PROGRESSION OF APPROXIMAL CARIOUS LESIONS: A REVIEW

Technical Report

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COMMUNITY DENTAL HEALTH SERVICES RESEARCH UNIT

CLINICAL DECISION-MAKING
REPORT NO. 1

1993

The Community Dental Health Services Research Unit is a joint project of the Faculty of Dentistry, University of Toronto and the Dental Division, North York Public Health Department. It is a Health Systems-Linked Research Unit funded by the Ontario Ministry of Health.

The opinions expressed in this report are those of the authors and no official endorsement by the Ministry is intended or should be inferred.

SUMMARY

The study of the progression of dental caries in the approximal surfaces of teeth can provide dentists with valuable information about the diagnosis of clinical caries, the scheduling of recall appointments and radiographs, and the determination of when approximal lesions should be restored. As well, information about the speed of dental caries progression and factors that affect it is essential to any formal decision making process, such as the formation of practice guidelines and "decision trees" about optimal computer-based diagnostic and restorative processes. Of course, this information and these decisions are also important to patients.

Despite its importance and the fact that dental caries progression has been studied for over 20 years, the methods employed to study and accurately measure it have inherent difficulties. However, many of these difficulties have only recently been identified.

This chronological review of the literature indicates that progression rates vary considerably among individuals and that many factors can affect lesion progression, including the patient's exposure to topical fluorides and age. However, the majority of approximal lesions in permanent teeth progress slowly, with the average approximal lesion requiring at least 3 years to progress through the enamel and into the dentin. This slow rate of progression allows the dentist to monitor most approximal lesions over a series of dental appointments before the possible need for restorative intervention. Fewer studies have investigated lesion progression in primary teeth, but the most recent studies indicate that the average outer enamel lesion will require 1.5 to 2 years to penetrate the dentin.

INTRODUCTION

The importance of studies on the progression of approximal carious lesions lies in the valuable information they supply to dentists. The main purpose of these studies is to determine how long decay, once initiated, will remain in enamel or dentine. Results of these studies have practical applications to clinical decision making by dentists. When incorporated into structured recommendations, such as "decision trees" or clinical guidelines, studies of lesion progression may aid the dentist in diagnosing approximal carious lesions and determining when such lesions should be restored or should receive preventive intervention. Progression studies can also help the dentist to schedule when recall appointments and radiographs are necessary. These decisions have a direct impact on patients when one considers the cost of restorative treatment compared to preventive intervention, the cost and health risk concerns of being subjected to frequent radiographs[1], the positive association between radiograph frequency and treatment frequency[2], and the fact that most restorations will need to be replaced and re-replaced during an individual's lifetime[3].

Progression studies of approximal carious lesions in posterior teeth were reported as early as the 1960's[4,5,6], and interest has grown over the last two decades. Studies have evolved in methodology and sophistication from counting lesions that progressed to fitting mathematical formulae to observations[7,8,9]. However, many methodological difficulties and problems in the study of caries progression still exist.

The purpose of this paper is to discuss the various methodologies used to investigate caries progression and to chronologically review studies of approximal caries progression. Using CD/ROM and Medline, the literature was searched for studies that investigated the progression of individual lesions over time. Based on our review of this literature, we have estimated the speed and probability of an approximal carious lesion progressing through tooth enamel.

1. Methods Employed in Progression Studies

In most studies, approximal caries progression is assessed by reading a series of bitewing radiographs taken successively over time. The usual method involves

taking bitewing radiographs at specified intervals and having one examiner view and score the progression of caries in terms of depth as evidenced by the radiolucent shadow. Methods are usually standardized so that at each session the exposure time and the distance between the radiographic source and the screen are the same. The same film type and method of development are used to ensure similar radiographic quality.

Caries extent is usually scored in terms of its depth or penetration through the tooth towards the pulp. Although scoring systems differ, many studies use numeric scores to record the observed lesions. For example, a '0' may denote a caries-free surface or state, while a '1' may describe a lesion within the outer one-half of the thickness of enamel and a '2' in the inner one-half of enamel.

Some studies have used less specific demarcations, classifying enamel lesions with only one score and disregarding how close to dentine the lesion had progressed [4,10,11]. However, using an index that does not divide the enamel into two degrees of penetration reduces the precision that can be achieved when estimating progression rates[12]. Haugejorden and Slack[12] found that with one score, only 11% of the lesions were found to progress but with two scores, 23-25% of the lesions were found to have progressed over the same time period. The increased accuracy that is achieved by dividing the enamel into an outer and inner half is very important with today's emphasis on preventive treatment[12].

Three studies did not quantify caries progression using depth of lesion penetration into the tooth structure[5,13,14]. Muhler *et al.* [5] projected the radiographic image onto a screen, traced it onto a piece of paper, cut it out, and measured progression as differences in the weight of the pieces of paper over time. Rekola [13,14] used planimetry to measure the area of a carious lesion's radiolucency, rather than its depth. Rekola's studies focused on the effect of sucrose versus xylitol chewing gum[13] and sucrose versus fructose[14] on caries progression. Although acceptable, the results from these studies are difficult to compare to the 'depth studies', and are difficult to apply to a clinical setting.

Regardless of the method used to quantify caries progression, studies have

reported their findings in two ways:

(1) the percent of lesions that progressed within a given time period, most often measured as the proportion of lesions that went from one state to another state (e.g. from the outer half of the enamel to the inner half of the enamel), or the proportion of lesions that remained in one state and;

(2) the mean or median survival time of a lesion, calculated by measuring the period of time that each of a number of carious lesions remain in a specific state. This estimate can also be reported as the mean time required for a lesion to progress through a state.

