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Decision making in implant dentistry: an evidence-based and decision-analysis approach

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Decision making in oral healthcare

Decision making is an essential part of oral healthcare. It involves diagnostic and therapeutic uncertainties, providers' heuristics and biases, patients' preferences and values, as well as cost considerations. A model for the factors influencing decisions in healthcare was described in 2000 by Chapman & Sonnenberg (10) and has been adapted here to discuss decision making in implant dentistry. The decision-making model describes two major components, the normative and the descriptive, which are involved in decision making (Fig. 1). The normative aspect of decision making relies on quantitative information derived from systematic reviews and predictive models on the probabilities and uncertainties of treatment outcomes. Clinical outcomes, such as survival or success of a tooth or a restoration, are assessed based on the utility they offer to the patient and their costs. Normative analyses allow quantitative comparisons of alternative therapies and can identify optimal treatments for multiple attributes. The descriptive aspect in decision making involves cognitive processes and biases of both providers and patients that translate the normative information into clinical action.

Decision making in healthcare occurs at three broad levels: the level of lawmakers and governmental regulators; the level of insurance plans that determine coverage and reimbursement for healthcare; and the level of the provider and patient. This review will focus on the decision-making process at the provider–patient level regarding treatments aimed at retaining diseased teeth or extracting diseased teeth and replacing them with an implant-supported prosthesis. Although implant-supported prostheses have become the treatment of choice in an increasing number of patients (32), it remains controversial under which conditions retaining a tooth may be futile and replacing a tooth with an implant-supported prosthesis may be considered over-treatment. Owing to the complexity and variability in designs of removable dental prostheses, the discussion will be limited to fixed dental prostheses.

The evidence-based approach and decision analysis constitute two major approaches in decision making in implant dentistry. Recently, a number of systematic reviews have been published regarding the success and survival rates of teeth following periodontal and endodontic treatments and of dental prostheses supported by teeth or implants. The present narrative review does not intend to replicate these systematic reviews; instead this review will attempt to build upon the compiled information, synthesize the provided data and apply them in a clinical context to assess which may offer greater benefits, namely removing natural teeth and replacing them with an implant-supported fixed dental prostheses or treating diseased teeth with the goal of retaining them.

Outcome variables for decision analysis

Before summarizing the available evidence for treatment outcomes aimed at tooth retention or replacement, a brief discussion regarding the impact of the natural dentition or dental prostheses on patients' masticatory function and satisfaction is warranted.

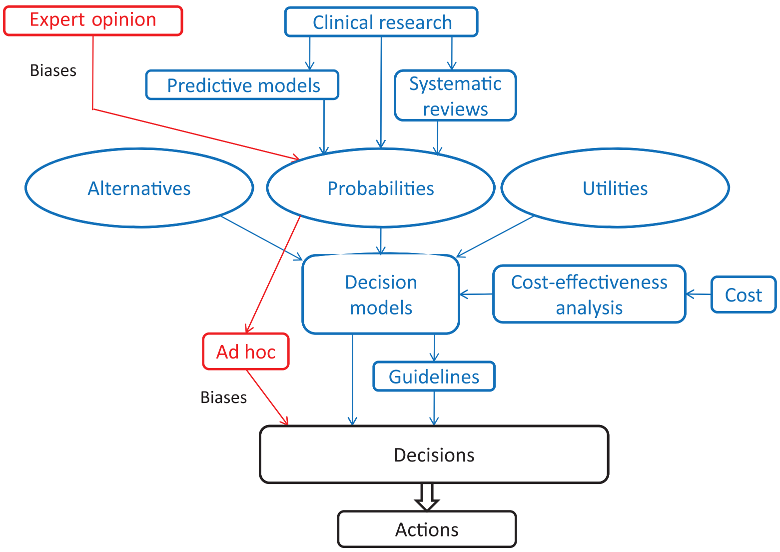

Fig. 1. Overall scheme of dental decision making (adapted from Chapman & Sonnenberg, 2000) (10). The normative components of decision making are marked in blue and the descriptive components are marked in red.

Number of teeth needed for masticatory function

Studies that assessed the impact of the dentition on oral function found that masticatory efficiency, as determined by comminution efficiency and self-reported masticatory ability, are associated with the number of existing teeth in a dentition (29). Twenty teeth with nine to ten pairs of contacting units, including anterior teeth, were found to be sufficient for adequate masticatory efficiency and masticatory ability. Most people were satisfied when they retained a premolar dentition. Retaining molars beyond the premolar dentition often added little to patients' satisfaction. Occlusal support and stability was maintained with three to four functional posterior units with a symmetrical pattern of tooth loss or five to six units with an asymmetrical pattern. When fewer than 20 teeth were present, masticatory efficiency and ability were likely to be impaired. Furthermore, loss of anterior teeth markedly impaired esthetics, and also the patients' satisfaction and utility (2, 29). Significant variations in subjective measures of esthetics and psychosocial comfort were found between social classes and geographic regions (71, 72).

Impact of implant-supported dental prostheses on oral health-related quality of life

Conclusive evidence has indicated that patients with implant-supported overdentures in the mandible report improved satisfaction with chewing compared to patients with conventional complete removable dental prostheses (78). Support by two implants was usually sufficient for patients and more implants did not increase patient satisfaction or oral health-related quality of life (76). Although patients rated the implant-supported complete denture higher than the conventional complete denture for chewing ability and function, the overall rating was not significantly different between the two types of prostheses. The available information is insufficient regarding the economics of different treatment modalities, perception of esthetics, therapies avoiding active treatment (e.g. adoption of a shortened dental arch compared with the prosthetic provision) and quality of life outcomes with respect to fixed conventional prostheses compared with implant-supported or removable prostheses (78).

Success and survival of teeth and dental prosthesis

As a result of the limited data regarding patient-centered outcomes and oral health-related quality of life, most of the quantitative information available to support normative decision making in implant dentistry is based on success and survival rates. Survival is a dichotomous variable and is often interpreted as a hard data point and not subject to interpretation, which needs to be questioned with respect to teeth, implants, or dental prostheses. Differently from medicine, where mortality is generally a result of the natural disease process, tooth loss or the loss of a prosthesis in most cases occurs following a dentist's deliberate decision to remove a tooth or prosthesis. The thresholds at which teeth with no coronal destruction are extracted, presumably because of periodontitis, have been found to vary considerably with attachment levels ranging from 20% to 100%, with a marked increase in extraction frequency seen at attachment levels below 70% (75). Although the decision to remove implants or a dental prosthesis may also vary from case to case, one may wonder whether providers are more or less likely to remove an implant or dental prosthesis they have previously inserted compared with extracting a natural tooth with some form of pathologic condition.

Evidence-based dentistry approach to decision making

The evidence-based approach, a process for reviewing large volumes of clinical and scientific data, emerged in medicine and dentistry during the 1990s. This approach was implemented in therapeutic decision-making with the aim of maximizing the potential for successful patient care outcomes. Based on the original definition of Evidence-Based Medicine (65), the American Dental Association defined Evidence-Based Dentistry as an approach to oral healthcare that requires the judicious integration of systematic assessments of clinically relevant scientific evidence relating to patients' oral and medical condition and history, along with the dentists' clinical expertise and the patient's treatment needs and preferences (1). Information derived from clinical trials is considered more reliable than information based on intuition, authority, or custom. There is a hierarchy when considering the levels of evidence. Systematic reviews of randomized controlled trials are considered to be at the highest level, whereas expert opinion is considered the lowest level of evidence (53).

Overall retention of natural teeth

The incidence of tooth loss has been shown to range from 1.3% to 5% in general populations in developed countries and in subjects classified as regular dental care attendants over a follow-up period of 10 to 30 years. The most frequently reported reasons for tooth extraction were dental caries and tooth fracture. The mean alveolar bone loss around natural teeth was found to range from 0.2 to 0.8 mm over 10 years (79). A much higher incidence of tooth loss ranging from 14% to 20% over 10 years was reported for rural Chinese populations (5, 11). Factors that may explain the variance in the incidence of tooth loss include education, occupation, personal economic situation, attitudes to dental care, lifestyle factors such as smoking, and access to dental care (51).

