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REVIEW ARTICLE

Caries risk assessment. A systematic review

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Abstract

Objective. To assess the ability of multivariate models and single factors to correctly identify future caries development in pre-school children and schoolchildren/adolescents. ***Study design.*** A systematic literature search for relevant papers was conducted with pre-determined inclusion criteria. Abstracts and full-text articles were assessed independently by two reviewers. The quality of studies was graded according to the QUADAS tool. The quality of evidence of models and single predictors was assessed using the GRADE approach. ***Results.*** Ninety original articles fulfilled the inclusion criteria. Seven studies had high quality, 35 moderate and the rest poor quality. The accuracy of multivariate models was higher for pre-school children than for schoolchildren/adolescents. However, the models had seldom been validated in independent populations, making their accuracy uncertain. Of the single predictors, baseline caries experience had moderate/good accuracy in pre-school children and limited accuracy in schoolchildren/adolescents. The period of highest risk for caries incidence in permanent teeth was the first few years after tooth eruption. In general, the quality of evidence was limited. ***Conclusions.*** Multivariate models and baseline caries prevalence performed better in pre-school children than in school-children/adolescents. Baseline caries prevalence was the most accurate single predictor in all age groups. The heterogeneity of populations, models, outcome criteria, measures and reporting hampered the synthesis of results. There is a great need to standardize study design, outcome measures and reporting of data in studies on caries risk assessment. The accuracy of prediction models should be validated in at least one independent population.

Key Words: *Accuracy, prediction, prognostics, validity*

Introduction

Risk assessment of future caries is done for the individual patient, the most important aim being to institute appropriate preventive measures. Current methods for caries risk assessment comprise a range of strategies in everyday practice [1]. They may include past caries experience, information about socio-demography, socio-economy, oral hygiene, dietary habits, oral bacteria and saliva characteristics. These comparatively objective parameters are often accompanied by a subjective assessment of risk level. The literature on caries risk assessment addresses the accuracy of several single risk factors, combinations of factors and multivariate models. However, the proposed accuracy for assessing future caries risk varies considerably.

The aim of the present systematic review was to assess the accuracy and the quality of evidence of multivariate models and single factors for predicting future caries in pre-school children and schoolchildren/adolescents. The review originates from a systematic review, published in Swedish in 2008 by The Swedish Council on Health Technology Assessment [2], which aimed to assess the scientific evidence with reference to the following question: How accurate are individual risk factors or combinations of them in predicting caries incidence or caries increment in children, adolescents and adults?

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Methods

Literature search and selection of articles

The electronic literature search was performed by an information specialist and included the databases PubMed, The Cochrane Central Register of Controlled Trials and Cochrane Reviews from January 1966 to October 2006. An additional search was made in February 2012. Articles in English, German, Danish, Norwegian and Swedish were accepted. The search strategy is shown in Supplementary Table SI. In addition to the electronic search, a hand search was made and references from narrative reviews, text books and articles in international journals not identified in the main search were included. Grey literature was not included. The abstracts were evaluated independently by two reviewers (IM and ST) according to pre-determined inclusion criteria (Supplementary Table SII). An article was read in full text if one reviewer considered the abstract to be of potential relevance. All full-text articles were assessed independently by the same two reviewers. Any disagreement about inclusion or exclusion of an article was solved by consensus. If a reviewer was co-author of a paper, a third person performed the evaluation. Full-text articles that did not fulfil the inclusion criteria were excluded from further analysis. A flow chart showing the details and results of the search strategy is given in Supplementary Figure S1. A list of excluded articles, with the main reason for exclusion, is given in a Supplementary Appendix.

Quality rating of individual studies

Eighty-two original articles were tabulated and their scientific quality assessed using the QUADAS tool [3]. Each study was rated as high, moderate or poor quality according to pre-determined criteria given in Supplementary Table III. The accuracy of an individual factor or a model was expressed in different ways. Sensitivity and specificity were common, but odds ratio (OR), relative risk (RR), hazard ratio (HR) or incidence density were also used as outcome measures. In order not to lose information, all these outcome measures were accepted. Sensitivity relates to the ability of a risk factor or a model to correctly identify true risk individuals. Specificity, on the other hand, is the ability of a risk factor or model to correctly identify true non-risk individuals. The intention was to combine sensitivity and specificity of separate reasonably homogeneous studies with high or moderate study quality. Any disagreements on inclusion/exclusion criteria, rating quality of individual studies or quality of evidence of methods were solved by consensus. Studies concerning economic aspects of caries prediction could not be identified.

