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Root Caries Risk Indicators: A Systematic Review of Risk Models

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Abstract

Objective—To identify risk indicators that are associated with root caries incidence in published predictive risk models.

Methods—Abstracts (n=472) identified from a MEDLINE, EMBASE, and Cochrane registry search were screened independently by two investigators to exclude articles not in English (n=39), published prior to 1970 (none), or containing no information on either root caries incidence, risk indicators, or risk models (n=209). A full-article duplicate review of the remaining articles (n=224) selected those reporting predictive risk models based on original/primary longitudinal root caries incidence studies. The quality of the included articles was assessed based both on selected criteria of methodological standards for observational studies and on the statistical quality of the modeling strategy. Data from these included studies were extracted and compiled into evidence tables, which included information about the cohort location, incidence period, sample size, age of the study participants, risk indicators included in the model, root caries incidence, modeling strategy, significant risk indicators/predictors, and parameter estimates and statistical findings.

Results—Thirteen articles were selected for data extraction. The overall quality of the included articles was poor to moderate. Root caries incidence ranged from 12%–77% (mean±SD=45%±17%); follow-up time of the published studies was ≤10 years (range=9; median=3); sample size ranged from 23–723 (mean±SD=264±203; median=261); person-years ranged from 23–1540 (mean±SD=760±556; median=746). Variables most frequently tested and significantly associated with root caries incidence were (times tested; % significant; directionality): baseline root caries (12; 58%; positive); number of teeth (7; 71%; 3 times positive, twice negative), and plaque index (4; 100%; positive). Ninety-two other clinical and non-clinical variables were tested: 27 were tested 3 times or more and were significant between 9% and 100% of the times tested; and 65 were tested but never significant.

Conclusions—The root caries incidence indicators/predictors most frequently reported were root caries prevalence at baseline, number of teeth, and plaque index. This finding can guide targeted root caries prevention. There was substantial variation among published models of root caries risk in terms of variable selection, sample size, cohort location, assessment methods, incidence periods, association directionality, and analytical techniques. Future studies should emphasize variables frequently tested and often significant, and validate existing models in independent databases.

Introduction

Root caries is a prevalent and debilitating dental disease among older adults (1). Root caries causes tooth loss (2–3), which is the most significant negative factor in oral health-related quality of life for the elderly (4–5). The prevalence of root caries in the general population is increasing as the population ages, since root caries increases with age (6–13). The increased prevalence is associated with people retaining their teeth longer, and with root surfaces becoming physiologically (aging) or pathologically (periodontal disease) exposed, and therefore at risk (1,13–17).

Root caries is a preventable disease. However, available population-based prevention methods (e.g. water fluoridation, fluoridated dentifrices) are not effective on all people equally (1,18–19). Office- and home-based intensive root caries prevention measures are more effective than current population-based prevention measures (13,20–24), but access to care, compliance issues, and cost preclude the use of many of the existing intensive prevention measures on the entire population.

It is known that about a third of the older adult population bears most of the root caries burden (1,18–19). Risk-based prevention has been advocated by researchers to the profession (25–31), but there is no generally accepted practice standard to identify individuals at high risk for root caries. If these high-risk individuals could be identified prior to experiencing the disease, or prior to experiencing advanced disease, they could be targeted with intensive prevention measures, and the disease could largely be prevented and/or mitigated.

The results of studies of risk indicators and of their contribution to disease incidence using regression modeling has successfully informed targeted prevention in medicine and in some dental disciplines for many years (27,32–41). A variety of risk indicators have been associated with root caries in cross-sectional and longitudinal studies (15,42–50), but the heterogeneous results of these many studies are difficult to interpret and apply concisely in clinical situations. Additionally, cause-effect relationships cannot be established solely from associations based on cross-sectional studies.

In view of the increasing prevalence of root caries and the aging of our population, there is a growing need for a better understanding of the associated risk indicators to guide targeted prevention activities. To date, the literature on the prediction of root caries has not been systematically studied. Thus, the purpose of this systematic review was to identify which risk indicators are associated with root caries incidence in published models of risk prediction. Specifically, the key questions examined were: (1) can root caries incidence be predicted by risk models based on subject characteristics, and if so, (2) which risk indicators are consistently and strongly associated with root caries incidence?

Materials & Methods

MEDLINE, EMBASE, and the Cochrane Controlled Trials Registry were searched using the relevant terms “*root caries*” AND *risk*, “*risk model*,” *prediction*, *incidence*, *prevalence*, *epidemiology*, *statistical models*, *logistic models*, *forecasting*, “*risk factors*,” *sensitivity*, OR *specificity*. The inclusion criteria were articles in English, articles published between 1970 and June of 2009, and articles that reported information on root caries incidence, risk indicators, and/or regression models. These criteria were deliberately inclusive to maximize the sensitivity of the search, given that Medline indexing of dental studies in the 1980s was not detailed.

The initial search yielded 472 citations. All citations (titles and abstracts) were screened independently by two investigators to exclude articles not in English (39 citations excluded due to cost of proper translation from the various languages into English), published prior to 1970 (none), or containing no information on either root caries incidence, risk indicators, or risk models (209 citations). The included 224 citations were copied or downloaded from the internet when available through a site license. The reference sections of the articles were searched for additional citations that were not found in the initial search, but no additional citations were identified. Two reviewers conducted independent reviews of the articles. The single full-article inclusion criterion was articles reporting predictive risk models based on original/primary longitudinal root caries incidence. Full-article exclusion criteria were duplicate articles (5 articles), articles with no relevant information on risk indicators for root caries (93 articles), review articles (20 articles), articles reporting cross-sectional studies (57 articles), articles reporting non-original study results (13 articles), and articles reporting no risk model (23 articles). Only articles deemed ineligible by both reviewers were excluded.