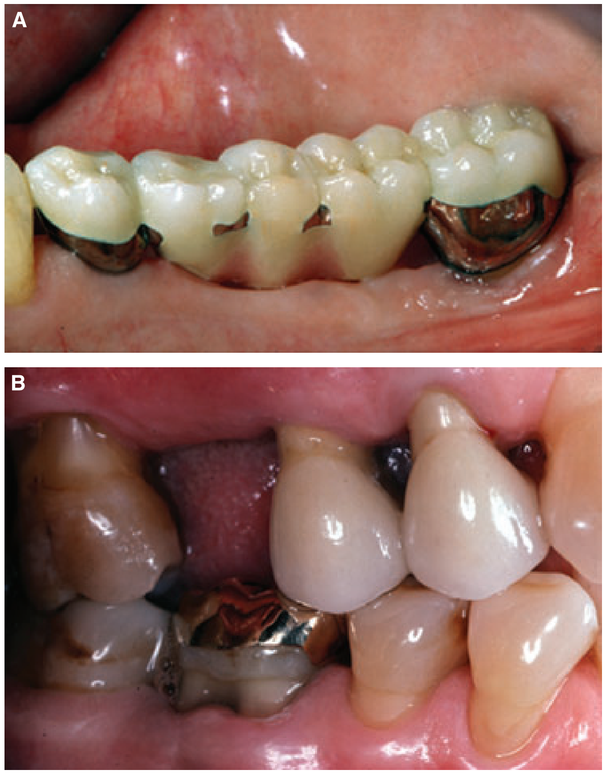

Fig. 2. In posterior bounded edentulous spaces, the adjacent teeth have a greater 10-year survival rate when the space is restored with a tooth-supported fixed dental prosthesis (92%) (A) or remain untreated (81%) (B) compared with teeth that serve as retainers for a removable partial denture (66%) (3).

It has been shown that teeth adjacent to posterior bounded edentulous spaces have a greater estimated 10-year survival rate when the space was restored with a fixed dental prosthesis (92%) compared to when the space remained untreated (81%) (Fig. 2). Teeth adjacent to spaces restored with a removable partial denture had the poorest 10-year survival rate of 66% (3).

Outcomes following periodontal therapy

Treatment outcomes have been reported in patients with periodontitis who had completed active periodontal therapy and received regular periodontal supportive therapy with a mean follow-up of at least 10 years. In a number of studies, tooth survival rates following completion of active therapy have ranged from 88% to 97%, and average annual tooth-loss rates were between 0.07 and 0.14 (23, 35, 44, 50, 85).

Outcomes following endodontic treatment

Root canal treatment has been shown to result in an overall success rate of 84% (95% confidence interval: 81–87%) and a tooth survival rate of 97% (95% confidence interval: 97–97%) over an observation period of longer than 6 years (80). The success rates of teeth treated with a vital pulp was significantly higher than the success rates for teeth treated with a nonvital pulp. In teeth with an overextended root canal filling, the success rate was significantly reduced (70.8%, 95% confidence interval: 69.4–72.2%) compared to those with a flush or under-extended root canal filling (43). In terms of radiological success and frequency of short- or long-term complications, no difference in the outcomes of endodontic therapy was found between a single- and multiple-visit endodontic approach (24). Retreatment of failed root canal treatments showed no differences in terms of long-term outcome following either a surgical or a nonsurgical approach (14).

Outcomes of oral implants placed in pristine (nonaugmented) bone

An overall survival rate of 82–94% in oral implants with an observation period of 10 years has been reported (36). It has also been shown that the incidence of implant loss with a follow-up of at least 10 years ranged from 1% to 18%. In clinically well-maintained patients, peri-implant bone loss of 0.7–1.3 mm over 10 years has been found (79).

More than 1300 types of dental implants in different materials, shapes, sizes and lengths, and with different surface characteristics or coatings, are currently marketed. A current systematic review did not show enough evidence to demonstrate superiority of any particular type of implant or implant system (22), or between a one-stage vs. a two-stage implant placement (21). Moreover, there is limited evidence showing that implants with rougher surfaces are more prone to peri-implantitis than implants with relatively smooth (e.g. machined) surfaces (22).

Smoking has been identified as a significant risk factor for implant failure (34, 77). In patients with periodontitis-associated tooth loss compared with patients who lost their teeth largely unrelated to periodontitis, the risk for developing peri-implantitis was significantly increased over a 10-year follow-up period (risk ratio of 9, 95% confidence interval: 3.94–20.57%) (69) (Fig. 3). Despite the higher incidence of biological complications in patients with periodontitis-associated tooth loss, survival rates of implants were not significantly different from those found in patients with nonperiodontitis-associated tooth loss. The 5- and 10-year survival rates were reported to be greater than 90% in both groups of patients (69).

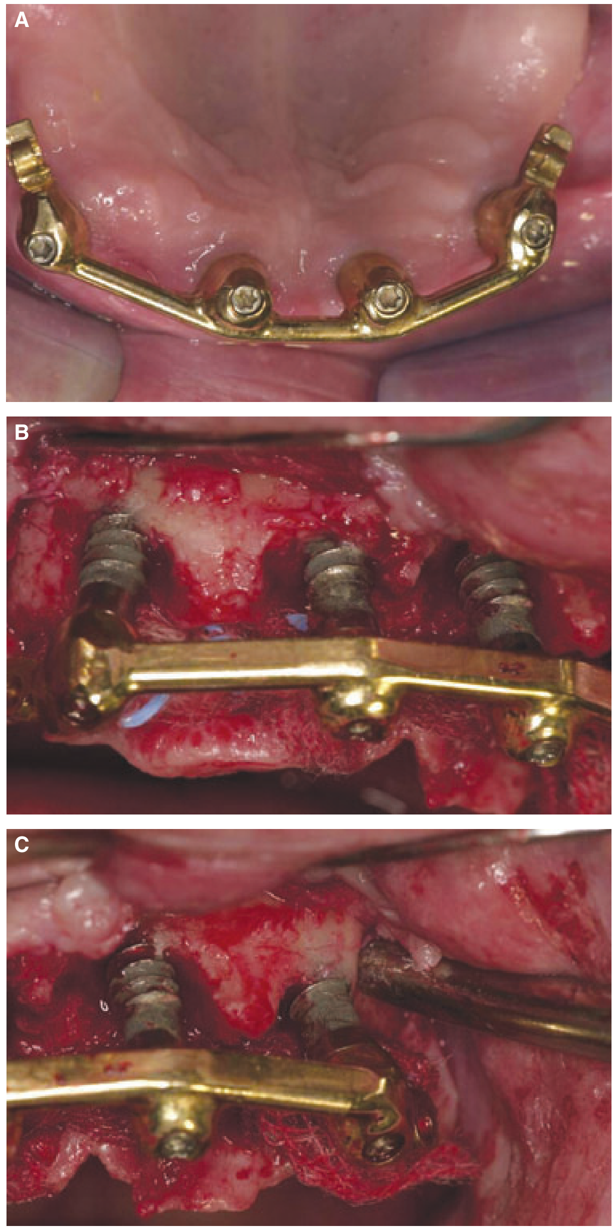

Fig. 3. Peri-implantitis developed at all four implants in the maxilla 2 years after implant placement in a patient who lost all of his maxillary teeth because of aggressive periodontitis.

Outcomes of oral implants placed in augmented bone

Cumulative survival rates for implants in bone that has been regenerated by barrier membranes ranged from 79.4% to 100% after 5 years of function. The survival rates of implants in augmented bone were found to be similar to those generally reported for implants placed in nonaugmented sites (31). The method of bone augmentation does not seem to affect the outcomes of implant therapy because implant survival rates were comparable following guided bone regeneration and distraction osteogenesis (95.8% and 96.5–97%, respectively) (25, 67). The risk for severe complications, however, appears to be greater for distraction osteogenesis than for guided bone regeneration (20). Comparable survival rates of implants inserted in pristine and regenerated bone could also be demonstrated in periodontitis-susceptible patients over an observation period of 3–5 years (69).

The survival rate of implants placed in sinuses augmented using the lateral window technique ranged between 61.7% and 100%, with an average survival rate of 91.8% (81). Survival rates for implants placed in augmented maxillary sinuses were comparable to survival rates for implants placed in pristine bone of the posterior maxilla (95.1%). Implants placed in sinuses augmented with particulate grafts showed a higher survival rate (92.3%) than those placed in sinuses augmented with a block graft (83.3%). The use of autogenous bone alone or as a component of a composite graft does not seem to affect implant survival. Implant survival rates were higher when a membrane was placed over the lateral window (93.6%) compared to when no membrane was used (88.7%) (81). Similar results were found by other authors who reported an overall survival rate of 91.5% when implants were placed in grafted sinuses (15). The implant survival rate in grafted maxillary sinuses was found to be 87.7% with autogenous bone grafts, 94.9% when autogenous bone was combined with various bone substitutes, and 96.0% following the use of bone substitutes alone (15).