One systematic review on the association between asthma and caries [4] and one on the relationship between sugar consumption and caries [5] were included and assessed using AMSTAR [6].

Quality of evidence

The quality of evidence of the accuracy of multivariate models and single predictors across studies was rated in four levels according to GRADE [7].

- High (⊕⊕⊕⊕). Based on high or moderate quality studies containing no factors that weaken the overall judgement.
- Moderate (⊕⊕⊕O). Based on high or moderate quality studies containing isolated factors that weaken the overall judgement.
- Limited (⊕⊕OO). Based on high or moderate quality studies containing factors that weaken the overall judgement.
- Insufficient (⊕OOO). The evidence base is insufficient when scientific evidence is lacking, quality of available studies is poor or studies of similar quality are contradictory.

Factors that can weaken the quality of evidence are study limitations, indirectness, inconsistency, imprecision and publication bias. Each of these factors may downgrade the quality of evidence. Publication bias was not considered. Study limitations (risk of bias) were recorded if there was uncertainty about blinding of the outcome assessor, insufficient adjustment for confounders or obvious risk of bias due to treatment during follow-up. Indirectness was recorded if a multivariate model or a single predictor was not validated in another independent population. Inconsistency was used to rate down when there was large variability in the results and imprecision lowered the quality of evidence if confidence intervals were wide.

The performance (accuracy) of models and single predictors was graded in three levels according to the sum of sensitivity and specificity: moderate/good: ≥ 1.5, limited: < 1.5 but ≥ 1.3 and poor: < 1.3.

Results

Ninety original articles fulfilled the inclusion criteria. For pre-school children, three studies were graded as high quality [8–10], 14 as moderate [11–24] and the remaining 21 as poor quality [25–45]. For school-children and adolescents, four studies were graded as high quality [46–49], 15 as moderate [50–64] and the remaining 27 as poor quality [65–91]. Six studies reporting on post-eruptive age as a risk factor were of moderate quality [92–97]. The main characteristics of studies with high or moderate quality are presented in Supplementary Tables IVa–c. Studies of poor quality were not included in the tables. The results are summarized in Tables I,II,III. Summaries of the

Table I. Summary of predictors, outcome measures and outcomes from 17 studies of high or moderate quality that used models/combinations or single risk factors to predict future caries in pre-school children.

