete denture models, including their centric relation, are combined with data from a jaw movement analyzer, which enables the virtual movement and diagnosis of dynamic occlusal contacts and interferences [73].

Treatment planning, pretreatment, and treatment: steps of clinical decision making

This phase of "clinical data mining" is decisive and is based on the dentist's expertise in the particular domain. For instance, if the dentist considers implant treatment, effects of findings, such as bone condition, jaw site, and age, are important parameters for the long-term outcome [74]. Prosthodontic determinants for successful long-term treatment outcomes are challenging in defining the best application. Consensus among professionals is necessary but has not met the broad context of prosthodontic options [75]. As described recently by Umar [76], the patient can remain in or change to different clinical states. The prediction of clinical states of individual patients can be vital and is modeled using probabilistic inference for definitive surgical therapy for primary cutaneous melanoma [77] and clinical pathology using image-guided decision support systems [78]. These modeling techniques are superior to traditional statistical procedures of multivariate logistic analysis [79,80] in acquiring incomplete data for prediction [81–83].

The use of computer technology for clinical decision making started in the late 1970s and early 1980s, particularly in medical domains that implemented knowledge and transferring strategies that were developed and identified by cognitive scientists [84–86]. A good overview of this period for medical decision making in primary care can be found in a 1990 article by Taylor [87] that describes the target values of making knowledge accessible to the clinician at the point of decision. The three dimensions of formal evaluation for primary care settings emphasized by Corey as accurate for prediction, useful, and acceptable for clinicians are still valid [88]. The primary focus of constructing these decision-making systems for primary health care settings was based initially on statistically available findings and knowledge-based data [89,90].

During the early 1990s, decision-making systems in primary care improved further in conjunction with new strategies on implementations of judgment under uncertainty [91–94] and the use of guidelines to construct decision-making systems [95–97], with special emphasis on probability theory and Bayesian approach [98–100]. The effectiveness of active and passive diagnostic decision-making systems is reviewed and discussed in a 1995 article by Elson and Connelly [101].

To determine whether an artificial system can distinguish novice and expert strategies during complex medical diagnostics, artificial neural networks were able to identify a small number of expert-like strategies after training the system [102]. Monitoring an expert system performance can be achieved using continuous user feedback, in which the design of an expert system incorporates measures of system performance. These metrics can be collected and monitored during the routine use of the system [103]. During the past few years, the number of expert systems increased steadily, as reviewed in 1996 by Durkin [104]. The elicitation of domain knowledge from a human expert to build an artificial system is complex and time consuming because it is mainly based on intuitive strategies as opposed to theoretically sound reasoning rules; however, errors and inconsistencies in their judgment are apparent. The processes of decomposing and formalizing a decision problem into simpler components are well defined and understood [89,95,99].

The description of various medical systems being developed is not within the scope of this article. Studies of influence of expert systems on training [105,106], testing and validation [107], implications for systems design [108], guidelines to improve compliance with care standards [109], and effects on physician performance and patient outcomes [110] show important findings that are also valid in the dental domain.

Needs and different modalities for dental decision-making systems are described in several articles [17,111–113]. First, dental systems evolved in histopathologic diagnosis of salivary gland neoplasms [114], orthodontic diagnosis [115], caries diagnosis [16], oral radiology [116], oral surgery [117], and partial denture design [118–120].

Only a few expert systems or other types of mathematical models have been developed in clinical dentistry and prosthodontics, respectively. For instance, oral radiographic differential diagnosis' (ORADs) designation is to evaluate radiographic and clinical features of patients with intrabony lesions to assist in their identification using Bayes' theorem [116]. After recognizing a dental problem and invoking the program, patient-specific information is entered to characterize the lesion in question. ORADs output is a listing of each of the diseases in the program associated with the probability for that described condition. It also computes a pattern match that estimates how closely the set of entered characteristics matches the typical presentation of each of the considered program's conditions. An online version is available at http://www.orad.org/.

Another approach using probabilistic reasoning to accomplish a dental clinical advisory system is described in by Umar and is currently a work in progress [121,122].

One example for prosthodontic treatment plan and design transfers active shape models and oral images into a computer-aided device (CAD)-like, knowledge-based assistant to design a removable partial denture [120]. Computer-assisted milling (CAM) of dental restorations using CAD/CAM techniques is under development [123–126], with few systems available for dental practitioners [127,128].

The next step in automated dental treatment is the use of robotics [129], neural interfaces to control computers [130], or virtual reality interaction techniques, which have been reported for medical imaging applications, such as virtual bronchoscopy and virtual angioscopy [8,131]. The first simulations for dental implant planning using virtual reality environment are described in a 1998 article by Seipel et al [132].