Outcomes of implant-supported fixed dental prosthesis

The estimated annual failure rate for implant-supported fixed dental prostheses was reported to range from 0.99 to 1.43 per 100 implant-supported fixed dental prostheses years, translating into a 5-year survival rate of 95.2% and a 10-year survival rate of 86.7% (57). The survival rates have been found to be closely related to the type of veneer material utilized. Five years following placement, metal-ceramic implant-supported fixed dental prostheses showed a significantly higher survival rate of 96.7% (95% confidence interval: 95.4–97.7%) compared to a survival rate of 90.4% (95% confidence interval: 79.9–95.6%) for gold-acrylic implant-supported fixed dental prostheses. Combined tooth-implant-supported fixed dental prostheses demonstrated annual failure rates of between 0.92 and 2.51 per 100 fixed dental prostheses years, translating into a 5-year survival rate of 95.5% and a drastically reduced 10-year survival rate of only 77.8% (57).

Implant-supported single crowns showed an annual failure rate of 1.12–1.14 per 100 implant-supported single crown years, translating into a 5-year survival rate of 94.5% and a 10-year survival rate of 89.4%. Metal-ceramic crowns showed a significantly higher 5-year survival rate (95.4%; 95% confidence interval: 93.6–96.7%) than all-ceramic crowns (91.2%; 95% confidence interval: 86.8–94.2%) (57).

Outcomes of tooth-supported fixed dental prostheses

The reported annual failure rate of tooth-supported fixed partial prostheses has been reported to be 1.28 per 100 tooth-supported fixed dental prostheses years over a mean follow-up time of 5.7 years, and 1.14 per 100 tooth-supported fixed dental prostheses years over a mean follow-up time of 11.9 years (56). This translates into a 5-year survival rate for tooth-supported fixed dental prostheses of 93.8% and a 10-year survival rate of 89.2%. No significant difference between the 10-year survival rates of metal-ceramic tooth-supported fixed dental prostheses (89.1%, 95% confidence interval: 82.9–93.2%) and gold-acrylic tooth-supported fixed dental prostheses (86.3%, 95% confidence interval: 72.6–93.5%) was found (57).

A recent systematic review assessed the outcomes of tooth-supported fixed dental prostheses on abutment teeth with severely reduced periodontal tissue support that received periodontal supportive therapy. The survival rates of these prostheses were found to be 96.4% (95% confidence interval: 94.6–97.6%) after 5 years, and 92.9% (95% confidence interval: 89.5–95.3%) after 10 years. The abutment teeth had an estimated survival rate of 97.5% after 5 years and 95% after 10 years, despite advanced loss of periodontal tissue support and increased abutment tooth mobility. It was concluded that teeth could be used successfully as abutments for extensive restorations (45) (Fig. 4).

For all-ceramic tooth-supported single crowns, the annual failure rate was estimated to be 1.4 (95% confidence interval: 1.0–1.9), translating into a 5-year survival rate for all-ceramic crowns of 93.3% (95% confidence interval: 91.1–95.0%). For metal–ceramic

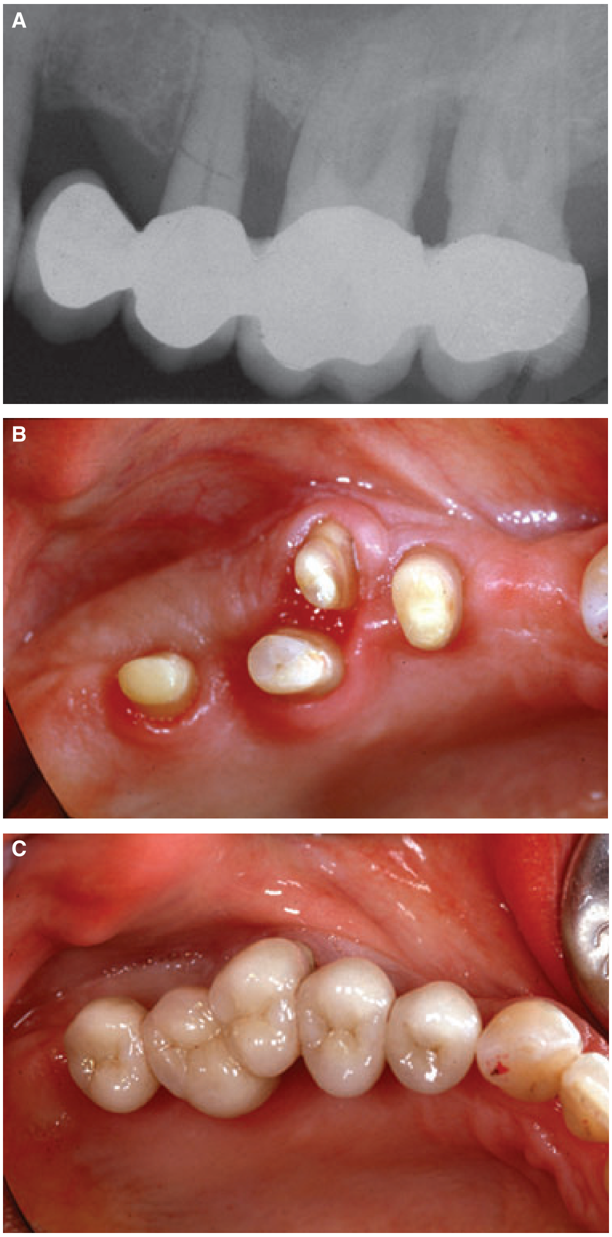

Fig. 4. Teeth with severe loss of periodontal tissue support can be used successfully as abutments for tooth-supported fixed dental prostheses, provided that periodontal therapy is rendered (46).

crowns, the annual failure rate was estimated to be 0.9 (95% confidence interval: 0.5–1.6), translating into a 5-year survival rate of 95.6% (95% confidence interval: 92.4–97.5%) (66).

Evidence-based approach to support decision making in implant dentistry

The evidence summarized above indicates that periodontal as well as endodontic therapies aimed at tooth retention and fixed-dental prostheses, either tooth or implant supported, show similar overall long-term survival rates close to or exceeding 90%. As these data are derived from various cohorts with considerable differences in patient inclusion criteria, treatment protocols and outcome assessments, the information is only descriptive in nature and is of limited use for decision making in implant dentistry. When publication bias is taken into account, it is likely that the reported outcomes are better than found in reality. Trials showing positive intervention outcomes are more than twice as likely to be published than trials with negative findings (18). Thus, every review, which is based on published information, is probably biased towards positive outcomes (73).

As there are no randomized controlled trials directly comparing the outcomes of treatments aimed at tooth retention with those using dental prostheses to replace lost teeth, the available evidence does not support or refute the superiority of one therapy over another. Although it has often been proposed to conduct randomized controlled trials for all conceivable clinical treatment alternatives, it is unlikely that this level of quality information will ever be available. It would be difficult, if not impossible, to design a single- or even a double-blind randomized controlled trial that compares a treatment aimed at tooth retention with the replacement of an extracted tooth using a dental prosthesis. Both the patient and the examiner would naturally be informed about the treatment that was rendered, thus introducing bias to the assessment. There could also be instances where even a random assignment would be unethical, when previous information indicates that one therapy is superior over another (40). As most definitive clinical trials involve multiple centers and a large sample size, it would need to be determined whether they are indeed cost-effective (16, 17, 37).

Decision analysis

Another approach to decision making, which so far has not been applied to implant dentistry, is decision analysis. Decision analysis provides a methodology for comparing alternative treatment strategies by calculating expected values of the resulting outcomes. Quantitatively describing the possible events and their likelihood enables an assessment of the effect of variations in basic assumptions on the optimal therapy. It provides a mechanism to evaluate the same clinical decision along multiple outcome dimensions, such as survival, utility, and costs (60).

Estimating prognosis

Prognosis is a prediction of the course of existing disease based on empirical data and should consider, among other factors, the seriousness of disease at treatment onset, the treatment prescribed, the clinician's skill and the patient's compliance with the treatment protocol (6). Assessing the prognosis of alternative treatments is crucial in making clinical decisions. Frequently used methods to determine prognosis are survival rates, as described for the evidence-based approach above. However, these are crude estimates of the natural course of a disease process and do not often support the decision-making process, especially when there are multiple attributes, value assessments and uncertainty. A formal decision analysis is needed to identify the treatment that would provide the greatest probability of survival or success.