Reference	Age start (years)	Predictor	Outcome measure	Outcome
Demers et al. [8]	5	Socio-demographic, MS, LB, salivary buffer (SB), oral hygiene, baseline caries prevalence	Se, Sp, OR	Best model: LB + baseline caries: Se = 0.82; Sp = 0.77 MS: Se = 0.28; Sp = 0.92. LB: Se = 0.17; Sp = 0.99 Baseline caries: Se = 0.78; Sp = 0.77. SB: NS
Gao et al. [11]	3–6	(1) Socio-demographic, behaviour, biological; (2) Cariogram	Se, Sp	(1) Best model: Se = 0.83; Sp = 0.92 (2) Se = 0.71; Sp = 0.66
Grindefjord et al. [9]	1	Socio-demographic, behaviour, MS (tongue)	Se, Sp	Best model: Se = 0.87; Sp = 0.83 Best single predictor: immigrant background MS: Se = 0.13, Sp = 0.97 Tooth brush ≤ 1/day: Se = 0.59; Sp = 0.63 Candy > 1/week: Se = 0.72; Sp = 0.45
Grindefjord et al. [12]	2.5	Salivary buffer (SB), LB, MS, baseline caries prevalence, diet, behaviour	OR	Best single predictor: baseline caries: OR = 8.8–13.5 Candy > 1/week = 2.3; MS = 3.2; SB: NS
Holgerson et al. [13]	2	Cariogram	Se, Sp	Se = 0.46; Sp = 0.88
Karjalainen et al. [15]	3	Mother's education, visible plaque, diet, oral hygiene	Se, Sp, RR	Combined: Se = 0.72; Sp = 0.47 Sweets: Se = 0.61; Sp = 0.54
Ismail et al. [14]	0–5 mean 2.6	Socio-demographic, behaviour, diet, oral hygiene, baseline caries prevalence	RR (Caries rate ratio)	Sweet drinks ≥ 2/day = 1.5 Best single predictor: Baseline caries = 1.6–2.3
MacRitchie et al. [16]	1	Socio-demographic (DCRAM model)	Se, Sp	dmft > 0: Se = 0.53; Sp = 0.77 dmft ≥ 3: Se = 0.65; Sp = 0.69
Morou-Bermudez et al. [17]		Saliva and plaque urease, MS, baseline caries prevalence	HR	Increased saliva/plaque urease = 4.98 MS > 10^6 = 4.1; Baseline caries = 3.0
Motohashi et al. [18]	5.5	Baseline dmft	Se, Sp, RR	DMFT > 0: Se = 0.74; Sp = 0.72 (cut-off dmft ≥ 4) Se = 0.74; Sp = 0.72 (cut-off dmft ≥ 5); RR = 2.6–2.7
Niji et al. [19]	1.5	Socio-demographic, behaviour, caries activity	OR	Mother's: Age at childbirth = 3.0; High caries activity = 2.1; Frequent snacking = 2.5
Pienihäkkinen and Jokela [10]	2	Incipient lesions, MS (plaque)	Se, Sp	Best model: Se = 0.72; Sp = 0.77
Pienihäkkinen et al. [20]	2	Visible plaque, incipient lesions, MS (plaque), fluoride use, diet	Se, Sp, OR, AUC	Best model: AUC = 0.81 Baseline caries = 7.3; Se = 0.29; Sp = 0.97 MS = 3.9; Se = 0.69; Sp = 0.78 Candies > 1/week = 3.6; Se = 0.84; Sp = 0.55 Visible plaque = 2.5; Fluoride use: NS
Skeie et al. [22]	5	Baseline caries prevalence including enamel caries	Se, Sp	Best model (predicting DFS): Se = 0.76; Sp = 0.72
Skeie et al. [23]	3	Socio-demographic, baseline caries prevalence	OR	Immigrant status = 3.4; Attitude to diet = 2.4 Baseline caries = 2.2
Wendt et al. [21]	1	Visible plaque, oral hygiene, diet, MS (saliva)	OR	Best predictors of no caries: No visible plaque = 3.6 No sugared liquid at night = 24
Zhou et al. [24]	birth	Demographic, enamel hypoplasia, visible plaque, MS	RR (Caries rate ratio)	High income = 3.1; Enamel hypoplasia = 4.9; Visible plaque = 9.1; MS > 0 = 7.6

Se, sensitivity; Sp, specificity; OR, odds ratio; HR, hazard ratio; RR, relative risk; AUC, area under the ROC-curve; MS, mutans streptococci; LB, lactobacilli; NS, not statistically significant in univariate analysis.

Table II. Summary of predictors, outcome measures and outcomes from 19 studies of high or moderate quality that used models or single factors to predict future caries in schoolchildren and adolescents.