The ongoing interest, growth, and use of Internet resources is also used for medical and dental decision making [113,133]. The World Wide Web is ideal for distributing developed applications from medical and dental domains, such as knowledge bases [134,135] and dental records [136]. Health care professionals are expected to use information services via the Internet and wide-band multimedia intranets more frequently for home care telemedicine, patient education, and online clinical decision making [137].

Diagnostic tools versus clinical decision making

"It may be part of human nature to err, but it is also part of human nature to create solutions, find better alternatives, and meet the challenges ahead" [1]. Perhaps this is the reason why so many solutions exist already in dentistry.

As described thus far, most of the computer systems or programs available in dentistry are designed to visualize some kind of result obtained during clinical assessment or other diagnostic procedures and represent more or less stand-alone systems. Even for treatment planning and carrying out and validation of dental treatment, computers are simpler than less intelligent assisting tools. Few of the systems make a clinical decision in lieu of the dentist. For example, the final touch and responsibility for extracting a tooth is still in the hand of the human expert. The fear of use and hesitation of implementing information technology at dental schools and in private offices are unfounded if we reflect on replacing dentists with computers.

Information technology and informatics as "the science of information technology" can do much more for dentistry than display nice charts and images. It is easier to develop stand-alone solutions and make prompt money with them, but who can afford at least three different digital radiographic systems (one for endodontics, one for periodontology, another for orthodontics, and possibly one for implant surgery), one or two charting systems, several databases, and one billing system? In the worst case, none of these systems can communicate or exchange data with the others. Vendors and developers are encouraged to take care of this problem and implement the digital imaging and communications in medicine (DICOM) standard, which defines a format for storing and exchanging digital images, including radiographic and images in general. Implementing DICOM allows dentists to combine imaging devices and software packages from different vendors. For more details, see the article on DICOM elsewhere in this issue.

Although most data required to implement a significant clinical decision are already available in some kind of electronic format at many dental schools or offices, they cannot be brought together because of analogous interface or format issues. Again, standards for exchange information such as HL7 and coding of these data are necessary. Prevalent problems unsolved include deciding which information should be coded, how it should be structured, and how unstructured free text should be used to provide decision-making support.

The use of computer-based decision-making systems does not mean results obtained are always true. Although computers can help reduce error and accident rates, they also can cause errors [4]. A reliability study on CAD of breast cancer showed that all tested CAD methods are still unreliable despite high accuracy of cancer diagnosis reported in the literature [138]. This situation clearly must be improved by thoroughly conducting evaluation studies repeatedly; otherwise, they will provide a false sense of security.

Further aspects to deal with are the economic downturn, the real and perceived vendor stability, after-sales service, training in use, press from opinion leaders, and issues of interoperability and portability. Any system developed for dentistry also should be useable by a dentist.

Recommendations

It is difficult to give recommendations to a dental practitioner regarding what to buy or implement because this decision depends on his or her specialty, readiness to get training on the new system, and available money. Only general suggestions can be made. The limit of the available budget in most cases is reached quickly and requires long-term planning. For costly systems such as digital radiographic solutions, including CT, the future trend is to purchase those packages in teams of three or more dentists. It is not necessary for all team members to be located in the same office because data can be accessed and transferred easily via telecommunication lines such as integrated services digital network (ISDN) or digital subscriber line (DSL). This arrangement ensures working to capacity and reaching the break-even point of investment earlier.

Despite the growing number of available digital systems, we can identify a five-step development with basic and advanced modules toward the digitalization of a dental office. They are listed in the order of increasing complexity and lead to a computer-aided decision-making support system.

Specific recommendations are given if applicable. Some of the submodules may not yet be available.

Basic or "independent" components (can be implemented and used in all dental disciplines)

1. Computer-based oral health record (COHR), including scheduling and recall program. On the patient's side, an anonymous smart card contains his or her encrypted complete health record, which can be unlocked by the patient (eg, by his or her fingerprint). Emergency medication, allergies, and other contraindications are available without further lock or encryption. On the dentist's side, an intelligent card reader accesses a patient's file, presents all recent radiographic images for endodontic treatment, and shows a to-do list for the actual session and further planned treatment. A holographic or other three-dimensional display enables the dentist and the patient to discuss findings and possible treatments while performing virtual simulations on the particular case. The scheduling and recall program automatically sends a reminder e-mail or voice message 1 day before the next appointment. The tech laboratory automatically verifies both parties' completion of the next lab/processing step during making of a denture (eg, model, wax-up, articulation, etc). Findings and procedures of the treatment session are recognized by the voice of the dentist or dental assistant and are saved as standard codes in the record. During treatment, the chair, lamp, and tray are automatically repositioned by voice.
2. Practice management. Codes relevant for billing are accessed from the COHR and are prepared for electronic claims submission and financial management and indicate if payment is received.