Decision trees

Decision trees are often used for decision analysis, but can also be used for the graphical presentation of prognosis. A decision tree for the prognosis of a tooth with periodontitis receiving periodontal therapy is shown in Fig. 5. The first chance node for periodontal therapy (Periodontal Tx) has two branches for clinical attachment loss (CAL Loss) and no disease progression (Stable). The terminal branches indicate the state of the tooth at the end of the cycle. If attachment loss occurs, the state is termed a complication and if the disease is arrested it is considered a treatment success (Fig. 5A). As disease may progress over time following periodontal therapy, this can be modeled using a recursive decision tree by adding additional branches (Fig. 5B,C). Each repetition of the tree represents a cycle of appropriate length for the events that can occur. In the second cycle the decision is made whether to treat the progressing sites or to extract the tooth, resulting in tooth loss. If the decision is made to treat the condition, attachment loss (CAL Loss) will either continue to progress, rendering the tooth to remain in the complication state, or attachment loss will be arrested (Stable), thus transitioning the tooth into the post-complication state (Fig. 5B). As can be seen from the depiction of the third cycle (Fig. 5C), decision trees can become quite complex ('bushy') when recurrent events are modeled over several cycles. Decision trees can nicely illustrate decision problems, but are limited in their ability to account for the time perspective in chronic conditions where risk remains over time.

Markov model

The Markov model is more convenient for using to model the prognosis of clinical problems with ongoing risk and in the following discussion will be applied to decision making in implant dentistry. Basic assumptions of the Markov model include that a patient, or for the purpose of the present discussion, a tooth or prosthesis, is always in one of a finite number of health states, referred to as Markov states, and that there is no memory in the process. If appropriate data are available, each state can be assigned to a utility and a cost. All events are modeled as transitions from one state to another, using transition probabilities derived from the literature. The time horizon of the analysis is divided into equal increments of time that are called Markov cycles (7, 74).

The state-transition diagram for a tooth undergoing periodontal therapy from the example described in Fig. 5 is shown in Fig. 6. Arrows emanating from and returning to the same state indicate that the tooth has a certain chance of remaining in the same state during subsequent cycles. Tooth loss is the absorbing state as there can be no further transition to another state from this point. For the purpose of this analysis, the cycle length was set to 1 year as most available data present transitions from one health state to another in the form of annual rates. Annual transition rates r retrieved from the literature (23, 28, 38, 61) were transformed into transition probabilities $P[t]$ using the following formula: $P_{[t]} = 1 - e^{-rt}$ (74). Constant transition probabilities were used in accordance with the assumption of the Markov chain because there is little information indicating that transition rates change over the modeled time frame. All teeth were assigned to the same transition probabilities, and patient-specific factors were disregarded because of the lack of appropriate data. These assumptions may only be realistic in patients who are not exposed to any significant prognostic factors for periodontitis and in teeth that have suffered only moderate amounts of alveolar bone loss. As there are no data regarding the utilities of the various health states, only direct treatment costs for the treatments required in each health state could be

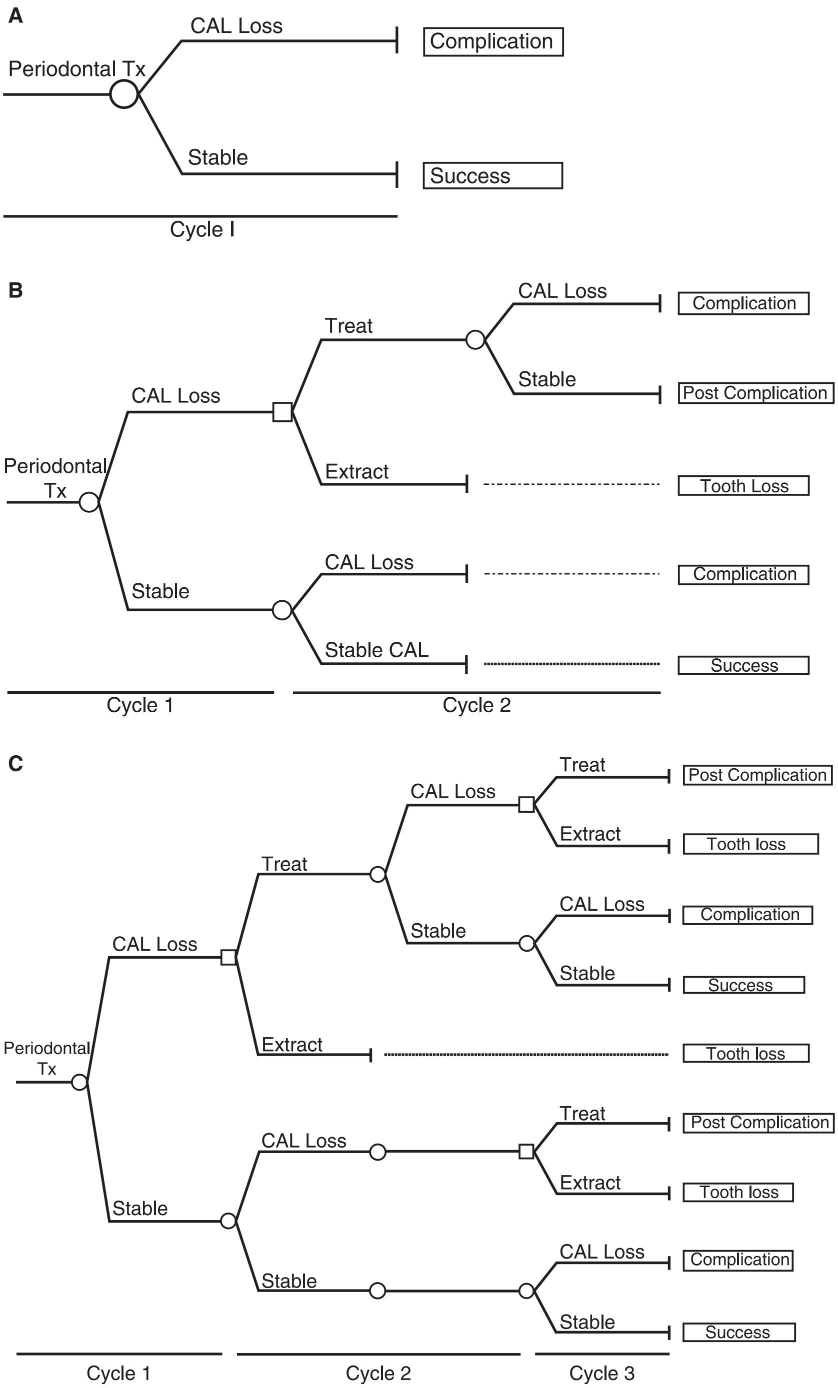

Fig. 5. Decision tree used for modeling the prognosis of a tooth with periodontitis through three cycles (Fig. 5A–C). CAL loss, clinical attachment level loss; Periodontal Tx, periodontal therapy; Stable, stable clinical attachment level. Health states at the end of the last cycle are success, complication, postcomplication, and tooth loss.

considered using median fees from the National Dental Advisory Service in the USA in 2007 (http://www.ndas.com). Costs incurred during active therapy (i.e. scaling and root planing) and periodontal surgery as well as opportunity costs, were disregarded. All costs were discounted at a rate of 3%, as suggested by the Panel on Cost-Effectiveness Analysis in Health and Medicine (62).

A cohort simulation is the most intuitive representation of the Markov process. In this example, all teeth were considered to start in the same state, and following each cycle, teeth transition into another state according to the given transition probabilities. For periodontal therapy, a cohort of 1000 teeth treated for periodontitis was modeled over 10 cycles, representing 10 years in this model. After 10 years, 802 of the 1000 teeth remained in the successful state (80.2%), 15 teeth were in the complication state, 124 were in the post-complication state and 58 teeth were lost, corresponding to

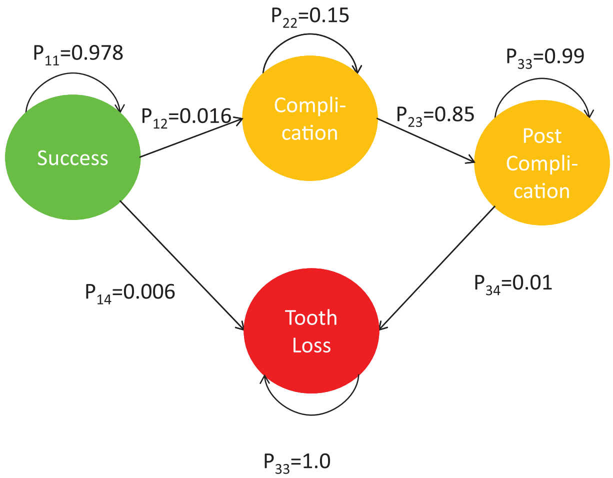

Fig. 6. State-transition diagram for teeth with periodontitis receiving therapy. Arrows indicate the transition from one state to another; transition probabilities are given as fractions of 1. Transition probabilities are derived from Faggion et al. 2007, Gordon et al. 1990, Hujoel et al. 1999, and Rosling et al. 2001 (23, 28, 38, 61).

a 94.2% survival rate (Table 1). The present value of the total costs incurred over 10 years to treat complications and extract teeth (i.e. failure) amounted to $49.2 (=$49,176 ⁄ 1000) per tooth. If the model is run through a sufficient number of cycles, all teeth would eventually be lost. Because the annual failure rate is low, it is not meaningful to calculate the life expectancy of a tooth as it would exceed the average life expectancy of humans.