Reference	Age start (years)	Predictor	Outcome measure	Outcome
Alm [50]	1 and 3	Socio-demographic, oral hygiene	OR	Parents´ satisfaction/situation, DFSa ≥ 4 = 2.1–2.3 Insufficient fluoride use at age 3: DFSa ≥ 8 = 7.6
Baca et al. [51]	6–7	Baseline caries prevalence, MS, LB, Alban tests	AUC	No significant relation to MS AUC: dft = 0.67; LB = 0.64. Alban tests = 0.69–0.74
Beck et al. [99]	6 and 10	Socio-demographic, diet, oral hygiene, LB, MS, baseline DMFS, gut feeling	Se, Sp	Model: Low risk area: Se = 0.66–0.76; Sp = 0.71–0.78 High risk area: Se = 0.80–0.84; Sp = 0.54–0.61
Burt et al. [52]	10-15	Sugar intake	RR	Proximal DMFS = 1.8
Chankanka et al. [53]	5	Socio-demographic, dietary, oral hygiene, baseline caries prevalence	HR	Socio-demography: −0,55; juice: −0.69, toothbrushing −0.40, permanent vs primary dentition 0.37
Disney et al. [47]	6 and 10	Baseline caries prevalence, fissure morphology and subjectively predicted caries (gut feeling)	Se, Sp	Best model: Grade 1. Se = 0.59; Sp = 0.84 Grade 5. Se = 0.62; Sp = 0.83
Fontana et al. [54]	5-13	Socio-demographic, behaviour, baseline caries prevalence	Se, Sp	Best models: Any progression: Se = 0.75; Sp = 0.61 Progression to cavitation: Se = 0.73; Sp = 0.62
Hietasalo et al. [55]	11-12	Behaviour, dietary habits	OR	Tooth brushing: 0.31; Candies > 5 times/day: 2.72
Julihn et al. [56]	13	Socio-demographic	OR	Maternal smoking: 1.33; Maternal overweight: 1.37
Kassawara et al. [57]	7-8, 9-10	Baseline initial caries, dmft, DMFT	OR	DMFT >: Initial caries: 1.2 (7–8 years)–1.8 (9–10 years). dmft/DMFT: 9.9 (7–8 years); 3.0 (9–10 years)
Källestål and Fjelddahl [58]	12	Socio-demographic	RR	Low socio-economy: 1.04 Ethnic background: 1.26; Tooth brushing < 1/day: 1.08
Masereijan et al. [59]	6–7, 8–9, 10–11	Socio-demographic, behaviour	RR	Age: 1.09. Baseline caries: 1.03 Tooth brushing < 1/day: 1.45
Peres et al. [60]	6	Socio-demographic, behaviour, baseline caries prevalence	RR, Se, Sp	Baseline caries: 2.7; Se = 0.60; Sp = 0.60. Gingival bleeding: 1.5
Russel et al. [48]	12.6	Baseline DMFS, plaque, several bacterial species, saliva tests	Se, Sp	Best model: combined DMFS, LB and Veilonella: Se = 0.71; Sp = 0.74. DS single best predictor: Se = 0.54; Sp = 0.72
Sanchez-Perez et al. [61]	6	Morphology, baseline caries prevalence, salivary flow rate, MS, LB, Snyder test	OR, Se, Sp	Best model: Se = 0.79; Sp = 0.80 OR: Fissure morphology = 19; Baseline caries = 13; Snyder test = 6
Stenlund et al. [62]	12–13	Baseline proximal DMFS	RR	Baseline ≥ 3 lesions = 3.6; Baseline > 8 lesions = 4.9
Tamaki et al. [63]	5–6	MS, LB, salivary pH, fluoride use, sweet snacks	Se, Sp	Best model: Se = 0.73; Sp = 0.77
Vanobbergen et al. [49]	7	Socio-demographic, plaque, diet, oral hygiene, baseline dmfs	Se, Sp	Best model: almost all from baseline dmfs: Se = 0.59; Sp = 0.73
Vallejos-Sanchez et al. [64]	6–9	Baseline caries prevalence, age, sex	RR	DMFT > 0 = 2.84

Se, sensitivity; Sp, specificity; OR, odds ratio; HR, hazard ratio; RR, relative risk; AUC, area under the ROC-curve; MS, mutans streptococci; LB, lactobacilli.

Table III. Summary of findings from six studies of high or moderate quality that used post-eruptive tooth age as the predictor of caries incidence in schoolchildren and adolescents.