Data were extracted from the included articles by one investigator using a data extraction form. A second investigator independently extracted data from a randomly selected sub-sample of articles ($n=8$) using the same data extraction form. There were no disagreements between the two investigators. The data from the extraction forms were then compiled into evidence tables, which included information about the cohort location, incidence period (study duration), sample size, age of the study participants, risk indicators (variables) included in the model, root caries incidence, modeling strategy, significant risk indicators/predictors, and parameter estimates and statistical findings.

The quality of the articles was assessed based both on selected criteria of methodological standards for observational studies (40–41,51) and on the statistical quality of the modeling strategy (52). The quality items covered aspects of internal and external validity (e.g. assessment of outcome, follow-up completeness, proper model specification, strategy for variable selection, overfitting, model validation, etc).

Results

A summary of the total number of excluded and reviewed citations and articles is presented in Figure 1. Thirteen articles reporting root caries risk models that were based on original longitudinal root caries incidence studies were selected for data extraction (16,47,49,53–62). There was no disagreement between investigators at the data extraction phase. A summary of the articles selected for data extraction is presented in Table 1. Follow-up time of the published studies ranged from 1–10 years (median = 3); sample size ranged from 23–723 (interquartile range = 271; mean $\pm$ SD = 264 ± 203 ; median = 261); and person-years ranged from 23–1540 (interquartile range = 1,095; mean $\pm$ SD = 760 ± 556 ; median = 746).

A quality assessment summary is presented in Table 2. The overall quality of the included articles was moderate, while the quality of the statistical modeling approach was poor. Proper description of the cohort and recruitment strategy was given for all but three articles (60–62), and follow-up length was adequate for all but three studies (53–54,60). All articles adequately reported the rationale for variable selection. Outcome assessment methods, including examiner training and calibration, were considered adequate in 9 of 13 studies. Independent validation was not described in any of the reviewed risk models.

Table 3 summarizes the variables examined, modeling strategy, and key findings for the articles included. The root caries incidence ranged from 12–77% (mean $\pm$ SD = $45\% \pm 17\%$). Most models were developed using logistic regression statistics. The significant variables also varied substantially among articles. A summary of the variables tested and

their significance frequency is presented in Table 4. Of the 95 variables tested, only three were tested at least four times and were significantly associated with root caries incidence a majority of the time. These variables were root caries prevalence at baseline (tested 12 times; significant in 58% of the times tested; positive association); number of teeth (tested 7 times; significant in 71% of the times tested; 3 times positive association, twice negative association), and plaque index (tested 4 times; significant in 100% of the times tested; positive association). Ninety-two other clinical and non-clinical variables were tested: 27 were tested 3 times or more and were significant between 9% and 100% of the times tested; and 65 others were tested between 1 and 7 times, but were never significant.

Discussion

Root caries is a preventable dental disease that affects a growing number of adults. Prevention can be optimized if high-risk individuals could be identified, as not all of the adult population carries the same root caries burden. Although predictive modeling has been used in other health areas to help identify high-risk groups for targeted prevention (32,40–41), research in the field of root caries prediction by risk modeling is inconclusive and inconsistent as confirmed in this review.

In the 13 studies reported, over 90 clinical and non-clinical risk indicators were measured and tested. Of these, 30 risk indicators were significantly associated with root caries incidence at least once in at least one study. These risk indicators were selected because of their perceived association with caries either in clinical observational studies or cross-sectional studies, or because of hypothesized associations or convenience. Given the findings to date from the very broad set of risk indicators that have been studied, future approaches to studying root caries risk indicators and risk modeling should be more targeted, as the application of a model with a large number of exploratory variables is no longer justified, nor likely to be clinically practical.

The most frequently tested risk indicator was root caries prevalence at baseline. This variable was significantly associated with root caries incidence in 7 out of the 12 models in which it was tested (47,49,54,56,60–62). Raval & Birkhed (61), reporting on the prediction of root caries in periodontally-treated patients using different fluoride regimens, reported that baseline decayed and filled surfaces (DFS) was significantly correlated with new root DFS during a 24-months incidence period ($R^2 = 0.18$, $p=0.0002$). No detail is provided by the authors in terms of strategy for variable reduction. The generalizability of the study may be questioned, since all included participants ($n=99$) received periodontal maintenance treatment every 3rd to 4th month of the study, and 2/3 of the sample received topical fluoride treatment at every maintenance visit, while the remaining 1/3 of the sample used a daily fluoride rinse at home. However, despite the intense preventive measures, the 2-year incidence of root caries in the entire sample was high (50%). The authors reported no significant difference in root caries incidence among the three fluoride treatment groups.

Joshi *et al.* reported the root caries incidence and risk model in a healthy, community-dwelling middle-aged and older population recruited by the Tufts' Nutrition and Oral Health Study (54). The 16-month incidence of root caries in the sample was 51%, and the population is described as health conscious, compliant, and well educated. In this sample, baseline DFS was significantly correlated with root caries incidence ($\beta=0.13$, $p=0.004$). The odds of developing new root caries were 1.14 times higher for individuals per unit increase of baseline DFS.

Baseline root caries was also a significant predictor of root caries incidence in the Florida Dental Care Study ($\beta=0.83$, $p=0.01$) (47), and in a Japanese cohort ($OR=3.71$, 95% $CI=2.07$,

6.67, $p < 0.001$) (49). Both studies reported a similar 2-year incidence of 36%. Scheinin *et al.* (62) reported that baseline root DFS was a highly significant predictor of 3-year root caries incidence ($OR = 12.8$; $p < 0.0001$), and that the root caries incidence was 51%. Powell *et al.* (60) reported that the baseline root caries index (RCI_{log}) was significantly correlated with root caries incidence in a 1-year study of 21 subjects 65 years-old and older. The overall root caries incidence for the study was high (62%), and the regression coefficient for baseline RCI_{log} was 0.42 ($SE = 0.15$). It is unclear why the authors selected RCI_{log} as their exposure variable as opposed to baseline prevalence.