Markov model in decision making

The Markov process described above can be used in decision making by which each model incorporates all events, and the decision analysis is reduced to compare the values of the three separate Markov models (Fig. 7). For the purpose of this discussion, a rather simple example for the treatment decision of a single tooth presenting with periodontitis is used. Three Markov processes were developed for alternative therapies, including (i) periodontal therapy aimed at tooth retention (Fig. 6), (ii) tooth extraction and replacement using an implant-supported single crown (Fig. 8), or (iii) tooth extraction and replacement using a tooth-supported fixed dental prosthesis (Fig. 9). Transition probabilities for implant-supported single crowns and tooth-supported fixed dental prostheses were derived from the literature (57, 58).

The results of the individual Markov chains for the three alternative treatments demonstrated no major differences in the survival estimates (Fig. 10). Comparing success estimates, which represent the units that had survived and also had no complication during the entire time frame, however, revealed marked differences. Success estimates were higher for tooth retention by periodontal therapy over tooth replacement using either an implant-supported single crown or a tooth-supported fixed dental prosthesis (Fig. 10). It may be noted here that the

Table 1. Cohort simulation of a Markov chain for 1000 teeth with periodontitis receiving periodontal therapy; the corresponding transition probabilities are shown in Fig. 6

Years	States					PV 3%
	Success	Complication $124	Post-complication	Failure $121	Year costs	
0	1000	–	–	–		
1	978	16	–	6	2686	2608
2	957	18	14	11	3622	3415
3	936	18	29	17	4307	3942
4	916	18	44	23	4961	4408
5	896	17	58	29	5616	4845
6	876	17	72	35	6277	5257
7	857	17	86	40	6945	5647
8	838	16	99	46	7618	6014
9	820	16	112	52	8297	6359
10	802	15	124	58	8981	6683
Total						49,176

The present values (PV) of cost for treating complications ($124 for scaling and root planing and antimicrobials) and failures ($121 for extraction) were calculated using a discount rate of 3%.

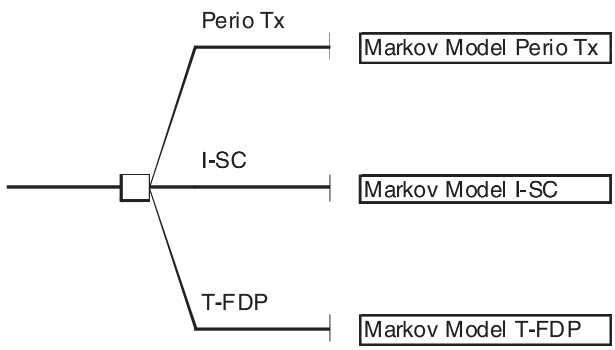

Fig. 7. Markov process used for decision making regarding the treatment of a single tooth with periodontitis. Each Markov Model incorporates all events for each treatment alternative [i.e. periodontal therapy (Perio Tx), implant-supported single crown (I-SC) and tooth-supported fixed dental prosthesis (T-FDP)]. The decision is reduced to comparing the values of the separate Markov Models.

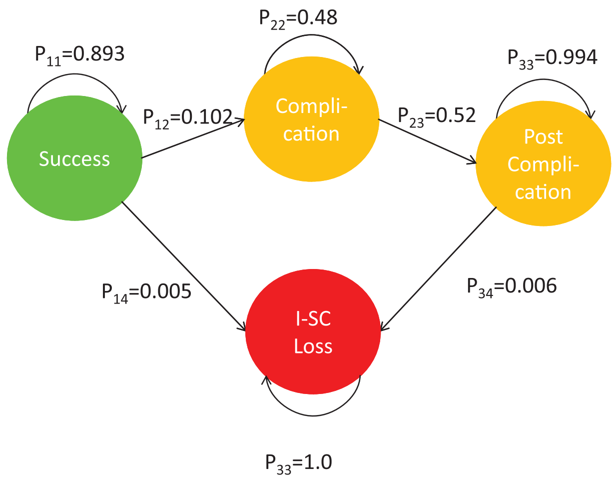

Fig. 8. State-transition diagram for an implant-supported single crown (I-SC). Arrows indicate the transition from one state to another; transition probabilities are given as fractions of 1. Transition probabilities are derived from Pjetursson et al. 2007 (57).

complication rates for the implant-supported single crown applied in this model were derived from studies published between 1999 and 2002 based on implant systems used in the early to mid-1990s (8, 39, 56, 82). As most implant systems have changed in design, complication rates may now differ. Furthermore, there may be limited clinical relevance, depending on the severity of the technical and biological complications included in this category and the extent of therapy needed to repair or manage the complication (Table 2).

The Markov models resulted in survival and success rates comparable to those reported in the systematic reviews for periodontal therapy, tooth-supported fixed dental prostheses and implant-supported single crowns discussed under the evidence-based

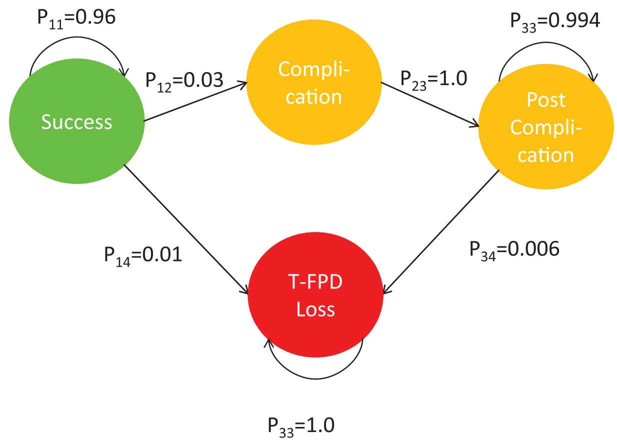

Fig. 9. State-transition diagram for a tooth-supported fixed dental prosthesis (T-FDP). Arrows indicate the transition from one state into another; transition probabilities are given as fractions of 1. Transition probabilities are derived from Pjetursson et al. 2007 (57).

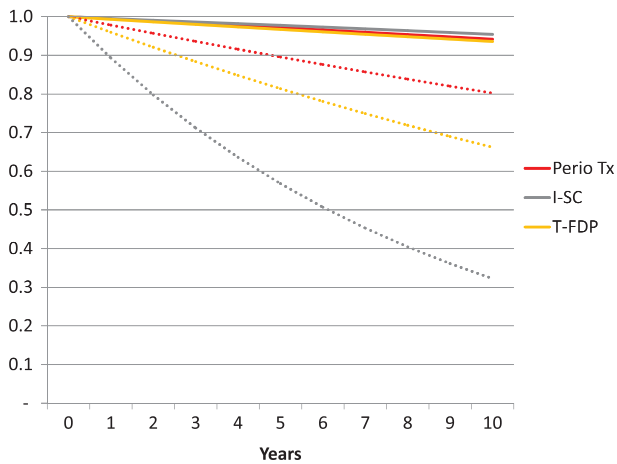

Fig. 10. Overall survival and success rate estimates for a tooth with periodontitis receiving periodontal therapy (Perio Tx), an implant-supported single crown (I-SC) and a tooth-supported fixed denture prosthesis (T-FDP). The estimates result from the Markov Models depicted in Figs 6, 8 and 9. Survival rate estimates are shown as solid lines; success rate estimates are shown as dotted lines.

approach. The advantages of the Markov model over survival curves are its ability to assess utility and to perform a cost analysis. In order to use this advantage for decision making in implant dentistry, more information on patient-centered outcomes and oral health-related quality of life are needed.