Reference	Age (years at start)	Tooth surface	Outcome measure	Outcome
Abernathy et al. [92]	7–8, 12	1st and 2nd molars	Annual caries rate from life table	Highest risk during the first 2–3 post-eruptive years. Caries rates: year 1: 1st molar: 0.16; 2nd molar: 0.12 year 5: 1st molar: 0.06; 2nd molar: 0.08
Baelum et al. [93]	10–15	All surfaces except permanent 1st molars	Relative risk (RR), Hazard ratio (HR)	Highest risk of both enamel and dentin caries during the first 3 post-eruptive years. RR year 1: 1.9
Carlos and Gittelsohn [95]	4–18	All surfaces	Incidence	Highest caries incidence during the first 3–4 post-eruptive years
Mejàre et al. [94]	12–13	Occlusal and approximal surfaces of permanent teeth	Annual caries rate, Survival analysis	Caries incidence highest during the first 2–3 post-eruptive years. Caries rates (all surfaces): Age 12–15: 2.0; Age 16–19: 0.9; Age 20–27: 0.7
Månsson [96]	5–6	Occlusal surfaces of permanent 1st molars	Life table	Highest risk during the first post-eruptive year. Probability of being caries-free after: 3 months: 0.92; 1 year: 0.57; 2 years: 0.41
Shwartz et al. [97]	6–7, 13–14, 17–18	Approximal surfaces	Survival analysis	Highest risk during the first 4 post-eruptive years. Survival in enamel at age: 11: 4 years; 18: 7 years; 22: 8 years

findings, including the level of accuracy and quality of evidence of the multivariate models and single predictors, are given in Tables IV and V. Pooling of data was not considered possible due to the heterogeneity of the studies regarding both population characteristics, age at start, diagnostic criteria, follow-up times and outcome measures.

Pre-school children

The results of individual studies are summarized in Table I. Almost all studies used multivariate models to predict future caries. Some of the models gave moderate/good accuracy, with a combined sensitivity of > 80% and specificity of > 75% [8,9,11]; others were less accurate [10,15,16,22]. Two studies evaluated the Cariogram [11,13], both with limited accuracy.

Socio-demographic/socioeconomic variables were included in several multivariate models; immigrant background and parents' education/beliefs were significant predictors in six studies [8,9,15,23,24,98]. Baseline caries was the best single predictor in five studies [8,12,14,17,20]. Presence of lactobacilli or mutans streptococci contributed to the accuracy of models and was a statistically significant single risk factor in six studies [8,9,12,17,20,24]; however, accuracy was poor in the majority of the studies (Table I). The methods for collecting and analysing bacterial counts varied. The OR of dietary habits/attitude to diet varied between 1.5–3.6 [12,14,20,23]; one study expressed the OR of not having caries = 24 [21]. The accuracy was poor/limited [9,15,20].

A summary of the findings and quality of evidence of the accuracy of models and single predictors is given in Table IV. The level of accuracy was assessed by an overall judgement based on the outcome of individual studies. Multivariate models had moderate/good accuracy, whereas the accuracy of the Cariogram was limited. Of the single predictors, baseline caries had moderate/good accuracy, while the rest had limited or poor accuracy. The quality of evidence of the accuracy of both multivariate models and single predictors was limited. The most common reasons for this were lack of validation in independent populations (indirectness) and variability in the results (inconsistency).

Schoolchildren and adolescents

In schoolchildren and adolescents, predictor variables were reported as multivariable models in 13 studies [47–49,51,53–55,58,60,61,63,99,100]. In general, the accuracy in terms of sensitivity and specificity was lower than in pre-school children (Table II). Baseline caries experience was included in 11 of the 17 models and was the best single factor in several studies [47–49,60,64]. The contribution to the accuracy of oral bacteria both in models and separately was less obvious than in pre-school children. The predictive value of intake of sugary products was also less clear than in pre-school children; overall, sugar consumption was not a dominant

Table IV. Summary of findings and quality of evidence of level of accuracy of various methods used to predict future caries in pre-school children. Outcome measures were sensitivity, specificity, relative risk, odds ratio, caries rate ratios or hazard ratio. Quality of evidence was rated according to study limitation, indirectness, inconsistency and imprecision.