2. Problems with the Measurement of Caries Progression

The study of approximal caries progression is difficult and there are a number of problems associated with it. A major obstacle to the study of caries progression is that the use of radiographs to measure changes in lesion size over time may lack validity and reproducibility. The use of radiographs to measure changes in lesion size over time assumes that the radiographic image accurately represents the actual size of the lesion. However, a number of studies that histologically examined carious teeth after they were radiographed have shown that the radiolucency may underestimate or overestimate the size of the lesion[15,16,17,18]. Studies have also shown that two trained examiners will read a radiograph differently, resulting in different diagnoses and treatment decisions for the same lesion[19,20,21,22]. These measurement problems are the subject of another report in this series and will not be considered here.

Investigators are presented with a second obstacle when measuring of caries progression beyond the enamel. Many dentists restore carious lesions when they enter the dentine, making caries progression in dentin difficult to study. The placement of the restoration interrupts the normal course of lesion progression. Omission of restored lesions from the data or making a retrospective assumption about the state of the lesion when the tooth was restored may lead to underestimation or overestimation of the progression rate[9,23].

Many of the problems associated with the study of caries progression are related to the study's sampling procedure, and the biases it introduces into the estimates of lesion progression rates. Two published articles by Shwartz *et al.*[23,24] discussed these biases, which until then, had not been addressed.

In the past, estimating the time that it took for a lesion to progress through a state involved only uncensored observations (lesions) whose time of entry to and time of exit from a state, such as the outer half of the enamel, are known. Censored observations, lesions whose time of entry to or exit from a state were unknown, were excluded from studies. These censored lesions may have been left censored (the time of entry to a state is unknown), right censored (time of exit from a state is unknown), or doubly censored (both time of entry to and exit from a state are unknown).

Shwartz *et al.*[23] employed the Kaplan-Meier method of survival analysis to take into account censored data when estimating rates of caries progression. Including only uncensored lesions resulted in an overestimate of the progression rate. Using individual cases as examples, the authors showed that when censored and filled lesions were included in the calculations along with the uncensored data, the average time that a lesion remained in the outer half of the enamel increased substantially from 18.9 months to 37.6 months. A similar increase, from 19.8 to 47.4 months, was also reported for inner-enamel lesions.

Shwartz and his colleagues[24] also reported on two biases that occur in most lesion progression studies and offered some study designs to help reduce these biases. The first bias is similar to excluding left censored data and occurs when the post-eruptive age of the surface is not considered. Slowly progressing lesions, present at a study's baseline examination, may have been present for months or years prior to this exam. However, some of these lesions progressed to another state by the time the second examination was carried out, and were recorded as requiring only the time between the baseline and the second examinations to progress; this will result in an overestimate of the percentage of lesions that progress over the period of time between the two successive examinations. A second bias, "length bias sampling", may occur if lesions that progress very rapidly through two or more states are excluded

from the calculation of the percentage of lesions that progress through only one state. For example, if the investigators are studying the percent of lesions that progress from state 0 to state 1 over time 'one', and they exclude lesions that progress from state 0 through state 1 and into state 2 over time 'two', they will underestimate the actual percent of lesions that progressed from 0 to 1.

Shwartz *et al.*[24] proposed two methods for reducing these biases. One suggestion is to perform a study's baseline examination shortly after tooth eruption or caries onset, if this can be determined. This minimizes error when calculating progression rates and probabilities because the investigators know approximately how long each lesion has been present. An alternative is to perform a pre-study examination prior to the baseline exam and include in the study only those lesions that were not present at this pre-study examination. Therefore, the approximate time of initiation of each lesion is known, and the estimate of the percentage of progressed lesions should be more accurate. However, this may still overestimate progression percentages for a specific time period because slowly progressing lesions, present at the pre-study examination, will be excluded.

A further problem is that lesions which appear to have regressed are sometimes counted as examiner errors and are often classified as non-progressed lesions. In 1986, Pitts[25] reported that lesion regression can occur. Studies that recorded reversals as unchanged lesions[26,27,28] or that, for one reason or another, did not include any regressed lesions in their data, possibly assuming them to be errors[29,30,31,32,33], may have overestimated progression rates.

Statistical problems in the study of lesion progression have been addressed by Ekanayake and Sheiham[34]. They reported that the individual should be the sampling unit rather than each lesion or tooth surface. Many statistical tests assume independence of each sampling unit; however, surfaces of the same mouth are exposed to the same environment and hence are not independent.

STUDIES OF APPROXIMAL DENTAL CARIES PROGRESSION

This section is a chronological review of studies of proximal caries progression in permanent teeth, followed by a review of caries progression in primary teeth. A number of these studies have also been summarized in Tables 1, 2, and 3. Studies that investigated lesion progression through the outer and/or inner half of the enamel and reported the number of lesions that progressed over a given time period are listed in Tables 1 and 2. Table 3 was created to summarize studies that estimated survival times or progression rates.

1. Progression Studies in the 1960's

Analyses of the progression of approximal carious lesions towards the pulp were fairly new in the 1960's. Only three studies were found in this period that dealt with the progression of approximal carious lesions in permanent posterior teeth, all of which used bitewing radiography as their diagnostic tool[4,5,6].

In 1966, Backer Dirks[4] reported that 50% of enamel lesions on the mesial surfaces of first and second permanent molars of children between the ages of 7 to 15 remained in the enamel over four years, and 26% remained in the enamel over a period of eight years. However, Backer Dirks[4] did not classify the enamel into inner and outer halves. Thus, slowly progressing lesions that remained in the enamel were classified as non-progressing lesions.