The use of the Markov model to perform costs analysis is shown in Table 3. Using median fees from the USA in 2007 (National Dental Advisory Service, http://www.ndas.com), the total direct costs for periodontal therapy, including guided tissue regeneration and a bone graft, were considerably lower when compared with the costs for implant-supported

Table 2. Types of complications reported following periodontal therapy (Perio Tx), root canal treatment, implant-supported single crown, and tooth-supported fixed dental prosthesis (15, 57, 61, 80)

Complications	Treatable	Resulting in failure
Perio Tx	Attachment of bone loss Abscess	Increasing mobility
Root canal treatment	Persistent periradicular disease New periradicular disease Abscess	
Implant-supported single crown	Soft tissue complication Bone loss Esthetic complication Abutment or screw fracture Loose abutment or screws Loss of retention Veneer fracture Ceramic chipping or fracture	Implant fracture Framework fracture
Tooth-supported fixed dental prosthesis	Caries of abutment Loss of vitality Loss of retention Venner of framework fracture Ceramic chipping or fracture	Caries of abutment Periodontitis Abutment fracture

Table 3. Present values of direct treatment costs (US $ in 2007) of periodontal therapy including guided tissue regeneration and bone graft (Perio Tx) for a tooth with an intraosseous alveolar bone defect, extraction of the tooth and replacement with either an implant-supported single porcelain fused to metal crown (I-SC), or by a tooth-supported three-unit porcelain fused to metal fixed dental prosthesis (T-FDP)

	Perio Tx	I-SC	T-FDP
Initial cost	$1780	$3327	$2550
Complication and failure cost	$63	$411	$188
Total	$1843	$3738	$2738

The present values of complication and failure costs over 12 years were calculated using a Markov chain.

single crowns or tooth-supported fixed dental prostheses. As the outcome of a cost analysis depends on the fees for the alternative procedures as well as opportunity costs, cost-effectiveness analyses need to take the costs of an individual healthcare system into account. This is demonstrated by a recently published cost-effectiveness analysis comparing implant-supported single crowns and tooth-supported fixed dental prostheses using the prevailing fee schedule in Switzerland. Including opportunity costs, the analysis showed a slight cost advantage for implant-supported single crowns (9).

Prognostic models

The application of the Markov models discussed above determined overall survival and success estimates for treatment alternatives. They, however, do not include tooth- or patient-specific factors that may influence the prognosis of individual teeth. In patients receiving treatment for periodontitis, various prognostic factors for tooth survival had been identified; these include tooth type, furcation involvement, alveolar bone loss, tooth mobility and compliance (4, 27, 35, 50, 83, 85).

A prognostic model for tooth survival in patients treated for periodontitis over a 12-year period was recently developed using baseline findings from the medical history as well as clinical and radiographic examinations (23). Patients included in this study presented with various systemic conditions and clinical findings with teeth that had bone levels ranging from <10% to ≥90%, pocket probing depth ranging from <3 to ≥13 mm, caries, endodontic lesions and dental restorations. A logistic regression model revealed the diagnosis of diabetes mellitus (odds ratio: 4.2, 95% confidence interval: 1.5–11.6); alveolar bone level (odds ratio: 1.0, 95% confidence interval: 1.03–1.06 for each 1% increment in reduced bone level); tooth mobility (class III vs. class 0; odds ratio: 5.5, 95% confidence interval: 2.1–14.8); root type (multi- vs. single-rooted: odds ratio: 1.8, 95% confidence interval: 1.1–3.0); and a nonvital pulp (odds ratio: 2.2, confidence interval: 1.4–3.6) at baseline examination as significant predictors for tooth loss during supportive periodontal therapy. Although the overall tooth-survival rate following initial therapy in this cohort was 94%, the prognostic model revealed 12-year survival estimates for individual teeth to range from <20% to ≥90% (24). Considering the range of initial disease severities, this finding was not surprising. A graphic presentation of the prognostic model allows estimation of the survival probability for individual teeth (Fig. 11). The prognostic model provides a quantitative estimate for tooth survival prob-

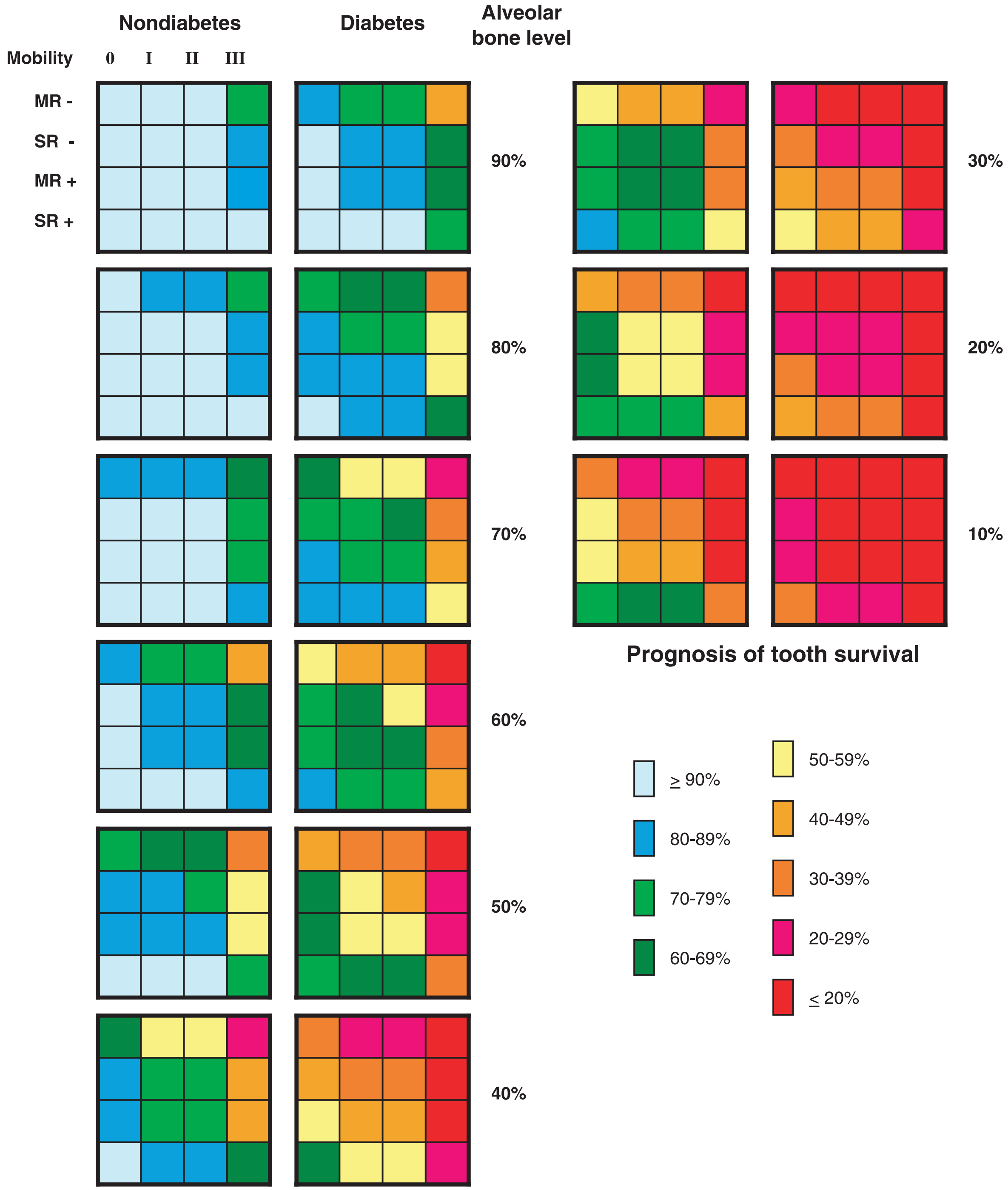

Fig. 11. Prognosis of tooth survival in patients treated for periodontitis. Each square represents a unique combination of predictors. The color coding on the bottom right indicates the tooth survival estimate over an average of 12 years. SR+, single-rooted and vital tooth; MR+, multi-rooted and vital tooth; SR−, single-rooted and nonvital tooth; MR−, multirooted and nonvital tooth. Adapted from Faggion et al. 2007 (23).