Prediction method	Sample size/no of studies	Outcome*	Level of accuracy** comments	Quality of evidence
Multivariate model	4006/5 [8–11,16]	Best models: Se > 0.80;Sp > 0.70 [8–11]	Moderate/ good accuracy. Not validated in independent populations	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Cariogram	1837/2 [11,13]	Se = 0.71; Sp = 0.66 Se = 0.46; Sp = 0.88	Limited accuracy	⊕⊕◯◯ Study limitation -1 Inconsistency -1
Baseline caries prevalence	2852/8 [8,12,14,17,18,20,22,23]	Se = 0.78; Sp = 0.77 [8] Se = 0.76; Sp = 0.72 [22] Se = 0.74; Sp = 0.72 [18] Se = 0.29; Sp = 0.97 [20] OR = 2.2–13.5 [12,23] RR/HR = 2.3–3.0 [14,17]	Moderate/ good accuracy. Varying ages, baseline caries prevalence (risk) and outcome caries level	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Socio-demography/ socio-economy	5282/8 [8,9,11,14–16,23,24]	Immigrant background: Se = 0.77; Sp = 0.59 [9]; OR = 3.4 [23] Parents education: Se = 0.69; Sp = 0.57 [8]	Limited/poor accuracy. Not validated in independent populations. Statistically significant in univariate analysis	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Dietary habits/ attitude to diet	2482/6 [9,12,15,20,21,23]	Candies > 1/week: Se = 0.72; Sp = 0.45 [9] Sp = 0.84; Sp = 0.55 [20] Se = 0.72; Sp = 0.47 [15] OR: 1.5–2.3 [12,23]; No sugar at night: OR (to avoid caries) = 24 [21]	Poor accuracy Statistically significant in univariate analysis	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Oral bacteria (MS, LB)	2437/6 [8,9,12,17,20,24]	MS: Se = 0.13; Sp = 0.97 [9] Sp = 0.28; Sp = 0.92 [8] Se = 0.69; Sp = 0.78 [20] OR = 3.2–3.9 [12]; HR = 4.1–7.6 [17,24] LB: Se = 0.17; Sp = 0.99; OR = 32 [8]	Poor accuracy (high specificity) Statistically significant in univariate analysis	⊕⊕◯◯ Study limitation -1 Inconsistency -1
Oral hygiene/use of fluoride	1442/3 [8,9,20]	Se = 0.55; Sp = 0.63 [8] Se = 0.59; Sp = 0.63 [9] One study: NS [20]	Poor accuracy	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Salivary buffer capacity, urease	1200/3 [8,12,17]	NS [8,12] Increasing saliva urease: HR = 4.98 [17]	Salivary buffer capacity of no predictive value	⊕⊕◯◯ Indirectness -1 Imprecision -1
Post-eruptive age	No data		Insufficient evidence.	⊕◯◯◯

*Available confidence intervals are given in Supplementary Table SIVa. **The accuracy (utility) of models and single predictors was graded in three levels according to the sum of sensitivity and specificity: ≥ 1.5 = moderate/good; < 1.5 but ≥ 1.3 = limited and < 1.3 = poor. ***NS = not statistically significant in univariate analysis. MS, mutans streptococci; LB, lactobacilli.

factor in the models. Burt & Szpunar [52] concluded that caries incidence was poorly correlated to sugar consumption in a low caries prevalence population of schoolchildren aged 10–15 years (Supplementary Table SIVb). High consumption of candies (> 5 times/day) was, however, a significant risk factor (OR = 2.7) in one study [55]. Salivary buffer capacity did not contribute to the prediction of future caries. The subjective assessment of risk level ('gut feeling') was reported only in one study [47]. Together with previous caries experience and fissure morphology, it was as accurate as when the whole model was used.

Post-eruptive tooth age as a predictor of caries incidence was investigated in six studies [92–97]. The first few years after tooth eruption was the period with the highest risk of caries incidence and

Table V. Summary of findings and quality of evidence of level of accuracy of various methods used to predict future caries in schoolchildren/adolescents. Outcome measures were sensitivity, specificity, relative risk, odds ratio, caries rate ratios or hazard ratio. Quality of evidence was rated according to study limitation, indirectness, inconsistency and imprecision.