Muhler *et al.*[5] measured the effects of SnF_2 on lesion progression in dental students. Changes in lesion size were calculated by tracing the lesion's radiolucency onto paper, cutting out the tracing, and weighing it. Their study found that the average lesion in the control group increased in size by about 50% in six months and 83% in twelve months. When multiple SnF_2 treatments were provided, the size of the lesion increased by only 14% in six months and about 16% in twelve months. The authors predicted that it would take three years for a fluoride-treated lesion to double in size and only nine months for a non-treated lesion. However, the actual sizes of the lesions in terms or area or depth were never reported; thus, the results are difficult to apply to a clinical setting.

In 1969, Hollender and Koch[6] corroborated the findings of Muhler *et al.*[5], using ten year-old children. About 50% of the lesions in the control group remained confined to the enamel, but this figure increased to about 60% in the fluoride treated experimental group. Although Hollender and Koch[6] also provided data on the various progression patterns of lesions, their methods do not allow for accurate estimates of progression rates to be made.

2. Progression Studies in the 1970's

Based on the substantial increase in the number of published studies, interest in the study of approximal caries progression grew in the 1970's.

Berman and Slack[10] studied approximal lesion progression in permanent molars of 353 children aged 11 to 13 years of age at baseline. They found that 52.6% of the enamel lesions diagnosed at the baseline exam remained confined to enamel three years later and 78% of the sound surfaces remained caries free. For newly erupted teeth, 13.8% of the surfaces developed lesions which remained confined to the enamel over three years, while only 4.8% surfaces developed lesions that progressed to the dentine over the same time period. These results suggest that caries progression is slow. However, only one score was used to classify all enamel lesions, resulting in a less accurate measure of lesion progression. Like the other studies of its time, the authors also did not account for the post-eruptive age of the teeth which may overestimate the percent of caries progressing[23].

Hyde[11] studied the effect of three proposed caries inhibiting agents on the progression of enamel lesions, but did not divide the enamel into an outer and inner half. Hyde found that 6.0%, 37.0%, 71.0%, and 82.0% of the lesions in the control group, who received no topical fluoride treatment, progressed to the DEJ over 6, 12, 18, and 24 months respectively. In a group that received silver nitrate, 0%, 15.6%, 58.3%, and 68.7% of lesions progressed to the DEJ over the same time periods. The other two treatment groups also showed slightly lower caries progression than the control, with 0%, 13.0%, 33.7%, and 51.1% of the phosphate-fluoride treated lesions and 1.0%, 6.7%, 43.8%, and 67.4% of the stannous-fluoride treated lesions progressing

to the DEJ over 6, 12, 18, and 24 months respectively. Over a three year period, Grondahl *et al.*[29] found that almost 90% of the surfaces studied in sixteen year-olds remained sound, while most of the new lesions discovered remained confined to the enamel. Of the surfaces with caries in the outer-half of enamel, 37.7% remained in this stage, and 26.8% progressed to the inner half of enamel[29]. However, only 18.1% of the inner enamel lesions did not progress over this three year period, suggesting that deeper enamel lesions may have a greater probability of progressing.

After another three years, Grondahl and Hollender[30] re-examined 100 of the original 204 subjects examined at the baseline of the study by Grondahl *et al.*[29] and found that 86.1% of the surfaces still remained caries free over the entire six years. Of the outer enamel lesions found at the beginning of the six year period, 25.9% were found to have remained in the outer enamel and 22.6% had progressed to the inner enamel[30]. Of the inner enamel lesions, only 13.5% did not progress over the entire six years. However, progression into and through the dentine was difficult to determine in both studies because most of these lesions were interrupted by treatment. The authors assumed that restorations were placed only when caries had reached the dentine, but this assumption may have led to an overestimation of caries progression since some of the lesions may have been restored at an earlier stage.

Grondahl and Hollender[30] also compared the rates of progression from 16 to 19 years of age [29] and 19 to 22 years of age[30] and found that progression was slower in the older subjects. Similar findings were later reported by Zamir *et al.*[35], although the findings were not statistically significant.

Hollender and Ronnerman[31] studied the effect of orthodontic appliances on the progression of carious lesions in 109 adolescents. They found that the majority of lesions in every state remained in that state after a two year period, indicating a slow rate of caries progression. Only 1.8% of the sound surfaces developed caries over a two year period. Of the 323 surfaces that were initially diagnosed with outer enamel caries, about 72.5% remained in the outer half of enamel while 11.5% progressed to the inner half and only 16.1% progressed to the dentine or were filled. Their study concluded that orthodontic appliances had no aggravating effect. However, as was

pointed out in their paper, no control group existed.

The 1970's marked the beginning of studies which calculated survival times or caries progression rates based on the length of time that the average lesion required to progress to a certain state. Based on observations of 133 children, Marthaler and Wiesner[36] calculated a mean time of 1.33 years for a lesion to penetrate through the outer half of enamel. However, this estimate did not include lesions that were filled before the investigators had diagnosed an inner enamel or dentine lesion. If the authors assumed that all filled lesions had only progressed to the inner half of enamel before being filled, then the mean time to progress through the outer enamel would be 1.71 years. If they assumed that all filled lesions had reached the dentine, the mean time to progress through the outer enamel would be 1.55 years.

Marthaler and Wiesner[36] also determined the median (and other quartile) survival times, which is important because the mean progression rate does not apply to all individuals. A probability distribution of caries progression rates may be more helpful when studying a population. For example, their study found that within 6 months about 10% of the outer enamel lesions penetrated the inner enamel. If non-progressing and filled lesions were excluded, then the median survival time of a lesion in the outer enamel was found to be 0.87 years or 10.5 months. However, the omission of apparently non-progressing lesions, and their assumptions regarding filled lesions, may bias these estimates[23,34]. Including filled lesions, with the assumption that the lesion had only penetrated the inner enamel before being filled, increased the median time to 1.51 years.