3A. Trouble-free imaging devices. Start with a basic digital extraoral camera and connect it to the COHR. One can train documenting before-and-after results in orthodontics, for example, or fixed and removable dentures. Try video conferencing with colleagues, the tech laboartory, and patients. Expand one's system with an intraoral digital camera also connected to the COHR to explain and visualize findings to the patient. Start documenting before-and-after results in areas such as periodontics, restorative dentistry, and prosthodontics. Expand the system with a digital impression-taking system; typically, a noncontact impression takes 5 seconds for upper and lower jaw together. One should make sure that all cameras and COHR can communicate with each other.

Advanced modules

3B. Special imaging devices. Depending on one's discipline and needs in radiographic images, intraoral and extraoral digital radiographic systems, including micro-CT, might become necessary. Talk to colleagues and discuss options of purchasing these pricey systems as a team. Make sure that all these devices talk DICOM and can communicate with each of the COHR systems. Proprietary file formats or databases are not recommended.

4. Centralized database. As one reaches this step of digitalization, it is time to implement a database that contains not only the name and SSN of patients. The reason to add COHR data, including all radiographic and intraoral and extraoral images, of other colleagues and offices is to build a knowledge base useable by all participating dentists. The structured knowledge base contains problem-oriented input with all necessary historical, diagnostic, and treatment data. This enables other dentists to see how certain problems can be treated successfully using a particular type of material or technique. All identifying personal patient data are scrambled and are available only to the actual practitioner.
5. Intelligent dental assistant (IDEA). This system has access to all findings stored in the centralized database and takes comparable cases into consideration before providing an evidence-based intelligent dental assistant and information on how to treat a particular patient. It measures and prevents adverse consequences, monitors continuously, and makes quality structures meaningful. This information is used to make ongoing changes. Vendors refuse or "water down" action-oriented clinical decision-making support in their proprietary systems because they fear being sued. Using this large data set can help to solve the problem, however, as algorithms are being developed to calculate ongoing risk and cost-effective analyses become available.

These recommendations reveal that many things are not done yet, but they show a path toward the development and implementation of action-oriented clinical decision making in dentistry.

References

[1] Kohn LT, Corrigan JM, Donaldson MS. To err is human: building a safer health system. Washington, DC: National Academy Press; 1999.

[2] Leape LL. Institute of Medicine medical error figures are not exaggerated [comment]. JAMA 2000;284:95–7.

[3] McDonald CJ, Weiner M, Hui SL. Deaths due to medical errors are exaggerated in Institute of Medicine report. JAMA 2000;284:93–5.

[4] Bates DW, Cohen M, Leape LL, et al. Reducing the frequency of errors in medicine using information technology. J Am Med Inform Assoc 2001;8:299–308.

[5] Famighetti R. The world almanac and book of facts 2000. Mahwah (NJ): PRIMEDIA Reference Inc; 1999.

[6] Jokovic A, Locker D. Dissatisfaction with oral health status in an older adult population. J Public Health Dent 1997;57:40–7.

[7] Zafar A, Overhage JM, McDonald CJ. Continuous speech recognition for clinicians. J Am Med Inform Assoc 1999;6:195–204.