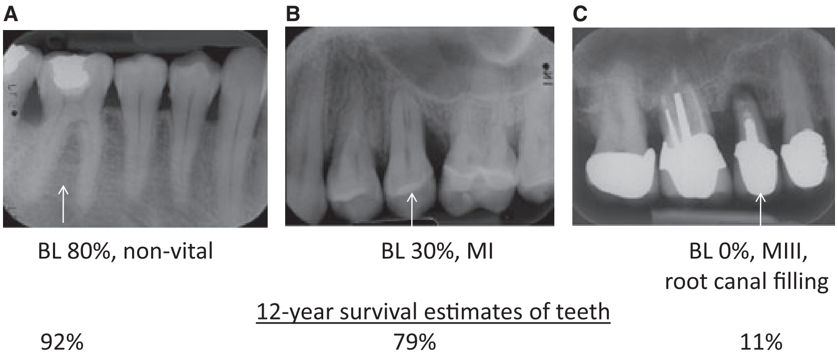

Fig. 12. The prognostic model by Faggion et al. 2007 (24) shown in Fig. 11 applied to the following teeth: (A) mandibular first molar with a bone level of 80% at the most severe site and nonvital pulp; (B) maxillary second premolar with a bone level of 30% and class I mobility; and (C) maxillary second premolar with a bone level of 0%, class III mobility and root canal filling. BL, bone level; MI, class I mobility; MIII, class III mobility.

ability, which may be used for decision modeling, as discussed in further detail below.

When estimating the survival chance of individual teeth, such as those shown in Fig. 12, the dilemma of assessing the prognosis of individual teeth may be exemplified. In all three cases, patients suffered from periodontitis, but the prognosis of the individual teeth may vary considerably under therapy. When determining the prognosis of the cases shown in the left pane (Fig. 12A) and the right pane (Fig. 12C), one may assume that there would be agreement among most providers about the prognosis of these teeth. In qualitative terms, one may give the first molar in the left pane (Fig. 12A) a good prognosis and the second premolar in the right pane (Fig. 12C) a hopeless prognosis. When it comes to the second premolar in the middle pane (Fig. 12B), the prognostic assessment may be more difficult and range from fair to questionable.

There are, however, several problems with these qualitative prognostic terms. The terms are largely based on subjective estimates and therefore do not allow quantitative comparison with alternative therapies. In addition, the interpretation of such qualitative terms may vary largely between providers and patients (70).

Similarly to the model described above for the prognosis of tooth survival, a predictive model for dental implant survival has been reported. In a cohort of 677 patients with a total of 2349 implants, implant survival was found to be statistically associated with smoking status (yes or no), timing of implant placement (delayed vs. immediate) and implant staging (one-stage or two-stage) (13). Although the overall 5-year Kaplan–Meier survival rate estimate was 91.2% (95% confidence interval: 88.8–93.6%), the predicted 5-year survival probabilities ranged from 27.6% in smokers with implants placed immediately following extraction in a one-stage procedure to 93.4% in nonsmokers with delayed implant placement using a two-stage approach (12) (Table 4).

Table 4. Predicted five-year survival probabilities for dental implants: effect of smoking status, timing of implant placement, and staging of implant on survival

Staging	Placement	Five-year survival (%)	
		Nonsmoker	Smoker
Two-stage	Delayed	93.4	81.3
	Immediate	88.2	68.4
One-stage	Delayed	79.2	49.6
	Immediate	64.2	27.6

Adapted from Chuang et al. 2002 (12).

These two prognostic models indicate that there may be considerable variability in the survival probability of individual teeth or implants when certain risk factors exist. In such situations, decision models may identify the best alternative treatment option. In cases where the prognosis is at either end of the spectrum (i.e. good or hopeless), as in the cases presented in Fig. 12A,C, decision models may be of limited clinical value.

There is an important distinction between the two prognostic models. The model for tooth survival used patient and tooth factors, whereas the model for implant survival used procedural factors to forecast outcomes. In the prognostic model for tooth survival, the predictors are immutable to change and the model may be used primarily for aiding the decision of whether or not to treat and retain or extract and replace an individual tooth. The prognostic model for implant survival, on the other hand, identifies the procedures or protocol associated with the best outcomes.

Sensitivity analysis

An important advantage of decision analysis is the ability to assess outcomes over a wide range of disease states and outcome attributes. To explain this further, let us consider the treatment alternatives for the three teeth depicted in Fig. 12. When the prognostic model for tooth survival under periodontal therapy is applied to the tooth types shown in the example and plotted over the full range of bone levels, the range of 12-year survival probabilities can be compared with the survival probability of implant-supported single crowns derived from the Markov model (Fig. 13). As insufficient bone can be augmented before or during implant placement, and as implants in augmented bone seem to present similar survival rates to implants in pristine bone, it may be reasonable to assume that implant survival probability is independent of the bone level at the time of tooth extraction.

The 12-year survival probability for the first molar in Fig. 12A following endodontic and periodontal therapy would be 92%. Comparing this with the 94% survival of the implant-supported single crown estimated from the Markov model, gives an absolute-risk-reduction of 2% (Fig. 13). With an absolute-risk-reduction of 2%, a total of 50 teeth need to be extracted and replaced with implant-supported single crowns in order to have one more implant-supported single crown surviving (47 implant-supported single crowns) after 12 years than the number of teeth surviving following root canal and periodontal therapy (46 teeth). The number-needed-to-treat are calculated by the formula ‘number-needed-to-treat = 1 ⁄ absolute-risk-reduction’ and may be illustrated to the patient as depicted in Fig. 14 to aid shared decision making between providers and patients (46). For the second premolar depicted in Fig. 12B that has an estimated survival probability of 79% following periodontal therapy, the number-needed-to-treat equals 7 (Figs 13 and 15). The number-needed-to-treat for the second premolar in Fig. 12C is only 2 (Fig. 13).

The sensitivity analysis of the three cases probably supports the clinical judgment of most providers regarding the preferred course of action for the two cases at the extreme ends of the disease-severity spectrum shown in Fig. 12A,C, at least with regard to retaining or extracting the teeth. Whether or not an implant-supported single crown or a tooth-supported fixed dental prostheses with the adjacent teeth as abutments is preferable to replace the maxillary second premolar in Fig. 12C may be more contentious. As both treatments have com-

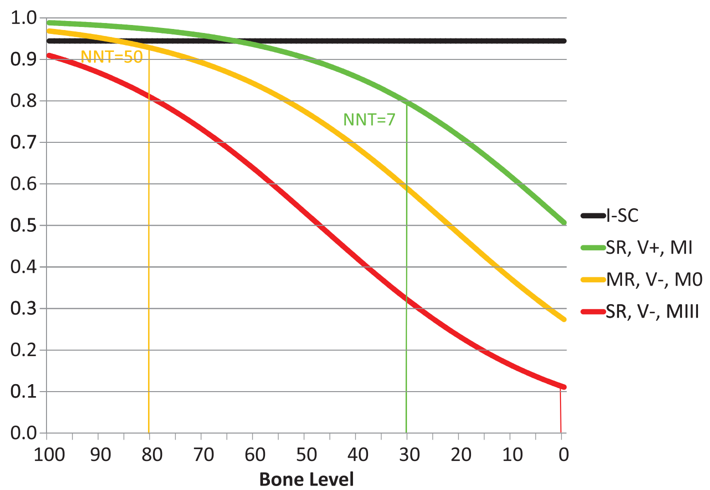

Fig. 13. Sensitivity analysis for estimated 12-year tooth and implant-supported single crown (I-SC) survival rates. The black horizontal line represents the 94% survival probability of the implant-supported single crown calculated in the Markov process shown in Fig. 8. The other lines model the survival probabilities of the teeth shown in Fig. 12 over the entire range of bone levels using the prognostic model of Faggion et al. 2007 (23). The green line represents a single-rooted (SR) tooth with class I mobility (MI) and vital pulp (V+) such as the second premolar in Fig. 12B; the amber line represents a multirooted (MR) tooth with nonvital pulp (V–) and no mobility (M0) such as the first molar in Fig. 12A; and the red line represents a single-rooted tooth with nonvital pulp and class III mobility (MIII) such as the second premolar in Fig. 12C. All situations were modeled for patients not having a history of diabetes mellitus. The number-needed-to-treat for replacing the teeth with implant-supported single crowns at the bone levels of the mandibular first molar in Fig. 12A equals 50, at the bone level of the maxillary second premolar in Fig. 12B the NNT equals 7 and at the bone level of the maxillary second premolar in Fig. 12C the NNT equals 2. I-SC, implant-supported single crown; NNT, number-needed-to-treat.