Zamir *et al.*[35] also calculated the mean survival time for lesions in 24 adolescents aged 14-15 years and 27 adults aged 21-24 years. Their study found a mean of 13.6 months in the younger group and 17.1 months in the older group for a lesion to progress through the outer enamel into the inner enamel. The mean time to progress through the inner enamel to the dentine enamel junction was calculated to be 12.8 months in the younger group and 15.2 months in the older group. However, no statistically significant difference was found between the two age groups and so combined means survival times of 14.4 months for the outer enamel and 13.6

months for inner enamel were calculated. Zamir *et al.*[36] also determined the median survival time for a lesion in the outer half of enamel to be 9.7 months and 12.5 months for a lesion in the inner half of enamel. This study also excluded non-progressing and filled lesions from its calculations, possibly resulting in an overestimation of the progression rates.

The differing purposes and methods of the studies carried out in the 1970's make it difficult to compare results directly. However, in all cases, progression was reported to be quite slow, with most lesions requiring at least one year to progress through the outer enamel and slightly less time to progress through the inner enamel.

3. Progression Studies in the 1980's

Judging from the number of studies on the progression of approximal caries in the 1980's, interest in caries progression has continued to intensify.

In 1980, Granath *et al.*[26] reported on lesion progression in 126 children aged 12 and 13 years at baseline. After one year, they found that 43% of the outer enamel lesions had progressed to the inner enamel, but only 8% of lesions in the outer half of enamel had progressed to dentine or were filled. After two years, 24% of the outer enamel lesions had progressed through to the dentine or were filled. Of the lesions initially in the inner-half of enamel, 35% and 58% had progressed to the dentine or were filled after one year and two years, respectively.

Powell *et al.*[37] compared fluoride-treated lesions to non-treated controls over a four year period, starting with children aged 12-14 years. Their results indicated that the most effective method for reducing caries progression was a combined treatment of 10% SnF_2 topical solution and a 0.4% SnF_2 dentifrice. After one year, 57% of outer enamel caries in the control group remained unchanged, compared to 69% in the combined fluoride group. Of those lesions that did progress over the first year, 11% of the control group lesions progressed to the dentine or were filled compared to only 3% of the combined fluoride group. After two years, 33% of the control group's lesions and 57% the experimental group's lesions had not progressed,

while 23% and 46%, respectively, had not progressed after three years, and 12% and 35%, respectively, had not progressed after four years.

Powell *et al.*[37] also reported median survival times for the lesions they studied, although they do not make clear how these values were calculated. They calculated the median time for lesion progression from the outer half of enamel to the inner half to be 16 months for both the control group and a group treated with SnF_2 solution. Outer enamel lesions in subjects who were treated with SnF_2 dentifrice or both SnF_2 solution and dentifrice required 19 and 34 months, respectively, to penetrate the inner enamel. The authors determined that it would take an outer enamel lesion about 38 months to reach the dentine in the control group and in the SnF_2 solution group, and projected that this would require 49 months for the SnF_2 dentifrice group and 72 months for the group treated with both fluoride agents.

Methods of analyzing progression data became more complex in the 1980's. Pitts (1983)[7] published a mathematical model to calculate the proportion of lesions that will remain confined to the enamel after a certain period of time. Using this model and results of previously published studies, he estimated that the average enamel lesion remains radiographically confined to the enamel for 3 to 4 years. This estimate increased to 5 to 6 years if only outer enamel lesions were considered rather than all enamel lesions. Pitts concluded that the majority of approximal caries progress slowly. However, the survival time can be much shorter in "caries active individuals".

Darvell and Pitts (1984)[8] also published a mathematical model taking into account age and the period of observation. Using this model and the results of a number of studies previously summarized by Pitts (1983)[7], they estimated the half-life of an enamel lesion in children aged 11-13 years to be 2.7 years. Above and below the ages of 11-13 years, the rates of progression were reported to be slower.

Shwartz *et al.*[9] studied lesion progression in individuals from Sweden and the U.S.A. Overall, they found that the average approximal carious lesion in a newly erupted first permanent molar required 21-23 months to progress through the outer enamel and between 19 to 28 months to progress through the inner enamel.

Progression through the inner-half of enamel was found to be slower in the Swedish subjects than in the U.S. subjects, perhaps due to the greater exposure to fluorides in the Swedes. Rates of progression also appeared to be slower in older adolescents. However, progression rates were found to be extremely variable between individuals, and even between lesions in the same individual.

Shwartz *et al.*[9] also re-analyzed the results of a number of studies already discussed in this paper[4,6,10,11,26,30,38,39], and found that most studies supported their estimates of lesion progression; the average lesion required at least 3-4 years to move through the enamel of permanent teeth.

Modeer *et al.*[40] looked at the effect of fluoride varnish on caries progression in teenagers and concluded that it had a significant effect in subjects that had from two to eight new lesions over the three year study period. However, no effect was found in individuals with a greater incidence of caries, suggesting that the varnish may not be as effective in very high caries-risk individuals. Grouping all of the treated individuals together, it was found that 33% of the lesions in the outer half of enamel remained in the outer enamel over three years while the corresponding value for the control group was 32%. About 25% of the fluoride treated lesions progressed to dentine or were restored while this value was 31% of the non-treated lesions. In both the treatment group and the control group, 7% of the lesions appeared to have regressed. Of lesions initially in the inner half of enamel, 36% of the fluoride-treated lesions and 21% of the controls remained at this stage, but 62% of the treated and 77% of the non-treated lesions progressed to the dentine or were restored.