[8] Krapichler C, Haubner M, Losch A, et al. Physicians in virtual environments: multimodal human-computer interaction. Interacting with Computers 1999;11:427–52.
[9] Ramaswamy MR, Chaljub G, Esch O, et al. Continuous speech recognition in MR imaging reporting: advantages, disadvantages, and impact. AJR Am J Roentgenol 2000; 174:617–22.
[10] Chase PF, Rosenoer L. Parameters of odontostomatognathic disability: guidelines for evaluation of impaired simple and complex human functions involving the odontostomatognathic functional system. Journal of Craniomandibular Practice 1999;17:70–6.
[11] Foote J. An overview of audio information retrieval. Multimedia Systems 1999;7:2–10.
[12] Eisner J, Chasteen JE, Schleyer T, et al. The computer based oral health record: a new foundation for oral health information systems. Chicago (IL): American Fund for Dental Health; 1993. p. 269.
[13] Schleyer T, Eisner J. The computer-based oral health record: an essential tool for cross-provider quality management. Journal of the California Dental Association 1994;22:57–64.
[14] American Dental Association. Computer-based oral health record: concept model. Chicago: American Dental Association; 1996.
[15] Lowe HJ. Multimedia electronic medical record systems. Acad Med 1999;74:146–52.
[16] Benn DK, Clark D, Dankel DD, et al. A practical approach to evidence-based management of caries. J Am Coll Dent 1999;66:27–35.
[17] Benn DK, Dankel DD, Kostewicz SH. Can low accuracy disease risk predictor models improve health care using decision support systems? Chute CG, editor. American Medical Informatics Association: AMIA 1998 Annual Symposium. Philadelphia: Hanley & Belfus; 1998. p. 577–81.
[18] Benn DK, Dankel DD, Kostewicz SH, et al. A tooth chart for severity and activity of caries lesions [IADR abstract]. J Dent Res 1999;78:1762.
[19] Ireland RS. Initial experience of the ORATEL computerised information tools in general practice. Br Dent J 1996;181:289–95.
[20] Koumi J. Media comparison and deployment: a practitioner's view. British Journal of Educational Technology 1994;25:41–57.
[21] Northrup PT. Concurrent formative evaluation: implications for multimedia designers. Educational Technology 1996;35:24–36.
[22] Schroeder EE, Grabowski BL. Patterns of exploration and learning with hypermedia. Journal of Educational Computing Research 1995;13:313–35.
[23] Ayersman DJ. Effects of knowledge representation format and hypermedia instruction on metacognitive accuracy. Computers in Human Behavior 1995;11:533–55.
[24] Cooper PA. Paradigm shifts in designed instruction: from behaviorism to cognitivism to constructivism. Educational Technology 1993;23:12–9.
[25] Johnson L, Schleyer T. Developing standards for the design of educational software. Quintessence Int 1999;30:763–8.
[26] Sciubba JJ. Improving detection of precancerous and cancerous oral lesions: computer-assisted analysis of the oral brush biopsy. J Am Dent Assoc 1999;130:1445–57.
[27] Wenzel A. Computer-automated caries detection in digital bitewings: consistency of a program and its influence on observer agreement. Caries Res 2001;35:12–20.
[28] Farman AG, Scarfe WC. Pixel perception and voxel vision: constructs for a new paradigm in maxillofacial imaging. Dentomaxillofacial Radiology 1994;23:5–9.
[29] Schuler JM, Scribner DA. Increasing spatial resolution through temporal super-sampling of digital video. Optical Engineering 1999;38:801–5.
[30] Ader DN, Seibring AR, Bhaskar P, et al. Information seeking and interactive videodisc preparation for third molar extraction. J Oral Maxillofac Surg 1992;50:27–31.
[31] Holt RD, Rule DC, Basker RM, et al. The influence on partial denture design of a teaching video for general dental practitioners. Br Dent J 1994;176:379–80.
[32] Wright DN. Interactive multimedia dental education: the next five years and beyond. Medinfo 1995;8:1305–7.