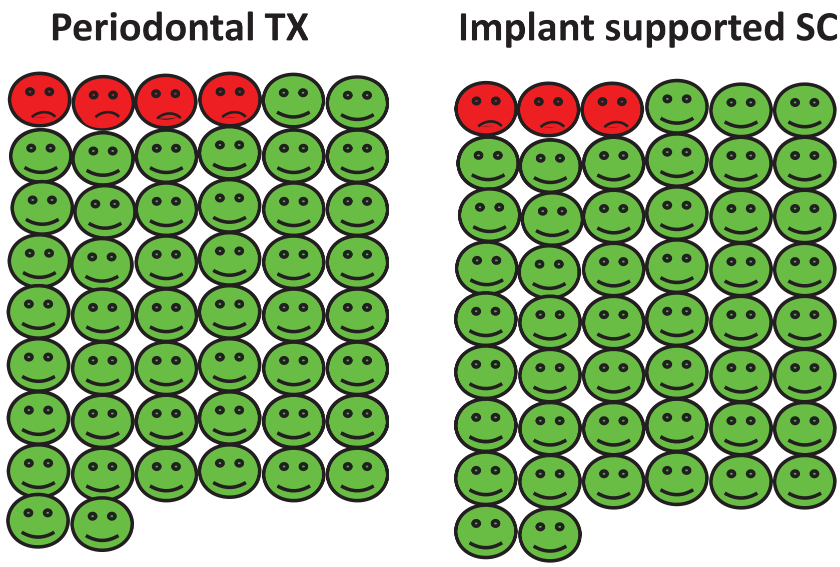

Fig. 14. Patient decision aid to illustrate the difference in outcome between alternative therapies. In this figure, the difference of a 92% survival probability of teeth following periodontal therapy is compared with a 94% survival probability of an implant-supported single crown. It represents the choice between treating the first molar in Fig. 12A vs. extracting and replacing it with an implant-supported single crown. The number-needed-to-treat for this case equals 50. The happy faces in green indicate surviving teeth or implants and the sad faces in red indicate lost teeth or implants. Adapted from Man-Son-Hing et al. (46). SC, single crown; TX, therapy.

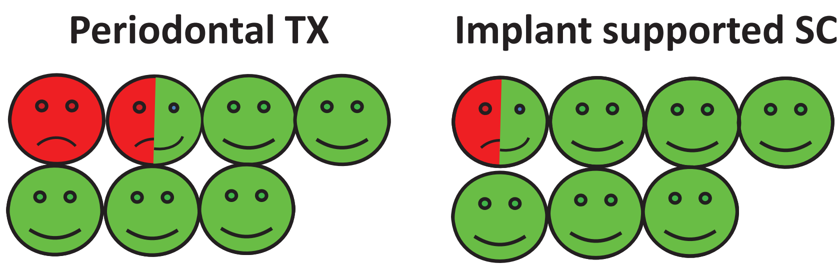

Fig. 15. Patient decision aid to illustrate the number-needed-to-treat for replacing the second premolar in Fig. 12B that has an estimated survival probability of 79% with an implant supported single crown that has a survival probability of 94%; the number-needed-to-treat equals 7. Adapted from Man-Son-Hing et al. (46). SC, single crown; TX, therapy.

parable survival rates and arguably offer similar utilities to the patient, costs may be a deciding factor.

The interpretation of the sensitivity analysis for the case in Fig. 12B, however, requires a more detailed discussion. Based on our lack of information about the utility of various treatment options offered to the patient, especially when more than 20 occluding teeth with greater than four pairs in the posterior arches are present, one may safely assume that the following treatment options offer a similar utility to the patient: (i) retain the tooth and render periodontal therapy, (ii) extract the tooth and replace it with an implant-supported single crown, (iii) extract the tooth and replace it with a tooth-supported fixed dental prosthesis; and possibly even, and (iv) extract the tooth and leave a tooth-bound edentulous space. When the costs are considered from the perspective of a patient bearing the full cost, periodontal therapy (option i) would cost $1843 in today's monies to have a 5.5 out of seven chance of retaining the tooth over 12 years; implant-supported single crown (option ii) would cost $3738 and result in a 6.5 out of seven chance of retaining the implant-supported single crown over 12 years; and tooth-supported fixed dental prostheses (option iii) would cost $2738 with a similar survival chance as an implant-supported single crown. As most of the individuals are risk averse according to the prospect theory (41), several individuals may be willing to trade off higher costs for a lower risk of failure. Providers want to maximize patients' utility and at the same time also have an incentive to maximize the profit of their practice. As providers understandably are concerned about the economic performance of their business, a profit differential between alternative treatments that offer similar utility to the patient may present a conflict of interest and influence decision making.

It is important to note that the above calculation can only be interpreted as a model to illustrate the normative aspect of decision making. Caution should be taken in making any clinical inference. The data used in the decision model were derived from various studies and represent outcomes from different cohorts that have not been directly compared. The predictive model used for estimating the probability of tooth survival under periodontal therapy is far from ideal as it only explains 14% of the variance in tooth loss ($R^2 = 0.14$) (23). Furthermore, point estimates have been used, which may imply a false sense of precision owing to a lack of probabilistic models that better reflect the level of uncertainty involved in forecasting outcomes.

Descriptive aspects in decision making

High-quality research and well-supported data alone are not sufficient for good decision making. Even in areas where there is a high level of scientific evidence or carefully established guidelines from professional or scientific organizations, there is a startling lack of agreement among providers with respect to clinical decision making. For example, when several providers were asked to make treatment recommendations for the same group of patients, unanimous agreement was found in only 21 (8%) of the 275 diagnosed teeth. At the level of the tooth surface, agreement was even lower and merely reached 0.1% (two out of 2435 tooth surfaces) (55, 64). These findings were corroborated by a widely publicized case, where treatment recommendations of various providers given to an individual patient ranged from the restoration of a single tooth to crowning all 28 teeth (19). Agreement on treatment recommendations appears to be somewhat higher among specialists than among general practitioners, at least in some cases, indicating that graduate education may influence decision making (33, 48). Furthermore, a phenomenon known as physician-induced demand may also play a role in the utilization of dental care (54). This may be exemplified by a case of a patient with four asymptomatic impacted third molars. Of the oral surgeons consulted, all of whom were working under a fee-for-service plan, 80% recommended the removal of all four teeth compared with 45% of general dentists working under a fee-for-service plan, and 27% of general dentists working under a capitation plan (33). In managed care, the economic risk is shifted from the third-party payer to the provider, thus giving the provider an incentive to be inactive in case of uncertainty ('when in doubt, don't do it'). A fee-for-service reimbursement, however, gives providers an incentive to be more active, even when uncertainty prevails ('when in doubt, do it') (47).

Framing outcomes

The apparent discrepancy between the normative information and the decision-making process by the provider can be explained by innumeracy, risk preference, providers' heuristics, biases and scripts. Innumeracy and the way a problem is being framed influence the translation of normative decision analysis into clinical decision making. Consider how the treatment options for the second premolar example shown in Fig. 12B and the estimated outcomes in Fig. 13 can be framed. Following periodontal therapy, the tooth has an estimated 12-year survival probability of 79% while an implant-supported single crown replacing the tooth has an estimated survival probability of 94%; the implant-supported single crown has a 15% greater probability of survival than the periodontally treated tooth; in seven cases, there will be one more occlusal unit after 12 years following implant-supported single crown restoration compared with teeth following periodontal therapy; or the failure probability of the tooth is more than three times as high as that of the implant-supported single crown (21% vs. 6%). Although all statements refer to the same data, the way they are framed will influence the providers' and patients' preferences (26).

Providers' scripts

It has been proposed that the provider's knowledge base can be considered to be a collection of scripts that determine what to do in different types of situations (49, 68). Scripts are learned through explicit study, implicit modeling, practice and review. A certain script is then activated through a pattern-recognition process. Changing providers' scripts, even in light of a high level of evidence, is rather difficult and may even be futile in many cases (59). It may require identification of the individual scripts and rewards, determining scripts and situations that produce unsatisfactory outcomes, developing new scripts that can produce satisfactory decisions and training of all relevant people along with the system change needed (30). This may explain why treatment guidelines have had mixed effects (84). A rare example where guidelines have apparently influenced clinical practice stems from the United Kingdom. Guidance for the extraction of wisdom teeth has been issued by the professional body and the National Institute of Clinical Excellence, stating that the prophylactic removal of pathology-free impacted third molars should be discontinued in the National Health Service (52). From 1997 to 2002 the number of extracted third molars was reduced by half (63) and by 2001 there was complete compliance with the guidelines (42).

Concluding remarks

Decision analysis holds great promise for aiding providers and patients in shared decision making regarding the retention or replacement of diseased teeth with implant-supported dental prostheses. By quantifying outcomes for alternative treatments it may help to identify the most appropriate care for individual patients based on utility and costs and thereby mitigate under-treatment and over-treatment. With the increasing availability of electronic health records and progress in health informatics, robust decision-support tools may become available that can be integrated into the clinical workflow.

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