Prediction method	Sample size/ no of studies	Outcome*	Level of accuracy** Comments	Quality of evidence
Multivariate model	11 118/12 [47–49,51,53–55, 58,60,61,63,99,100]	Best model [99]: Low risk area: Se = 0.66–0.76; Sp = 0.71–0.78. High risk area: Se = 0.80–0.84; Sp = 0.54–0.61	Limited accuracy. Outcome from the only externally validated study	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Baseline caries prevalence	8234/9 [47–49, 57,59–62,64]	Se = 0.54–0.59; Sp = 0.72–0.73 [48,49]; RR: 1.03–4.9 [59,60,62,64]; OR: 3.0–13 [57,61]	Limited accuracy (best single predictor)	⊕⊕◯◯ Indirectness -1 Inconsistency -1
Gut feeling	2185/2 [47,99]	Not studied separately	Insufficient evidence	⊕◯◯◯
Dietary habits	3998/4 [5,49,52,55]	RR = 1.1–1.7 [52] OR = 2.7 [55] NS [49]; OR or RR: Moderate-to-weak [5]	Limited predictive value in populations with regular exposure to fluoride	⊕⊕◯◯ Study limitation -1 Inconsistency -1
Oral bacteria (MS, LB, Veilonella)	3322/5 [47,48,51,61,63]	Significant or non-significant contribution in models. MS as single predictor: NS [51]	Insufficient evidence	⊕◯◯◯ Study limitation -1 Indirectness -1 Inconsistency -1
Oral hygiene/ fluoride use	6435/4 [49,53,58,59]	HR: −0.54 [53] RR: Tooth brushing < 1or 2/day: 1.08–1.5 [58,59]	Insufficient evidence	⊕◯◯◯ Inconsistency -1 Indirectness -1 Imprecision -1
Saliva buffer capacity	1042/3 [48,61,63]	NS [48,61,63]	No predictive value	⊕⊕⊕◯ Imprecision -1
Post-eruptive age	11739/6 [92–97]	Highest caries incidence the first 3–4 post-eruptive years.	Significant predictor. Confounders not considered	⊕⊕◯◯ Study limitation -1 Inconsistency -1

*Available confidence intervals are given in Supplementary Table SIVb. **The accuracy (utility) of models and single predictors was graded in three levels according to the sum of sensitivity and specificity: ≥ 1.5 = moderate/good; < 1.5 but ≥ 1.3 = limited and < 1.3 = poor. NS, not statistically significant in univariate analysis; MS, mutans streptococci; LB, lactobacilli.

applied to both approximal and occlusal surfaces (Supplementary Table IVc and Table III). The quality of evidence was, however, limited (Table V).

A summary of the findings and quality of evidence of the accuracy of models and single predictors is given in Table V. As for pre-school children, the level of accuracy was assessed by an overall judgement based on the outcome of individual studies. Multivariate models had limited accuracy and the same applied to baseline caries as a single predictor. Dietary habits as a single predictor were of limited value in populations with regular exposure to fluoride. The quality of evidence of the accuracy of multivariate models, as well as of baseline caries and dietary habits, was limited. The evidence was insufficient to determine the accuracy of oral bacteria and oral hygiene/fluoride use. Salivary buffer capacity had no predictive value, with a moderate quality of evidence.

Two systematic reviews, both of moderate quality, were included (Supplementary Table SIVd). One concerned the association between asthma and caries [4]. The authors found no strong evidence of such an association. The other concerned the relationship between sugar intake and caries [5] and concluded that in the modern age of fluoride exposure this relationship is much weaker than it used to be.

Discussion

A systematic search of literature, followed by data extraction and quality assessment, is nowadays a well-established part of evidence-based dentistry. In this process, the inclusion criteria for eligible papers are crucial. The criteria used here were pre-determined by consensus in a working group at The Swedish Council on Health Technology Assessment. The

rationale for using rather strict criteria was to establish evidence on solid ground. The most common reasons for grading a study to poor quality were high risk of bias due to obvious treatment during follow-up, lack of information about examiners or that confounders were not considered in models.