Cook[41] investigated approximal lesion progression in three groups of dental students. Baseline radiographs for all three groups were taken in the same year, when all subjects beginning their third year of dental school. Individuals from each group were again radiographed after either 8.5 months, 19 months, or 32 months. The results showed that 79.2% of outer enamel caries remained unchanged or regressed over a period of 8.5 months. The second group showed very similar results, with 79.6% of outer enamel lesions remaining unchanged or regressing over 19 months. In the third group, 68.4% of outer enamel lesions did not progress over the

32 month period. Although some individuals from each group also completed a questionnaire about their oral hygiene practices, the sample sizes were small and no between group comparisons were made.

In 1984, Grondahl *et al.*[27] reported on the lesion progression of children aged 13 years at baseline, who received fortnightly fluoride rinses and biannual applications of fluoride varnish. They found that 51.4% of outer-half enamel lesions did not progress over a three year period. Of the remaining lesions, 30.9% progressed to the inner half of enamel, 9.1% progressed into the outer dentine and 8.6% were filled. Of inner enamel lesions present at the study's baseline examination, 44.6% did not progress while 19.8% progressed into the outer dentine and 35.6% were filled. Progression was again found to be relatively slow, but may increase slightly as the lesion advances closer to the dentine.

Hugoson *et al.*[42] studied caries progression over a five year period in 100 15 year-old subjects at baseline, and reported slow caries progression. Of the initial 223 outer enamel lesion, 14.3% regressed, 22.4% remained in the outer enamel, 6.3% progressed to the inner enamel, and 57% progressed to dentine, pulp, or were filled. Only 44 inner enamel lesions were reported at the study's baseline exam, of which 3 (6.8%) had regressed, 8 (18.2%) had remained in the inner enamel, and 33 (75.0%) had progressed to the dentine, pulp, or were filled after 5 years. Subjects were only examined twice however, at the beginning of the study and after 5 years with the result being that many of the lesions had been filled.

Bruun *et al.*[43] studied lesion incidence and progression over 3 years in 251 Danish children aged 9-12 years at baseline. Subjects were assigned to one of two treatment groups, one receiving a fortnightly fluoride rinse and the other receiving a biannual application of fluoride varnish. Using radiographs, lesions were divided into 5 categories, sound, in the enamel, at the DEJ, in the dentin, or filled. After three years, 56% of the enamel lesions in the rinse group, and 50% of the enamel lesions in the varnish group, remained in the enamel. Of the remaining lesions in the rinse group that were initially in the enamel, 6.7% reached the DEJ, and 37.3% progressed into the dentin or were filled. In the varnish group, 12% of the initial

enamel lesions progressed to the DEJ and 38% progressed into the dentin or were filled. The authors concluded that lesion progression was slow and that no statistically significant difference between the two treatment groups was found.

In 1986, Shaw and Murray[44] published the results of a study investigating the effect of fluoride toothpaste on the progression of carious lesions in children aged 11-12 years at baseline. Only lesions with a radiolucency in the inner half of the enamel were included in the study. After three years, the investigators found that the fluoride toothpaste had no significant effect on lesion progression. When the results from treatment groups and the control group were combined, it was found that 80% of the inner enamel lesions progressed to the dentin or were filled over the three year period. The authors also reported on the progression of lesions initially reported to be in the dentin, and found that 88% of the lesions had progressed or were filled over three years. However, most of these had been filled (85-90%), so the actual progression rate is difficult to estimate.

Pitts and Renson[45] investigated the use of radiographic image analysis to study lesion progression by depth and area rather than using the standard demarcations. Studying 50 approximal surfaces from two different populations, they grouped all of the data together, regardless of each lesion's initial state. For a group of Hong Kong dental students, they found that 76% of the lesions were arrested over 1.5 years when measured by depth and 68% when measured by area. In terms of both depth and area, about 18% of the lesions had progressed but 6% had regressed as assessed by depth and 14% had regressed as assessed by area. In a 1965 dataset of more caries active English children aged 11-12 years at baseline, they found that 52% of the lesions had progressed when measured by depth and 54% had progressed when measured by area over two years.

Slow progression rates were found by Bille and Carstens[33] in permanent molars and premolars of 278 thirteen year-olds who were followed for two years. Of the surfaces diagnosed as carious, 63.3% with outer enamel caries did not progress, 26.7% progressed to the inner enamel, 6.7% progressed to the dentine, and 3.3% were filled. Of the initial inner enamel lesions, 79.3% did not progress, 13.8% progressed to the

dentine and 6.9% were filled. However, because of their relatively high caries-risk status, 39% of these children received additional preventive services possibly reducing their caries progression rates. Therefore, without the preventive intervention, the overall progression rates of the children in this study may have been slightly higher.

Berkey *et al.*[28] studied the progression rates of untreated enamel caries in 602 adult American men over a 10 year period. Based on radiographs that were taken at three year intervals, their Kaplan-Meier survival curve suggested that after 18 months, 85% of lesions remained confined to the enamel. After 24 months 61% of the lesions remained in the enamel, and the chance of progression began to decline with 50% of the still being confined to the enamel after 73 months. However, the authors did not divide the enamel in half and the progression estimates do not include lesions that were restored, both of which may result in an underestimate of the percentage of lesions that progressed. Alternately, regressed lesions were defined as non-progressing and some of the enamel lesions diagnosed at baseline may have existed for years prior to the study, both of which may result in the authors overestimating progression rates. The authors also suggested that progression rates may be much faster in high caries-risk individuals and slower in low risk individuals.