Locker (56) tested risk indicators as predictors of root caries incidence with and without including baseline root caries in the models. When root caries experience at baseline was not included, the only variable predicting the probability of DFS increment was age ($OR = 2.5$; $p < 0.01$), but the predictive ability of the model was very low ($Sn = 6.7\%$). Modeling DS incidence, three variables entered the model: age ($OR = 2.9$; $p < 0.01$), dental visiting pattern ($OR = 1.9$; $p < 0.05$), and use of removable partial denture ($OR = 2.1$; $p < 0.05$), and the sensitivity of the model was even lower than the DFS model ($Sn = 1.5\%$). When baseline DS and DFS were included in the model, baseline DFS was the only variable predicting DFS incidence ($OR = 2.3$; $p < 0.001$; $Sn = 9.2\%$). Three variables entered the model predicting DS incidence: age ($OR = 2.5$; $p < 0.05$), dental visiting pattern ($OR = 1.9$; $p < 0.05$), and baseline DS ($OR = 2.2$; $p < 0.01$); the sensitivity of this model improved marginally to 7.5%.

Root caries prevalence at baseline was not associated with root caries incidence in 5 studies (16,53,55,58–59). In terms of sample size, subjects' age, location, and incidence period, these studies were not substantially different than those in which baseline root caries prevalence was associated with root caries. Powell *et al.* (59) measured baseline and 3-year incidence of root DMFS. Although the study did not show an association between baseline and 3-year incidence for root surfaces, their model suggests that baseline root caries best predicts coronal caries incidence, whereas baseline coronal caries is the best predictor of root caries incidence (59). One study (57) did not include baseline root caries prevalence in the logistic regression modeling calculations, although this variable was measured and used to calculate root caries increments. Lawrence *et al.* (55) reported that the lack of association between past caries experience and root caries incidence in their study could be attributed to the presence of root fragments in their model, which would have masked the effect of past disease experience.

Number of teeth at baseline was significantly associated with root caries incidence in 5 studies (16,47,54,58,61), but the association directionality was not the same in all studies. Two studies reported that the number of remaining teeth at baseline were negatively associated with root caries incidence (16,58), two reported the opposite (54,61), and one is inconclusive (47). Both Fure (16) and Phelan *et al.* (58), reporting a negative association, measured the number of remaining teeth as a continuous variable. Fure (16) noted that the younger age group (55–65 years) had more remaining teeth than the older age group (75–85 years), which is somewhat expected. In this case, the negative association can be related not only to the number of teeth *per se*, but also to the increased age in the group with fewer teeth. Hence, age and number of teeth may interact and affect root caries incidence. Phelan *et al.* (58) also reported that root caries increased with increasing age ($p = 0.01$). Joshi *et al.* (54) found that subjects with ≥ 22 teeth at baseline were 2.63 times more likely to develop root caries than subjects with less than 22 teeth, and Ravald and Birkhed (61) reported that number of teeth (as a continuous measure) at baseline were positively associated with root caries incidence ($r^2 = 0.28$, $p = 0.0246$). In general, the 2 studies showing a negative association between number of remaining teeth and root caries incidence had a longer duration (5 and 10 years) than the 2 studies showing a positive association between these variables (16 and 24 months). It is possible that in longer studies carious teeth (or teeth in

high-risk subjects) are repeatedly restored and may ultimately fail and have to be extracted, resulting in more disease being present in a lower number of teeth.

Gilbert *et al.* (47), measuring number of remaining teeth in four categories (1–8 teeth, 9–16 teeth, 17–24 teeth, and 25–32 teeth) reported that having 9–16 remaining teeth at baseline was positively associated with root caries incidence (OR=1.9, 95% CI 1.1, 3.4, $p=0.03$). The other three teeth groups were not significant. As the only significant category is a middle category, it is impossible to clearly determine what the direction of the association is based on the results reported.

Number of remaining teeth at baseline was not associated with root caries incidence in two studies (56,60). These studies were not substantially different than the 5 studies in which number of teeth was significantly associated with the outcome. Whether or not number of remaining teeth at baseline is a predictor of root caries incidence needs to be further investigated. Number of remaining teeth is related to age, but age was associated with root caries incidence in only two studies (56,58). In both studies age was measured as a categorical variable. Phelan *et al.* (58) measured age in three categories (<18, 18–44, and 45–64 years), while Locker (56) measured age in two categories (50–74 years, and over 75 years). Both studies found that older subjects developed more caries than younger subjects. These results can be expected as the higher age groups have in theory a higher number of surfaces at risk, but this theory only holds true if the number of teeth remains relatively stable as the subjects age increase. Number of teeth and number of surfaces at risk were not measured/reported in any of these studies, precluding any firm conclusions about age and its association with root caries incidence.

Plaque index was associated with root caries incidence in 3 studies (54,61–62). For Joshi *et al.* (54), a mean plaque score of ≥ 2.0 resulted in a parameter estimate of 0.99 (SE=0.45, $p=0.02$) when compared to a mean plaque score of <2.0. It is unclear how the plaque score was measured. For Ravalid *et al.* (61), root plaque index (%) resulted in a $R^2=0.23$, with a partial correlation=0.24 and $p=0.0069$. In this study, root plaque index was scored as the percentage of exposed root surfaces with visible plaque detected either directly or by probing the surface. Finally, for Scheinin *et al.* (62) visible plaque score (teeth, %) was scored as the percentage of teeth covered by visible plaque related to the total number of teeth, and yielded a OR=2.3 ($p<0.05$).