The only externally validated model was the Cariogram, the accuracy of which was limited in pre-school children (Supplementary Table IVa and Table I). In general, the prediction models had not been validated in independent populations and their generalizability is therefore uncertain. The reason for this is that the results of modelling data are valid only for that particular population and are not automatically applicable to another population with different characteristics. For schoolchildren and adolescents only one study could be identified where the model had been validated in another population [99]. The results showed that particularly the sensitivity of the original model differed considerably when applied to another population.

Combining the values of sensitivity and specificity is appropriate if it is assumed to be equally important to correctly identify individuals with and without risk of future caries. The level of accuracy that should be considered useful in clinical practice is a matter of judgement. In the present review, three levels were used: moderate/good, limited or poor. Based on this, multivariable models were judged to have moderate/good accuracy in pre-school children and limited accuracy in schoolchildren/adolescents (Tables IV and V). It should be noted that the evidence for these conclusions was limited due to the variability of the results and the lack of validation of the models (with one exception).

Of the single risk factors, past caries experience was the best predictor in both pre-school children and schoolchildren/adolescents. This measure reflects caries activity in the past. An individual's caries activity would be better reflected by methods that show the present metabolic activity in the biofilm. Counts of different bacterial species have been used for this purpose, but in general their accuracy was poor. The reason for this is probably that the methods used do not properly reflect the metabolic activity in the biofilm [101].

Besides sensitivity and specificity, odds ratio was a common outcome measure. The validity of this measure is also restricted to the particular population from which it is constructed, since the denominator of the ratio is unique to that specific study population.

In pre-school children, dietary habits as a single risk factor were statistically significant in univariate analysis in several studies, but the accuracy was poor (Table IV). Dietary habits are most probably important in pre-school children, since their exposure to fluoride is limited by the use of 'a little fingernail amount of tooth paste'. So it is important not to interpret the lack of accuracy as indicating that good dietary habits are not important, particularly in pre-school children. In schoolchildren/adolescents, no study reported the sensitivity and specificity of dietary habits. Our conclusion that this factor has limited predictive value for this age group was based on a systematic review by Burt & Pai [5], who concluded that sugar consumption is likely to be a more powerful indicator of the risk of caries in persons who are not regularly exposed to fluoride.

The heterogeneity of the studies made it difficult to synthesize data. Study design varied and represented different population characteristics, different ages, follow-up times, diagnostic criteria and definition of disease outcome (e.g. different cut-off points for caries incidence/increment). Varying methods for collecting and analysing bacterial counts were common and sometimes the methods were not well described. Furthermore, the outcome measures varied from sensitivity and specificity to odds ratio, relative risk, caries rate or hazard ratio.

The results of the present systematic review are in line with a recent systematic review of some currently used caries risk assessment systems/guidelines, where it was concluded that their validity is limited [102]. The authors also point to another important aspect of caries risk assessment, namely the benefit to the individual, i.e. are effective preventive measures instituted for individuals targeted as having a high risk of caries?

In summary, there is a great need of consensus regarding the methodological requirements of prospective studies on caries risk assessment; how they should be designed, conducted, analysed and reported. For example, it is important that the population under study is adequately described, that the risk of bias due to treatment during follow-up is considered and that results are reported in such a way that data from individual studies can be pooled. Ideally, as much raw data as possible should be presented. It is equally important that proposed models are validated externally. In addition, studies analysing the cost-effectiveness of caries risk assessment are called for.

Conclusions

In pre-school children the best models, including socio-economic and socio-demographic information, baseline caries and aetiological factors, resulted in moderate/good accuracy, with sensitivity > 80% and specificity > 70%. In general, similar models were less accurate in schoolchildren and adolescents. Past caries experience was the most powerful single predictor in all age groups, the level of accuracy being higher in pre-school children. The quality of evidence of the accuracy of both multivariate models and single predictors was limited. As an alternative or complement

to individual risk assessment, post-eruptive tooth age might be used by considering all individuals at risk during the first few years after tooth eruption. There is a great need of methods that more accurately reflect the activity in the biofilm. It is equally important to investigate the cost-effectiveness of caries risk assessment and whether more complex methods other than 'gut-feeling' contribute to improved dental health among children and adolescents.

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Supplementary material available online

Appendix
Figure S1
Table SI–SIV