[33] Tyndall DA, Boyd KS, Matteson SR, et al. Video-based teleradiology for intraosseous lesions: a receiver operating characteristic analysis. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1995;80:599–603.
[34] Hoss K, Sameshima GT, Grubb JE, et al. The accuracy of video imaging for mixed dentition and adolescent treatment. Angle Orthod 1997;67:355–64.
[35] Le TN, Sameshima GT, Grubb JE, et al. The role of computerized video imaging in predicting adult extraction treatment outcomes. Angle Orthod 1998;68:391–9.
[36] Sameshima GT, Kawakami RK, Kaminishi RM, et al. Predicting soft tissue changes in maxillary impaction surgery: a comparison of two video imaging systems. Angle Orthod 1997;67:347–54.
[37] Syliangco ST, Sameshima GT, Kaminishi RM, et al. Predicting soft tissue changes in mandibular advancement surgery: a comparison of two video imaging systems. Angle Orthod 1997;67:337–46.
[38] Clancy JM, Johnson L, Finkelstein MW, et al. Dental diagnosis and treatment (DDx & Tx): interactive videodisc patient simulations for dental education. Comput Methods Programs Biomed 1990;33:21–6.
[39] Chen SK, Yu KM, Chen RS, et al. Implementation of an oral and maxillofacial radiology image management and communication system. Dentomaxillofacial Radiology 1998;27: 358–62.
[40] Sanderink GC. Imaging: new versus traditional technological aids. Int Dent J 1993;43: 335–42.
[41] van der Stelt PF. Computer-assisted interpretation in radiographic diagnosis. Dent Clin North Am 1993;37:683–96.
[42] Wyatt CCL, Pharoah MJ. Imaging techniques and image interpretation for dental implant treatment. Int J Prosthodont 1998;11:442–52.
[43] Truhlar RS, Morris HF, Ochi S. A review of panoramic radiography and its potential use in implant dentistry. Implant Dent 1993;2:122–30.
[44] Farman AG, Farman TT. Extraoral and panoramic systems. Applications of Digital Imaging Modalities for Dentistry 2000;44:257–72.
[45] Gaggl A, Schultes G, Santler G, et al. Treatment planning for sinus lift augmentations through use of 3-dimensional milled models derived from computed tomography scans: a report of 3 cases. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998;86:388–92.
[46] Whitman DH, Connaughton B. Model surgery prediction for mandibular midline distraction osteogenesis. Int J Oral Maxillofac Surg 1999;28:421–3.
[47] Nasel C, Gahleitner A, Breitenseher M, et al. Localization of the mandibular neurovascular bundle using dental magnetic resonance imaging. Dentomaxillofacial Radiology 1998;27:305–7.
[48] Nasel CJO, Pretterklieber M, Gahleitner A, et al. Osteometry of the mandible performed using dental MR imaging. AJNR Am J Neuroradiol 1999;20:1221–7.
[49] Zhang X-N, Nishiyama H, Murakami S, et al. A study of condylar movement by bilateral simultaneous videofluorography. Dentomaxillofacial Radiology 1998;27:279–86.
[50] Lam EWN, Ruprecht A, Yang J. Comparison of 2-dimensional orthoradially reformatted computed-tomography and panoramic radiography for dental implant treatment planning. J Prosthet Dent 1995;74:42–6.
[51] Yang J, Cavalcanti MGP, Ruprecht A, et al. 2-D and 3-D reconstructions of spiral computed tomography in localization of the inferior alveolar canal for dental implants. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1999;87:369–74.
[52] Cavalcanti MGP, Vannier MW. Quantitative analysis of spiral computed tomography for craniofacial clinical applications. Dentomaxillofacial Radiology 1998;27:344–50.
[53] Befu S, Tsunashima H, Arai Y. A study on three-dimensional image processing method for 3DX multi image micro CT. In: Lemke HU, Vannier MW, Inamura K, et al, editors. Computer assisted radiology and surgery. Proceedings of the 15th International Congress and Exhibition CARS 2001. Amsterdam: Elsevier; 2001. p. 665–70.