Of the 8 studies which included Lactobacilli and *S. mutans* salivary counts as independent variables in their models, only three showed a positive association between Lactobacilli counts and root caries incidence (16,59,62). *S. mutans* was also significantly associated in one of these studies (59), but the variable is reported in aggregate as $\log_{10}$ of bacterial counts, so the contribution of each species to the model is unclear. Furthermore, this study (59) involved a convenience sample selected from a large clinical trial, which may lead to limited generalizability to other populations. Fure (16) reported that the overall salivary counts of *S. mutans* and Lactobacilli increased during the study period, and were higher in the older age groups. Lactobacilli were significantly correlated with root caries, but not *S. mutans*. For Scheinin *et al.* (62) both Lactobacilli and *Candida* were significantly associated with root caries incidence, and *S. mutans*, although tested in the model, was not significant.

Increasing age and gingival recession are biological factors required for the onset of root caries, given its etiology and anatomic location. However, this review showed that age was only associated with root caries incidence in 2 studies (56,58) out of the 10 in which this variable was tested, while gingival recession was only tested twice (55,60), one of them being a significant variable (55). Regarding age, one possible explanation for this variable to be missing from most models is the age range of the studies. Only Phelan *et al.* (58) studied

subjects in a wide enough age range to allow the model to be sufficiently discriminative to show age as a significant predictor of root caries incidence. Gingival recession may be considered a *sine qua non* factor for root caries and hence investigators may not use it as an explanatory variable. Additionally, gingival recession is ubiquitous in older adults, and therefore is not expected to be a significant predictor of root caries for this age group.

The quality assessment of the reviewed studies revealed that the overall quality of the included articles was moderate, while the quality of the statistical modeling approach was poor. Four studies did not have adequate outcome assessment methods (16,60–62) either because there was no examiner calibration, or the examinations were not blinded, or both. Follow-up length was at least 2 years in all but three studies (53–54,60), but follow-up completeness (defined as at least 85% of the baseline sample size if follow-up length was less than or equal to 2 years, and adjusted for a 5% annual attrition rate for studies extending over 2 years) was inadequate in 4 out of the 13 studies (55–58). Population characteristics and recruitment methods (inclusion and exclusion criteria) were adequately reported in most studies, as was the rationale for variable selection. However, given the relatively small sample size and the geographical restriction of most studies, generalizability of the findings is compromised. All studies reported on geographically-limited cohorts, and two included only subjects from a sub-set of a larger study (54,58). Only one of the reviewed studies included a relatively large sample size ($n=723$) (47), but even in this study generalizability of the findings can be questioned given that the sampling design targeted African Americans, residents of rural areas, and poor individuals.

Cohort age, study duration (incidence period), examination criteria, and cohort location are important variables that may influence the results of the included studies and, consequently, the results of this review. As already discussed above, cohort age may affect the number of surfaces at risk which directly affects root caries incidence. Similarly, longer studies increase the subjects' probability to develop disease, while different examination criteria may lead to more or less disease. Cohort location may also substantially affect the results of incidence studies, as it is related to the geographical characteristics of the specific cohort, such as diet habits, use of fluoridated water, use of other forms of fluoride, hygiene habits, access to preventive dental care, etc.

Lack of independent model validation was the most important limitation of the reviewed risk models. Risk models should be validated in a different set of subjects from those in which they were developed (41,51). Four out of the 13 reviewed studies tested the predictive ability of the reported models (54,56,60,62), but none of them on an independent cohort. The model reported by Joshi *et al.* (54) included baseline number of remaining teeth, baseline root caries prevalence, and plaque score. The authors reported a sensitivity and specificity of 69.7% and 64.1%, respectively, with 67% correct prediction of disease incidence. Locker *et al.* (56) reported that the predictive ability of their model (which included only age with an $OR=2.5$ and $p<0.01$) was poor, as indicated by the model sensitivity of 6.7%. The predictive power was marginally improved when baseline root caries experience was added to the model as an independent variable ($Sn=9.2\%$). Powell *et al.* (60) tested their model accuracy in a sub-sample of 18 individuals (not part of the study sample), and reported that their ≥ 1 vs. < 1 new root caries model classified correctly 71% of the cases, with a sensitivity of 69% and specificity of 75%. The model has improved predictive ability when the dependent variable is ≥ 2 vs. < 2 new root caries (90% correctly classified; $Sn=100\%$; $Sp=88\%$). Scheinin *et al.* (62) reported accuracy, sensitivity and specificity for their final model including baseline root caries, Lactobacilli counts, and Candida counts. The model's accuracy was 77.1%, with 77.6% sensitivity and 76.6 % specificity.

In addition to lack of validation, none of the reported models described strategies to address model specification bias and inappropriate linearity assumptions. When the initial model is formulated in such a way that creates model specification bias, all later analytical steps may be compromised. One strategy that has been recommended to avoid linearity assumptions is the use of regression splines or nonparametric regression(52).

Root caries risk indicators are, by definition, expected to be related to caries etiological factors: susceptible tooth surfaces (number and anatomic location), biofilm (type of colonizing organisms, adherence factors), availability of fermentable carbohydrate (frequency, type), and host factors (quality and quantity of saliva, other putative immune factors). Known prevention measures, such as use of chemotherapeutic agents (via dentifrices, rinses, and/or professional applications), proper oral hygiene, and proper dietary habits, are also expected to be related to (reduce) caries incidence. Many of these etiological and prevention factors were identified in the risk models summarized in this systematic review. This review may be useful in the planning of root caries prevention studies. Prevention trials should target high-risk individuals, and screen potential participants who fit the risk categories identified in this review may be a strategy for inclusion criteria. For example, high risk individuals would have disease (baseline caries experience), and high plaque index. Future studies should test models containing the variables identified as significant in this review in independent databases, provided that the databases contain information on the variables of interest.