Ekanayake and Sheiham[34] used the Kaplan-Meier approach to estimate the survival times of carious lesions from a 1960's data set of children aged 11 and 12. However, in this study each person was the unit of measurement rather than each lesion. Ekanayake and Sheiham argued that in order to apply the Kaplan-Meier estimate to any data, the observations or sampling units must be independent. Their results also suggested progression rates are slow. Although no statistical difference between the two groups existed, they reported a median survival time for enamel lesions of 33 months for children using a fluoride dentifrice and 24 months for the control group. As was the case in previous studies, a large degree of variation in progression rates was found between individuals and between lesions, suggesting that it may be more important to focus on the distribution of the survival times rather than the mean survival times.

Using the Kaplan-Meier estimate and only uncensored data, Lervik *et al.*[32]

found the average survival time of a lesion in the outer enamel of the teeth of Norwegian teenagers to be 18.6 months. However, when "right" censored data were also included, this estimate increased by 15% to 21.4 months. Similarly, the survival time of lesions in the inner enamel was increased by 32% from 16.4 months to 21.0 months when right censored lesions were considered. Inclusion of doubly censored lesions was also found to increase the mean survival time. Throughout the duration of this study, 60-70% of the lesions did not progress into dentine.

4. Studies of Caries Progression in the Deciduous Dentition

While most studies involving permanent teeth concluded that caries progression is quite slow, some studies of the deciduous dentition have found quite rapid rates of progression. Van Erp and Meyer-Jansen[46] reported that although many studies of permanent teeth include lesions that have arrested or regressed, no such lesions were discovered in the deciduous dentition. They estimated the survival time for a lesion in the enamel of a deciduous molar to be 7 months, with slight variation in this rate between the distal and mesial surfaces and between the first and second primary molars.

In 1978, Murray and Majid[38] reported on the detection and progression of radiographically diagnosed enamel lesions in the deciduous teeth. It is not clear from the study's results how many of the enamel lesions that were present at the beginning of the study, progressed into the dentine during the study. However, the authors did report on 71 enamel lesions that were diagnosed after the study's first year (uncensored lesions) and 69 of these lesions progressed into the dentin by the end of the second year. This relatively rapid rate of progression was attributed to two factors, (1) the thinness of deciduous tooth enamel, and (2) the fact that the criterion for an enamel lesion was a radiolucency in the inner-half of enamel. Murray and Majid also found that fluoride varnish had no effect on the initiation and progression of carious lesions in primary teeth.

In 1981, Craig *et al.*[39] studied caries progression in deciduous molars that were treated with metal fluorides and found much slower rates than those previously

reported (Van Erp & Meyer-Jansen 1970, Murray and Majid 1978). About 76% of enamel lesions remained in enamel after one year, and only 26% progressed to dentine or were filled after two years. The authors also presented data on deeper lesions at baseline, but restorative treatment interrupted progression, making the data unreliable. The effect of the fluoride treatment could not be determined because the study lacked a control group.

Slower progression rates in primary molars were also calculated by Shwartz *et al.*[9], who found that it took more than one year for a lesion to penetrate through the enamel in both Swedish and American children. Penetration through the inner enamel required a mean time of 20.5 months in Swedish children and 9.6 months in the American group. As was the case with permanent teeth, this difference may have been due to the increased exposure of the Swedish group to fluorides.

Solanki and Sheiham[47] reviewed the four studies of caries progression in primary teeth mentioned above. Their findings indicate that the diagnostic criteria employed by Murray and Majid[38] (including only inner enamel lesions in the analysis) resulted in an overestimate of caries progression in the primary dentition. Using the bitewing radiographs of 50 children from England, Solanki and Sheiham[47] showed that when outer enamel lesions were included, 60% of enamel lesions remained in the enamel after one year. However, if only inner enamel lesions were included, only 37% of the enamel lesions remained in the enamel after 1 year.

DISCUSSION

Numerous factors that may influence caries progression have been investigated and some of the studies discussed in this paper have investigated these factors. However, this report's principal purpose is to summarize current knowledge about the probabilities and rates of caries progression using studies that followed individual lesions over time. Therefore, our list of factors only includes those studies that were selected, during the literature search, to fulfil the paper's principal purpose.

The most frequently researched factor is the effect of various types of fluoride. Past studies have, in general, found that topical fluoride as well as systemic fluorides

reduce caries incidence[48,49,50]. However, many of these studies were carried out in the 1960's and early 1970's; the absolute effect of topical and systemic fluorides in many of today's fluoridated communities may be significantly reduced and this effect is now being questioned[48,49,50].

A number of studies reported in this paper investigated the effect of topical fluoride on caries progression. Muhler *et al.*[5], Hollender and Koch[6], and Hyde[11] found that fluoride treatment decreased caries progression rates. However, Murray and Majid[38], Cook[41], Ekanayake and Sheiham[34] and Shwartz *et al.*[9] did not find consistent or statistically significant results with fluoride. Modeer *et al.*[40] found that fluoride had a significant effect on reducing lesion progression only in individuals with a caries incidence during the study of 2 to 8 new lesions. Powell *et al.*[37] reported that a SnF_2 dentifrice "markedly retarded the growth of initial lesions over a four-year period", while SnF_2 solutions were reported to be ineffective against caries progression. Bruun *et al.*[43] did not find a significant difference in caries progression between children who rinsed with a NaF solution every two weeks and children who received a biannual fluoride varnish.

Pitts[7] reviewed many studies on caries progression and determined, overall, that progression was slower in studies where subjects received fluoride supplementation in one form or another. Many communities now have fluoridated drinking water as well as fluoride in many of the foods and beverages they consume. As well, most of the dentifrices on the market today are also fluoridated. Therefore, the effect of systemic and topical fluorides should be considered when estimating caries progression.