[54] Webber RL, Horton RA, Tyndall DA, et al. Tuned-aperture computed tomography (TACT TM): theory and application for three-dimensional dento-alveolar imaging. Dentomaxillofacial Radiology 1997;26:53–62.
[55] Yamamoto K, Farman AG, Webber RL, et al. Effect of number of projections on accuracy of depth discrimination using tuned-aperture computed tomography for 3-dimensional dentoalveolar imaging of low-contrast details. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1999;88:100–5.
[56] Tyndall DA, Clifton TL, Webber RL, et al. TACT imaging of primary caries. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1997;84:214–25.
[57] Nance RS, Tyndall O, Levin LG, et al. Diagnosis of external root resorption using TACT (tuned-aperture computed tomography). Endod Dent Traumatol 2000;16:24–8.
[58] Horton RA, Ludlow JB, Webber RL, et al. Detection of peri-implant bone changes with axial tomosynthesis. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1996; 81:124–9.
[59] Farman AG, Scheetz JP, Eleazer PD, et al. Tuned-aperture computed tomography (TM) accuracy in tomosynthetic assessment for dental procedures. In: Lemke HU, Vannier MW, Inamura K, et al, editors. Computer assisted radiology and surgery. Proceedings of the 15th International Congress and Exhibition CARS 2001. Amsterdam: Elsevier; 2001. p. 654–8.
[60] Bragger U, Pasquali L, Rylander H, et al. Computer-assisted densitometric image analysis in periodontal radiography. J Clin Periodontol 1988;15:27–37.
[61] Yoon DC. A new method for the automated alignment of dental radiographs for digital subtraction radiography. Dentomaxillofacial Radiology 2000;29:11–9.
[62] Wenzel A. Computer-aided image manipulation of intraoral radiographs to enhance diagnosis in dental practice: a review. Int Dent J 1993;43:99–108.
[63] Wenzel A, Aagaard E, Sindet-Pedersen S. Evaluation of a new radiographic technique: diagnostic accuracy for mandibular third molars. Dentomaxillofacial Radiology 1998; 27:255–63.
[64] Wenzel A, Hintze H, Horsted-Bindslev P. Accuracy of radiographic detection of residual caries in connection with tunnel restorations. Caries Res 1998;32:17–22.
[65] Mol A, van der Stelt PF. Application of computer-aided image interpretation to the diagnosis of periapical bone lesions. Dentomaxillofacial Radiology 1992;21:190–4.
[66] Koch S, Wagner I-V, Seipel S, et al. Controlled diagnosis-oriented enhancement of automatically segmented radiographs in dentistry. Comput Methods Programs Biomed 1998;57:125–31.
[67] Reddy M, Mayfield-Donahoo T, Jeffcoat M. A semi-automated computer-assisted method for measuring bone loss adjacent to dental implants. Clinics of Oral Implant Research 1992;3:28–31.
[68] Decorato DR, Kagetsu NJ, Ablow RC. Off-hours interpretation of radiologic images of patients admitted to the emergency department: efficacy of teleradiology. AJR Am J Roentgenol 1995;165:1293–6.
[69] Eraso FE, Scarfe WC, Hayakawa Y, et al. Teledentistry: protocols for the transmission of digitized radiographs of the temporomandibular joint. J Telemed Telecare 1996;2: 217–23.
[70] Ernst RD, Kawashima A, Shepherd W, et al. Distributing digital imaging and communications in medicine data and optimizing access over satellite networks. J Digit Imaging 1999;12:195–6.
[71] Farman AG, Farag AA. Teleradiology for dentistry. Dent Clin North Am 1993;37: 669–81.
[72] Karasti H, Reponen J, Tervonen O, et al. The teleradiology system and changes in work practices. Comput Methods Programs Biomed 1998;57:69–78.
[73] Kordass B, Gaertner CH. The virtual articulator: concept and development of VR-tools to analyse the dysfunction of dental occlusion. In: Lemke HU, Vannier MW, Inamura K,

et al, editors. Computer assisted radiology and surgery. Proceedings of the 15th International Congress and Exhibition CARS 2001. Amsterdam: Elsevier; 2001. p. 649–53.
[74] Bryant SR. The effects of age, jaw site, and bone condition on oral implant outcomes. Int J Prosthodont 1998;11:470–90.
[75] Carr AB. Succesful long-term treatment outcomes in the field of osseointegrated implants: prosthodontic determinants. Int J Prosthodont 1998;11:502–12.
[76] Umar H. A Markov process in clinical dentistry: the prosthodontic cycle. In: Lemke HU, Vannier MW, Inamura K, et al, editors. Computer-assisted radiology and surgery. Proceedings of the 15th International Congress and Exhibition CARS 2001. Amsterdam: Elsevier; 2001. p. 679–84.
[77] Braitman LE, Davidoff F. Predicting clinical states in individual patients. Ann Intern Med 1996;125:406–12.
[78] Comaniciu D, Meer P, Foran DJ. Image-guided decision support system for pathology. Machine Vision and Applications 1999;11:213–24.
[79] Afifi AA, Clark V. Logistic regression. In: Afifi AA, Clark V, editors. Computer-aided multivariate analysis. 2nd edition. New York: Van Nostrand Reinhold; 1990. p. 317–43.
[80] Tu JV. Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes. J Clin Epidemiol 1996;49:1225–31.
[81] Friedman N, Murphy K, Russel SJ. Learning the structure of dynamic probabilistic networks. In: Proceedings of the Conference on Uncertainty in Artificial Intelligence. Madison (WI): Morgan Kaufmann Publishers; 1998. p. 139–47.
[82] Glonek GFV. On identifiability in models for incomplete binary data. Statistics & Probability Letters 1999;41:191–7.
[83] Ramoni M, Sebastiani P. Discovering Bayesian networks in incomplete databases: technical report KMi-TR-46. Milton Keynes (UK): Open University, Knowledge Media Institute; 1997. p 1–5.
[84] Adelson B. Comparing natural and abstract categories: a case study from computer science. Cognitive Science 1985;9:417–30.
[85] McKeithen KB, Reitman JS, Rueter HH, et al. Knowledge organization and skill differences in computer programmers. Cognit Psychol 1981;13:307–25.
[86] Tversky A, Kahneman D. Judgements under uncertainty: heuristics and biases. Science 1974;185:1124–31.
[87] Taylor TR. The computer and clinical decision-support systems in primary care. J Fam Pract 1990;30:137–40.
[88] Corey GA. Cardiac ischemia decision-support tools [letter]. J Fam Pract 1988;27:576.
[89] Shachter RD, Heckerman DE. Thinking backward for knowledge acquisition. AI Magazine 1987;55:61.
[90] Spiegelhalter DJ, Knill-Jones RP. Statistical and knowledge-based approaches to clinical decision-support systems, with an application in gastroenterology. J R Statist Soc 1984; 147:35–77.
[91] Henrion M. Some practical issues in construction belief networks. In: Kanal LN, Levitt TS, Lemmer JF, editors. Uncertainty in artificial intelligence. New York: Elsevier; 1989. p. 161–73.
[92] Morgan MG, Henrion M. Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge: Cambridge University Press; 1992.
[93] Poole D, Provan GM. What is the most likely diagnosis? In: Bonissone PP, Henrion M, Kanal LN, et al, editors. Uncertainty in artificial intelligence. New York: Elsevier; 1991. p. 89–105.
[94] Tversky A, Shafir E. The disjunction effect in choice under uncertainty. Psychological Science 1992;3:305–9.
[95] Druzdzel MJ, Flynn RR. Decision support systems. In: Kent A, editor. Encyclodpedia of library and information science. vol 67. New York: Marcel Dekker, Inc; 2000. p. 120–33.