This review also provides insight into possible preventive approaches. Preventive measures that reduce Lactobacilli counts and plaque index would likely reduce disease incidence, given our findings. However, as already stated, future studies should re-examine the directionality of the number of missing teeth and its contribution to the disease process, as well as other variables that were frequently tested and significant.

An important limitation of the predictive root caries risk models in terms of identifying high-risk individuals is the finding that current disease (baseline root caries) is the best predictor of future disease. This finding compromises the use of a root caries risk model as a true preventive tool, as high-risk individuals may not be easily identified prior to having the disease. This systematic review is limited in that it excluded articles not written in English, and articles with cross-sectional study design. Foreign language articles were excluded from the full-review phase due to the high cost of proper English translation. From the 39 articles excluded because of language, a preliminary review of the English abstracts indicated that 5 had potential to be further reviewed, given the limited information available in the abstract. Therefore, some information may have been missed due to the exclusion of these articles. We also intentionally excluded articles reporting studies with cross-sectional study design because they did not contribute incidence information. Although available, risk models derived from cross-sectional data are limited in that any causal relationship between the outcome and explanatory variables cannot be established. Other limitations of this review are directly related to variations among the studies abstracted. For example, the outcome of interest, root caries, was not measured consistently across studies, and results were not always reported using the same outcome measures, which makes it impossible to summarize the data using meta-analysis.

This systematic review shows that caries incidence studies, whether they are interventional studies or not, are a great opportunity to study risk indicators and risk modeling, so long as these studies are properly designed and implemented, and collect information on the proper risk indicator variables. However, it is virtually impossible to conduct a longitudinal caries study and evaluate every possible demographic, behavioral, and health-related putative risk factor (variable). Variables that have been tested often do not necessarily correspond to

those which were positively associated with root caries incidence in risk models, but it is possible that the more a variable is tested, the higher the chances of it emerging as significant in a model due to overfitting. Future root caries studies should attempt to collect variables that were identified as significant in this review.

In conclusion, this systematic review revealed that root caries incidence can be predicted by risk models, and that the most frequently described predictors of root caries incidence in published studies of risk models are root caries prevalence, number of teeth, and plaque index. Root caries prevalence and number of teeth are more easily verified in both private and public oral health settings, and are somewhat logical predictors. High risk populations and individuals could be identified with microbiological tests and plaque measurements. Together, these predictors have the potential to have a positive impact on root caries prevention intervention programs, as resources can be used more selectively on high-risk populations/individuals. There is, however, substantial variation among root caries risk model publications relative to variable selection, sample size, outcomes assessment methods, incidence periods, association directionality, and analytical techniques, which limits the applicability of the findings to guide targeted prevention. Future studies are needed, and should emphasize variables frequently tested and often significant, and validate existing models in independent databases.

Acknowledgments

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Figure 1.
Flowchart summary of total number of reviewed and excluded citations and full articles

Table 1

Summary descriptive data for articles included in the systematic review (by year of publication, most recent first)

Article	Cohort, location	Incidence period	N analyzed	Cohort age at baseline (years)
Phelan <i>et al.</i> , 2004 (58)	Women's Interagency HIV Study - Oral Substudy, Bronx, Chicago, Los Angeles, San Francisco, USA	5 years	308	<18–64
Fure, 2004 (16)	Gothenburg, Sweden	10 years	102	55–75
Takano <i>et al.</i> , 2003 (49)	Niigata, Japan	2 years	373	72
Chalmers <i>et al.</i> , 2002 (53)	Adelaide, Australia	1 year	216	Not reported (Approx 80% <79 years)
Gilbert <i>et al.</i> , 2001 (47)	Florida Dental Care Study, FL	2 years	723	45+
Narhi <i>et al.</i> , 1999 (57)	Helsinki Aging Study, Finland	5 years	110	78.4
Powell <i>et al.</i> , 1998 (59)	Seattle, WA	3 years	256	60+
Lawrence <i>et al.</i> , 1995 (55)	Piedmont 65+ Dental Study, NC	3 years	164 blacks 188 whites	65+
Locker, 1996 (56)	Ontario, Canada	3 years	493	>50
Scheinin <i>et al.</i> , 1994 (62)	Turku, Finland	3 years	96	Mean=62, range= 32
Joshi <i>et al.</i> , 1993 (54)	Tufts' Nutrition and Oral Health Study, Tufts, MA	16 months	130	45–70+
Ravald & Birkhed, 1992 (61)	Linkoping, Sweden	2 years	99	Mean=51, range=43
Powell <i>et al.</i> , 1991 (60)	Not reported	1 year	21	65+