Another factor which was investigated by a number of the studies discussed in this paper is the caries 'activity' of the subjects involved. Four studies[27,28,40,42] reported that subjects with a higher caries risk, often defined using specific levels of caries incidence and prevalence, tended toward greater rates of caries progression. However, investigators should be cautious about the applicability of this correlation. The relationship may simply reflect the fact that individuals with faster rates of caries progression end up having a greater caries incidence and prevalence. Shwartz

et al.[9] found no statistically significant correlation between caries risk and caries progression.

A few studies discussed here investigated the effect of age on caries progression. Zamir *et al.*[35], Grondahl and Hollender[30], and Berkey *et al.*[28] all reported that older patients had slower progression rates, although the results of Zamir *et al.*[35] were not statistically significant. Darvell and Pitts[8] found a peak in the progression rate around the ages of 11 to 13 years, estimating the half-life of an enamel lesion at this age to be 2.7 years.

Berkey *et al.*[28] looked at many parameters and found that faster progression was positively associated with patient age, DFS, gingival inflammation, gingival recession, and plaque accumulation. Individuals with greater numbers of teeth experienced slower progression rates.

The numerous factors that may affect caries progression make calculating probabilities and rates of progression for large populations problematic. Therefore, a practitioner should exercise caution when devising a course of treatment for each individual patient. Caries progression in a population follows a probability distribution[7], and progression rates in some individuals will be much greater than the population average. Alternately, progression will be slower than average in other individuals and these individuals run the risk of being overtreated. Although past studies have shown topical fluorides to be successful at reducing caries incidence, its effect on lesion progression appears unresolved. Individuals defined as being at a higher risk to caries often appear to have higher caries progression rates but caution is advised when trying to apply this relationship to a clinical setting. Age and caries progression rates appear to be negatively associated, with adults having slower rates of progression than adolescents.

In general, caries progression appears to be slow. Tables 1, 2, and 3 were created to summarize information currently reported in the literature. Tables 1 and 2 summarize the probabilities of dental caries progression for studies that divided the enamel into an outer and inner half. Table 3 lists the studies that reported survival times for carious lesions in the inner and/or outer enamel. Overall means of the

results found in Tables 1 and 2 were also calculated. However, these means are only intended to represent a very general estimate of the probability of progression of carious lesions at various levels of enamel decay; probabilities of lesion progression will vary considerably among individuals and populations.

Based on Table 1, it appears that about 60% of outer enamel lesions in permanent teeth will remain in the outer enamel or perhaps regress over the first year, and less than 10% of these lesions will progress through the enamel and into the dentin or will have been filled. After two years, less than 50% of initial outer enamel lesions remain in the outer enamel and about 20% will have penetrated the dentin or will have been filled. Only about one third of the lesions appear to remain in the outer enamel after three years, while about one third have penetrated the enamel or have been filled. After four years or more, 50% or more of the initial outer enamel lesions will have penetrated the dentin or will have been filled and less than 25% will remain in the outer enamel. In adults progression appears to be slower, with about 60% of lesions remaining in the outer enamel after 30 months or more and only about 20% progressing to the dentin or being filled.

The rate of approximal caries progression in the inner enamel of permanent teeth also appears to be slow. Not surprisingly, the probability of reaching the dentin over a specific time period appears to be greater than for outer enamel lesions. After one year, about 35% of the inner enamel lesions in teenagers can be expected to have reached the dentin or to have been filled, while more than 70% appear to reach the dentin within 3 years. The probability of progression in adults again appears to be less than in teenagers.

Almost all studies reporting survival times, including those re-analyzed by Shwartz *et al.*[9], found that the average lesion required more than one year to progress through the outer enamel of a permanent tooth and more than one year to progress through the inner enamel. Most studies suggest that the average carious lesion in a teenager will require at least 3 years to progress through the entire enamel of a permanent tooth. This estimate is in general agreement with the mean probabilities of progression found in Table 1, with less than 50% of outer enamel lesions

progressing to the dentin or being restored after 3 years. The rate of caries progression appears to be less in adults than in teenagers.

Few studies have investigated approximal caries progression in primary teeth, and those that have reported varying results. Early studies may have overestimated progression rates[47] due to the methods they employed. More recent studies indicate that the average outer enamel lesion in a primary tooth may require at least 1.5 to 2 years to penetrate the dentin.

These relatively slow rates of caries progression support recent recommendations that the treatment of caries should take a more conservative and preventive approach than has been taken in the past[3,51]. Most lesions will progress slowly, arrest, or even remineralize and should be monitored over successive dental appointments rather than being promptly restored; the application of topical fluorides may aid the remineralization process[51]. Current recommendations in the literature indicate that restorative intervention for approximal lesions is generally not necessary until the lesion is cavitated or a radiograph indicates that the lesion has penetrated the dentin[3,51]. Lesions in some individuals may progress very rapidly and practitioners must use their professional judgement to determine if early restoration or additional preventive measures of these lesions is necessary. However, the high percentage of non-progressing or slowly progressing lesions reported by studies in this review provide a clear indication that these cases of rapid progression are rare.

CONCLUSION

Many factors may affect progression rates such as exposure to systemic and topical fluorides and patient age. In general, caries progression within the enamel of permanent teeth is a slow process, requiring an average of three or four years to reach dentine. Many lesions will not progress and may even regress, and this may be aided by the use of topical fluorides. This allows a practitioner to monitor the lesion over a number of successive dental appointments before the possible need for restorative intervention. However, treatment considerations based on a population with a slow caries progression rate are not appropriate for all patients, and treatment must be individualized.

TABLE 1: Progression of carious lesions in the outer enamel.