[96] Russel SJ, Norvig P. Making complex decisions. In: Russel SJ, Norvig P, editors. Artificial intelligence: a modern approach. Upper Saddle River (NJ): Prentice Hall; 1995. p. 498–522.
[97] Russel SJ, Norvig P. Making simple decisions. In: Russel SJ, Norvig P, editors. Artificial intelligence: a modern approach. Upper Saddle River (NJ): Prentice Hall; 1995. p. 471–97.
[98] Charniak E. Bayesian networks without tears. AI Magazine 1991;12:50–63.
[99] Henrion M, Breese JS, Horvitz EJ. Decision analysis and expert systems. AI Magazine 1991;12:64–91.
[100] Spiegelhalter DJ, Dawid AP, Lauritzen SL, et al. Bayesian analysis in expert systems. Statistical Science 1993;8:219–83.
[101] Elson RB, Connelly DP. Computerized decision support systems in primary care. Prim Care 1995;22:365–84.
[102] Stevens RH, Lopo AC, Wang P. Artificial neural networks can distinguish novice and expert strategies during complex problem solving. J Am Med Inform Assoc 1996;3: 131–8.
[103] Kahn M, Dunagan W, Steib S, et al. Monitoring expert system performance using continuous user feedback. J Am Med Inform Assoc 1996;3:216–23.
[104] Durkin J. Expert systems: a view of the field. IEEE Expert Intelligent Systems 1996;11: 56–63.
[105] Elstein AS, Friedman CP, Wolf IM, et al. Effects of a decision support system on the diagnostic accuracy of users: a preliminary report. J Am Med Inform Assoc 1996;3:422–8.
[106] Murphy GC, Friedman CP, Elstein AS, et al. The influence of a decision support system on the differential diagnosis of medical practitioners at three levels of training. Bethesda (MD): American Medical Informatics Association; 1996. p. 219–23.
[107] Sailors RMM, East TD, Wallace CJ, et al. Testing and validation of computerized decision support systems. In: Annual Fall Symposium. Bethesda (MD): American Medical Informatics Association; 1996. p. 234–8.
[108] Elson RB, Faughnan JG, Connelly DP. An industrial process view of information delivery to support clinical decision making: implications for systems design and process measures. American Medical Informatics Association 1997;4:266–78.
[109] Lobach DF, Hammond WE. Computerized decision support based on a clinical practice guideline improves compliance with care standards. Am J Med 1997;102:89–98.
[110] Hunt DL, Haynes RB, Hanna SE, et al. Effects of computer-based clinical decision support systems on physician performance and patient outcomes: a systematic review. JAMA 1998;280:1339–46.
[111] Feldman CA, Eisner J, Chasteen J, et al. Design of an oral health information system based upon a computer based dental record. Proceedings of 11th International Congress of the European Federation for Medical Informatics. Jerusalem: Israel, April 18–22, 1993. London: Freund Publication House; 1993. p. 169–73.
[112] White SC. Decision-support systems in dentistry. J Dent Educ 1996;60:47–63.
[113] Schleyer T. Clinical decision-making and the Internet. J Am Coll Dent 1999;66:29–39.
[114] Firriolo FJ, Levy BA. Computer expert system for the histopathologic diagnosis of salivary gland neoplasms. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1996; 82:179–86.
[115] Hammond RM, Freer TJ. Application of a case-based expert system to orthodontic diagnosis and treatment planning: a review of the literature. Aust Orthod J 1996;14:150–3.
[116] White SC. Computer-aided differential diagnosis of oral radiographic lesions. Dentomaxillofacial Radiology 1989;18:53–9.
[117] Brickley MR, Shepherd JP. Comparisons of the abilities of a neural network and three consultant oral surgeons to make decisions about third molar removal. Br Dent J 1997;182:59–63.
[118] Davenport JC, Hammond P, Hazlehurst P. Knowledge-based systems, removable partial denture design and the development of RaPiD. Dent Update 1997;24:227–33.