Table 2

Quality assessment for articles included in the systematic review.*

Article	Outcome assessment ¹	Follow-up length ²	Follow-up completeness ³	Population characteristics ⁴	Population recruitment ⁵	Variable selection ⁶	Model validation/overfitting ⁷	Model specification ⁸	Proper linearity assumptions ⁹	Total (+/−)
Phelan <i>et al.</i> , 2004 (58)	+	+	−	+	+	+	−	−	−	5/4
Fure, 2004 (16)	−	+	+	+	+	+	−	−	−	5/4
Takano <i>et al.</i> , 2003 (49)	+	+	−	+	+	+	−	−	−	5/4
Chalmers <i>et al.</i> , 2002 (53)	+	−	+	+	+	+	−	−	−	5/4
Gilbert <i>et al.</i> , 2001 (47)	+	+	+	+	+	+	−	−	−	6/3
Narhi <i>et al.</i> , 1999 (57)	+	+	−	+	+	+	−	−	−	5/4
Powell <i>et al.</i> , 1998 (59)	+	+	+	+	+	+	−	−	−	6/3
Lawrence <i>et al.</i> , 1995 (55)	+	+	−	+	+	+	−	−	−	5/4
Locker, 1996 (56)	+	+	−	+	+	+	−	−	−	5/4
Scheinin <i>et al.</i> , 1994 (62)	−	+	+	−	−	+	−	−	−	3/6
Joshi <i>et al.</i> , 1993 (54)	+	−	+	+	+	+	−	−	−	5/4
Ravald & Brkhd, 1992 (61)	−	+	+	−	−	+	−	−	−	3/6
Powell <i>et al.</i> , 1991 (60)	−	−	+	−	−	+	−	−	−	2/7
Total (+/−)	9/4	10/3	8/5	10/3	10/3	13/0	0/13	0/13	0/13	60/57

* + = yes, adequate; − = no, inadequate, or not reported. Sources (40,52)

¹ Outcome assessment blinded for both dependent and independent variables, and calibrated examiner(s)

² Follow-up length of at least 2 years

³ Follow-up completeness of at least 85% of initial (baseline) cohort if follow-up length ≤ 2 years, adjusted for 5% annual attrition rate if follow-up length > 2 years

⁴ Population characteristics described in sufficient detail (at least sex and age clearly described)

⁵ Population recruitment described in detail (inclusion/exclusion criteria clearly stated)

⁶ Variables selected based on clearly defined criteria (e.g. cross-sectional associations, risk factors), and not only on p value

⁷ Model validated in independent database (subset of development cohort or equivalent cohort)

⁸ Model strategy avoids model specification bias

Use of regression splines or nonparametric regression to address linearity assumptions

9

Table 3

Summary of variables examined, modeling strategy, and key findings of articles included in the systematic review (by year of publication, most recent first)

Article	Variables examined	Root Caries Incidence	Modeling strategy	Significant variables (predictors) included in the final model, and parameter estimate(s)		
Phelan <i>et al.</i> , 2004 (58)	HIV status, age, baseline coronal caries and RC(DMFS and DFS), # remaining teeth, ART types, CD4+ and CD8+ lymphocyte counts, stimulated and unstimulated salivary flow volume, HIV viral load, smoking status (controlled for race/ethnicity)	Not reported	Logistic regression	Variable	Estimate (95%CI)	p
				Age	0.55 (0.01, 0.08)	p=0.01
				# teeth	-0.09 (-0.13, -0.05)	p=0.00
				Unst. saliva	-0.50 (-0.96, -0.02)	p=0.04
				Current smoker	0.54 (0.14, 0.94)	p=0.01
Fure, 2004 (16)	Lactobacilli and S. mutans counts (log), # remaining teeth, # cigarettes/day, # drugs/day, oral hygiene (plaque score), baseline RC (DFS), unstimulated and stimulated saliva secretion rate, # carbohydrate intake/day	12.4%	Stepwise regression	Variable	Partial correlation	β coef
				Lactobacilli (log)	0.37	2.78
				# teeth	-0.45	-0.85
				# drugs/day	0.27	1.76
				Overall p<0.0001; R ² =0.36; F=5.2		
Takano <i>et al.</i> , 2003 (49)	Health (self-rated), hypertension drugs, weight change in 1 year, exercise regularly, smoking, have family MD, education, income, marital status, saliva thickness, gum/dental pain within last month, brushing frequency, use of ID brush/floss, use of fluoride toothpaste, regular dental check-ups/cleanings, have family DDS, frequency of having sweets, blood markers (total protein, albumin, cholesterol, TGC, Ca, inorganic P, creatinine, blood sugar, IgG, IgA, IgM), BMI, have prosthetic crown, root DFS and DFT, pocket depth, attachment loss, S. Mutans and Lactobacilli salivary counts	35.9%	Logistic regression	Variable	OR (95% CI)	p
				Baseline RC	3.71 (2.07, 6.67)	p=0.000
				Prosthetic crown	2.33 (1.24, 4.39)	p=0.009
				Attachment loss	2.32 (1.31, 4.12)	p=0.004
				ID brush/floss	2.05 (1.26, 3.35)	p=0.004
				Pseudo R ² =0.11; Log likelihood=-208.8		
Chalmers <i>et al.</i> , 2002 (53)	Dementia, sex, age (> or < 80), health insurance, education, medical conditions, medications, smoking, alcohol, diet information, swallowing problems, chewing ability, (time and reason for) dental visit since baseline, location and treatment provided at last dental visit, carer burden score, oral hygiene status, baseline DMF, functional status (IADL, ADL), cognitive testing (MMSE, GDS), source of fluoride	44.2% (control) 62.1% (dementia)	Linear regression	Variable	β (SE)	F
				Sex (male)	0.071 (0.291)	0.059
				Dementia	0.945 (0.287)	10.824
				Intercept	0.988 (0.287)	26.332
				R ² =0.075		