STUDY	COUNTRY, BASELINE AGE (yrs)	VARIABLES	STUDY LENGTH (mos)	REVERSALS (%)	REMAINING IN OUTER ENAMEL (%)	PROGRESS TO INNER ENAMEL (%)	PROGRESS TO DENTINE OR RESTORE (%)
Grondahl *et al.* 1977	Sweden, 16		36	NR	37.7	26.8	35.3
Hollender & Ronnerman 1978	Sweden, 10-17	Ortho. Study	26 (mean)	NR	72.5	11.5	16.1
Grondahl & Hollender 1979	Sweden, 16		72	NR	25.9	22.6	50.6
	Sweden, 19		36	NR	58.3	23.9	17.8
Granath *et al.* 1980	Sweden, 12-13		12	6	43	43	8
			24	4	29	43	24
Powell *et al.* 1981	Australia, 12-14	Control	12	NR	57	32	11
			24	NR	33	35	32
			36	NR	23	29	48
			48	NR	12	29	59
		F rinse	12	NR	62	31	7
			24	NR	35	33	32
			36	NR	22	30	48
			48	NR	15	22	63
		F Dentifrice	12	NR	67	30	3
			24	NR	41	44	15
			36	NR	28	33	39
			48	NR	23	28	49
		F rinse & Dentifrice	12	NR	69	28	3
			24	NR	57	29	14
			36	NR	46	34	20
			48	NR	35	36	29
Cook 1984	Australia, >18	Dental Students	8.5	8.3	70.8	14.6	6.3
			19	3.7	75.9	18.5	1.9
			32	NR	68.4	7.0	24.5
Grondahl *et al.* 1984	Sweden, 13	F rinse & F varnish	36	NR	51.4	30.9	17.7
Modeer *et al.* 1984	Sweden, 14	Control	36	7	32	30	31
		F varnish	36	7	33	35	25
Hugoson *et al.* 1985	Sweden, 15		60	14.3	22.4	6.3	57.0
Bille & Carstens 1989	Denmark, 13	F rinse & Topical F (NaF)	24	NR	63.3	26.7	10.0
MEAN	<18		12	60.8		32.8	6.4
			24*	47.8		31.7	20.4
			36	34.1		31.1	33.0
			≥48	22.2		24.0	51.3
	>18		8.5	79.1		14.6	6.3
			19	79.6		18.5	1.9
			>30	63.4		15.5	21.2

NR = not reported * includes Hollender and Ronnerman 1978

TABLE 2: Progression of carious lesions in the inner enamel.

STUDY	COUNTRY, BASELINE AGE (yrs)	VARIABLES	STUDY LENGTH (mos)	REVERSALS (%)	REMAINING IN INNER ENAMEL (%)	PROGRESS TO DENTINE OR RESTORED
Grondahl *et al.* 1977	Sweden, 16		36	NR	18.1	81.8
Hollender & Ronnerman 1978	Sweden, 10-17	Ortho. Study	26 (mean)	NR	62.3	37.8
Grondahl & Hollender 1979	Sweden, 16		72	NR	13.5	85.4
	Sweden, 19		36	NR	55.7	44.3
Granath *et al.* 1980	Sweden, 12-13		12 24	11 7	54 35	35 58
Cook 1983	Australia, >18	Dental Students	8.5 19 32	9.1 11.5 29.1	81.8 46.2 29.2	9.1 42.3 41.6
Grondahl *et al.* 1984	Sweden, 13	F rinse & F varnish	36	NR	44.6	55.4
Hugoson *et al.* 1985	Sweden, 15		60	6.8	18.2	75.0
Shaw & Murray 1986	England, 11		36	NR	19.8	80.2
Bille & Carstens 1989	Denmark, 13	F rinse & Topical F (NaF)	24	NR	79.3	20.7
MEAN	< 18		12 24* 36 >48	65.0 61.2 27.5 19.3		35.0 38.8 72.5 80.2
	>18		8.5 19 >30	90.9 57.7 57.0		9.1 42.3 43.0

NR = not reported
* includes Hollender and Ronnerman 1978

TABLE 3: Mean or median (underlined) times for a carious lesion to progress through tooth enamel.

Study	COUNTRY & BASELINE AGE (yrs)	VARIABLES	TIME (months) TO PENETRATE THE		
			OUTER ENAMEL	INNER ENAMEL	ENTIRE ENAMEL
Marthaler & Wiesner, 1973	Switzerland 7	Exclude filled lesions	16 10.5		
		Assumed filled lesions reached the dentine	18.6		
		Assumed filled lesions reached the inner enamel	20.5 18.1		
Zamir *et al.*, 1976	Isreal 14-15		13.6	12.8	26.4
	Isreal 21-24		17.1	15.2	32.3
Powell *et al.*, 1981	Australia 12-14	Control	16		38
		SnF2 Solution	16		38
		SnF2 Dentifrice	19		49
		SnF2 Solution & Dentifrice	34		72
Shwartz *et al.*, 1984	Sweden 10-11	F rinse	20.9	27.9	48.8
	Sweden 17	F rinse, F varnish	37.6	47.4	85.0
	Sweden 21-22	F rinse	41.2	56.4	97.6
	U.S. 4-17		22.6	18.6	41.2
	U.S. 17-18		15.5	26.5	42.0
Berkey *et al.*, 1988	U.S. 28-76				73
Ekanayake & Sheiham, 1988	England 11-12	control	24		
		F dentifrice	33		
Lervik *et al.*, 1990	Norway 14-18	F varnish	24.3	21.7	46.0
Van Erp & Meyer-Jansen, 1970	Netherlands	primary teeth	7-8		
Shwartz *et al.*, 1984	Sweden	primary teeth	11.8	20.5	
	U.S.	primary teeth	12.7	9.6	

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