[119] Hammond P, Wells P, Modgil S. Animating medical and safety knowledge. In: Horn W, Shahar Y, Lindberg G, et al, editors. Artificial intelligence in medicine. Proceedings of the AIMDM 1999. Berlin, Heidelberg: Springer-Verlag; 1999. p. 443–7.
[120] Hutton TJ, Hammond P, Davenport JC. Active shape models for customised prosthesis design. In: Horn W, Shahar Y, Lindberg G, et al, editors. Artificial intelligence in medicine. Proceedings of the AIMDM 1999. Berlin, Heidelberg: Springer-Verlag; 1999. p. 448–52.
[121] Umar H. Decision-making under uncertainty in clinical dentistry: a probabilistic approach to a dental clinical advisory system [Master's thesis]. Pittsburgh: University of Pittsburgh; 2000.
[122] Umar H, Druzdzel MJ, Brass S. A Bayesian approach to a dental clinical advisory system with EER prosthodontic knowledge representation. In: Lemke HU, Vannier MW, Inamura K, et al, editors. Computer-assisted radiology and surgery. Proceedings of the 14th International Congress and Exhibition CARS 2000. Amsterdam: Elsevier; 2000. p. 835–40.
[123] Denissen HW, van der Zel JM, van Waas MAJ. Measurement of the margins of partial-coverage tooth preparations for CAD/CAM. International Journal of Prosthodontics 1999;12:395–400.
[124] Joffe JM, Nicoll SR, Richards R, et al. Validation of computer-assisted manufacture of titanium plates for cranioplasty. Int J Oral Maxillofac Surg 1999;28:309–13.
[125] Tang CK, Medioni G, Duret F. Automatic, accurate surface model inference for dental CAD/CAM: medical image computing and computer-assisted intervention. MICCAI 1998;1496:732–42.
[126] Willer J, Rossbach A, Weber HP. Computer-assisted milling of dental restorations using a new CAD/CAM data acquisition system. J Prosthet Dent 1998;80:346–53.
[127] Mormann W, Schug J. Grinding precision and accuracy of fit of CEREC 2 CAD-CIM inlays. J Am Dent Assoc 1997;128:47–54.
[128] Nash RW. A new CAD/CAM esthetic crown system. Compendium 1998;19:560–6.
[129] Tsutsumi S, Nambu T. Parallel robots for 3D digitizing and motion-controlling in clinical dentistry. J Dent Res 1998;77:1609.
[130] Charles J. Neural interfaces link the mind and the machine. Computer 1999;32:16–8.
[131] Krapichler C, Haubner M, Engelbrecht R, et al. VR interaction techniques for medical imaging applications. Comput Methods Programs Biomed 1998;56:65–74.
[132] Seipel S, Wagner IV, Koch S, et al. Oral implant treatment planning in a virtual reality environment. Comput Methods Programs Biomed 1998;57:95–103.
[133] Anderson MF, Moazamipour H, Hudson DL, et al. The role of the Internet in medical decision making. Int J Med Inf 1997;47:43–9.
[134] Riva A, Bellazzi R, Lanzola G, et al. A development environment for knowledge-based medical applications on the World Wide Web. Artif Intell Med 1998;14:279–93.
[135] Schleyer T, Spallek H, Arsalan M. Dental resources on the World Wide Web. MD Comput 1998;15:252–5.
[136] Schleyer T, Dasari V. Computer-based oral health records on the World Wide Web. Quintessence Int 1999;30:451–60.
[137] Collen MF. A vision of health care and informatics in 2008. J Am Med Inform Assoc 1999;6:1–5.
[138] Kovalerchuk B, Triantaphyllou E, Ruiz JF, et al. The reliability issue of computer-aided breast cancer diagnosis. Comput Biomed Res 2000;33:296–313.