Article	Variables examined	Root Caries Incidence	Modeling strategy	Significant variables (predictors) included in the final model, and parameter estimate(s)		
Gilbert <i>et al.</i> , 2001 (47)	Age, sex, race, education, general health, area of residence, smoking, baseline RC, baseline root filling(s), baseline coronal caries, baseline root defect(s), # teeth at baseline (1–8, 9–16, 17–24), %teeth w/4mm attachment loss (13–33%, 34–64%, 65%+), lost 1 or more teeth, RPD, regular dental attender, flosses daily or more often, flosses but less than daily, able to pay but with difficulty, income, insurance, not able to pay.	36%	Logistic regression	Variable	OR (95% CI)	Estimate (SE)
				Baseline RC	2.3 (1.4, 3.7)	0.83 (0.24)
				Baseline fillings	3.6 (2.4, 5.7)	1.29 (0.22)
				9–16 teeth at BL	1.9 (1.1, 3.4)	0.64 (0.30)
				Lost 1+ teeth	1.6 (1.0, 2.5)	0.46 (–0.22)
				Intercept		–1.71 (0.35)
Narhi <i>et al.</i> , 1999 (57)	Type of dentition, gender, age, medication, stimulated saliva, buffer capacity, Lactobacilli, S. mutans counts, Candida, exposed root surfaces	Not reported	Multiple regression	None significant		
Powell <i>et al.</i> , 1998 (59)	Age, gender, ethnicity, birth country, education, smoking, diet (sugar), # medications, # xerostomic medications, self-efficacy, importance of oral health, baseline coronal caries (DMFS), baseline RC (DMFS), S. mutans counts, Lactobacilli counts, salivary flow, salivary buffer capacity	77%	Poisson regression	Variables	Coef (SE)	Rel.risk (95%CI)
				Log bact counts	0.258 (0.085)	1.29 (1.10, 1.53)
				Asian ethnicity	0.617 (0.237)	1.85 (1.16, 2.95)
				Intercept	–3.657 (0.485)	p=0.002 p=0.009
Lawrence <i>et al.</i> , 1995 (55)	Coronal and root surface caries, root and coronal restorations, root fragments, missing teeth, FPDs and RPDs, gingival recession (GR), perio pocket depth (PD), attachment loss, periodontal index of tx needs, saliva flow rate, salivary buffer capacity, S. mutans and Lactobacilli saliva counts, plaque, perio pathogens markers, social, sex, age, race, education, income, health history, dental attitudes and behaviors, health index, physical function or disability, social integration support index, social participation index, depression, use of tobacco, use of alcohol, marital and residential status, use of health services, past medical history, prescribed and OTC meds, weight, height, BP, memory, loneliness, cognition, activities of daily living, severe life events, xerostomic meds.	29% (blacks) 39% (whites)	Logistic regression	Variables	OR (95%CI)	
				Blacks:		
				RPD	3.43 (1.52, 7.76)	
				Root fragments	3.31 (1.28, 8.58)	
				Average GR	1.75 (0.75, 4.12)	
				P. intermedia	2.74 (1.27, 5.92)	
				Impact on appearance	2.24 (1.09, 4.60)	
				Activities of daily living	1.67 (1.12, 2.5)	
				Whites:		
				Worst gingival recession	4.5 (1.95, 10.39)	
				Average PD	3.81 (1.24, 11.69)	
				Worst GR + average PD	3.35 (1.28, 8.76)	
				Antihistamines	4 (1.45, 11.07)	
				Ever taken calcium	2.45 (1.08, 5.57)	
				Age-related problems (>40)	4.99 (2.17, 11.47)	

Article	Variables examined	Root Caries Incidence	Modeling strategy	Significant variables (predictors) included in the final model, and parameter estimate(s)
Locker, 1996 (56)	Age, sex, Canadian born, marital status, education, income, chronic medical condition, activities of daily living, prescription meds, life stress, major life event, dental attitudes score, diet, time since last visit, RPD, baseline RC (DFS), smoking, dental visit pattern, # teeth, health (self-rating), brush/floss frequency, fluoride exposure, recession, attachment loss.	27.4%	Logistic regression	Employment status 3.17 (1.32, 7.61)
Scheinin <i>et al.</i> , 1994 (62)	S. mutans, Lactobacilli, candida/yeast, salivary secretion rate, buffer capacity, sucrose activity, plaque index, age, sex, chronic medication (w/and w/o dry mouth effects), baseline coronal and RC (DFS)	51%	Logistic regression	Variables DFSr Candida Lactobacilli OR (95% CI) 12.8 (2.8, 58.5) 2.8 (0.9, 8.1) 8.6 (2.4, 31.2) Model Accuracy=77.1%, Sn=77.6%, Sp=76.6%
Joshi <i>et al.</i> , 1993 (54)	Baseline RC (DFS), plaque score, # remaining teeth, oral hygiene status, follow-up time	50.7%	Stepwise logistic regression	Variables Baseline RC # teeth Plaque score Model Chi-Sq=24.09; p=0.001; Sn=69.7%; Sp=64.1% Estimate (SE) 0.13 (0.04) 0.97 (0.39) 0.99 (0.45) OR (95%CI) 1.14 (1.05, 1.23) 2.63 (1.22, 5.66) 2.69 (1.11, 6.50)
Ravald and Brkhd, 1992 (61)	Smoking, general health, medication, fluoride use, diet, saliva secretion rate, salivary buffer capacity, Lactobacilli counts, MS counts, sugar clearance, smoking, baseline RC (DFS), root plaque score, baseline coronal caries (DFS), exposed root surfaces, BOP score, age, # remaining teeth	50%	Stepwise multiple regression	Variables Baseline RC Plaque scores # teeth R ² 0.18 0.23 0.28 Partial correlation 0.43 0.24 0.24 p=0.0002 p=0.0069 p=0.0246
Powell <i>et al.</i> , 1991 (60)	age, sex, meds, OH score, recession, prostheses, # remaining teeth, # surfaces, coronal caries, root caries (facial surfaces only, RCI _{log}), carbohydrate exposure, saliva (flow rate, buffer capacity) and micro counts (S. mutans, Lactobacilli)	61.9%	Logistic regression	Variables Gender RCI _{log} Regr. coeff (SE) (coronal+root) -1.06 (0.41) 0.42 (0.15)

RC: root caries; DMFS: decayed, missing, filled surfaces; DFS: decayed, missing surfaces; DFT: decayed fillet teeth; ART: antiretroviral therapy; S. mutans: *Streptococcus mutans*; ID: interdental; BMI: body mass index; OR: odds ratio; IADL: Instrumental Activities of Daily Living scale; ADL: Index Activities of Daily Living scale; MMSE: MiniMental State Examination; GDS: global deterioration scale;

RPD: removable partial denture; FPD: fixed partial denture; PD: pocket depth; GR: gingival recession; OTC: over the counter; BP: blood pressure; OH: oral hygiene; RCI: root caries index; BOP: bleeding on probing; Sn: sensitivity; Sp: specificity.

Table 4

Summary of variables examined, frequency tested, times significant, and percentage of times significant when tested

Variable name	Times tested	Model(s) tested	% times significant (n)	Model(s) significant
Baseline root DFS	12	(16, 47, 49, 53–56, 58–62)	58% (7)	(47, 49, 54, 56, 60–62)
Number of teeth at baseline	7	(16, 47, 54, 56, 58, 60–61)	71% (5)	(16, 47, 54, 58, 61)
Plaque index	4	(16, 54, 61–62)	75% (3)	(54, 61–62)
Lactobacilli counts	8	(16, 49, 55, 57, 59–62)	37% (3)	(16, 59, 62)
Age	10	(47, 53, 55–62)	20% (2)	(56, 58)
Smoking	9	(16, 47, 49, 53, 55–56, 58–59, 61)	11% (1)	(58)
Medication use	9	(16, 49, 53, 55, 57, 59–62)	22% (2)	(16, 55)
Sex	8	(47, 53, 55–57, 59–60, 62)	25% (2)	(53, 60)
<i>S. mutans</i> counts	8	(16, 49, 55, 57, 59–62)	12% (1)	(59)
Saliva flow rate	8	(16, 55, 57–62)	12% (1)	(58)
Saliva buffer capacity	6	(55, 57, 59–62)	17% (1)	(62)
Dental visit pattern	5	(47, 49, 53–54, 56)	20% (1)	(56)
Race/ethnicity	3	(47, 55, 59)	33% (1)	(59)
Prosthetic crown/FPD	3	(49, 55, 60)	33% (1)	(49)
Use of interdental brush/floss	3	(47, 49, 56)	33% (1)	(49)
Attachment loss	3	(47, 49, 55)	33% (1)	(49)
Use of RPD	2	(55–56)	100% (2)	(55–56)
Candida	2	(57, 62)	50% (1)	(62)
Gingival recession	2	(55, 60)	50% (1)	(55)
Teeth loss during study	1	(47)	100% (1)	(47)
Follow-up time	1	(54)	100% (1)	(54)
Dementia	1	(53)	100% (1)	(53)
Root fragments, <i>P. Intermedia</i> , impact of dental health on appearance (self), activities of daily living, pocket depth, taking Ca, more problems since age 40 (self), employment status	1	(55)	100% (1)	(55)
Diet	6	(16, 49, 53, 59–62)	0	-
General health (self-rated)	4	(49, 55–56, 61)	0	-
BL coronal DFS	4	(55, 59–61)	0	-
Education	4	(49, 53, 55, 59)	0	-
Oral hygiene status	3	(53–54, 60)	0	-
BMI	2	(49, 55)	0	-
Marital status	2	(49, 55)	0	-
Alcohol use	2	(53, 55)	0	-
Income	2	(49, 55)	0	-
Bleeding on probing	1	(61)	0	-

Variable name	Times tested	Model(s) tested	% times significant (n)	Model(s) significant
ART types, CD4+, CD8+, lymphocyte counts, HIV viral load	1	(58)	0	-
Health (self-rated), weight change in 1 year, regular exercise, have family, saliva thickness, gum/dental pain within last month, brushing frequency, use of F toothpaste, having family DDS, blood markers (total protein, albumin, cholesterol, TGX, Ca, inorganic P, creatinine, blood sugar, IgG, IgA, IgM)	1	(49)	0	-
Health insurance, medical conditions, swallowing problems, chewing ability, last dental visit location and tx, carer burden score, functional status (IADL, ADL), cognitive testing (MMSE, GDS), source of fluoride	1	(53)	0	-
Baseline root defects, ability to pay	1	(47)	0	-
Type of dentition	1	(57)	0	-
Secondary caries, pocket depths, periodontal index of tx needs, dental attitudes and behaviors, physical function or disability, social integration support index, social participation index, depression, residential status, use of health services, past medical history, blood pressure, memory, loneliness, activities of daily living, severe life events	1	(55)	0	-

RC: root caries; DMFS: decayed, missing, filled surfaces; DFS: decayed, missing surfaces; DFT: decayed fillet teeth; ART: antiretroviral therapy; S. mutans: *Streptococcus mutans*; ID: interdental; BMI: body mass index; OR: odds ratio; IADL: Instrumental Activities of Daily Living scale; ADL: Index Activities of Daily Living scale; MMSE: MiniMental State Examination; GDS: global deterioration scale; RPD: removable partial denture; FPD: fixed partial denture; PD: pocket depth; GR: gingival recession; OTC: over the counter; BP: blood pressure; OH: oral hygiene; RCI: root caries index; BOP: bleeding on probing; Sn: sensitivity; Sp: specificity.