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REVIEW ARTICLE

Radiographic display of carious lesions and cavitation in approximal surfaces: Advantages and drawbacks of conventional and advanced modalities

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Abstract

Background. Treatment strategies have changed with efforts on arresting carious lesions suspected to have an intact surface sparing operative treatment for cavitated lesions. Radiography is still the most recommended adjunct method in the diagnosis of clinically inaccessible approximal surfaces. ***Bitewing radiography.*** The major drawback of bitewing radiography for caries diagnosis is that the clinical state of the surface cannot be determined; i.e. if cavitation has developed or the demineralized surface is still intact. Based on studies of the relationship between radiographic lesion depth and clinical cavitation in approximal surfaces, a threshold for operative treatment decision has been suggested when a lesion is observed radiographically more than one-third into dentine. However, the results from previous studies are contradictory and the majority of studies are ~25 years old. In addition, there are few longitudinal observational studies on the behaviour of dentinal carious lesions, particularly in adults. ***Cone beam computed tomography.*** Cone beam CT is an advanced 3-dimensional radiographic modality, which seems much more accurate than intra-oral modalities for displaying cavitation in approximal surfaces. Nonetheless, there are several drawbacks with CBCT, such as radiation dose, costs and imaging artefacts. Therefore, CBCT cannot be advocated at current as a primary radiographic examination with the aim of diagnosing cavitated carious lesions. ***Conclusions.*** Bitewing radiography is, thus, still state-of-the-art as an adjunct in diagnosing carious lesions in clinically inaccessible approximal surfaces. The risk for cavitation is related to lesion depth, but new studies are needed in both child and adult populations to validate current thresholds for the operative treatment decision based on the radiographic lesion depth.

Key Words: *Radiography, dental, cone beam computed tomography, diagnosis, dental caries*

Background

Dental caries is one of the most prominent chronic diseases worldwide [1], leading to demineralization of the dental hard tissues. The demineralized area, the caries lesion, in the tooth surface is not the disease but a reflection of present or past microbial activity in the biofilm. A lesion beneath bacterial plaque will progress, but it can be arrested if the biofilm can be thoroughly removed [1]. The state of the disease is usually determined clinically and criteria have been published to facilitate classification of carious lesions by a clinical visual examination [2–4]. Such classification systems have been shown to be reliable in distinguishing between active and arrested lesions [5–9]. A careful clinical examination may be possible for smooth and occlusal surfaces; however, clinical access to approximal surfaces in contact may be limited. Thus, a clinical examination of smooth surfaces and to some extent of occlusal surfaces [10] will reveal whether the surface above the carious lesion is still intact or the caries process has reached a state where break-down of the surface has occurred, forming a cavity. Not all lesions cavitate at the same state and cavitation has been found to be more likely in molars followed by premolars and anterior teeth [11]. Also, lesions in occlusal surfaces seem to be more likely to cavitate, followed by buccal and lingual pits, approximal surfaces and free smooth surfaces [11].

In clinically inaccessible approximal surfaces, the cavitation disease stage may be difficult to detect and it has been shown that only ~12–50% of cavitated

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surfaces were diagnosed by a thorough visual examination by trained examiners [12]. While lesions in a still intact surface may be arrested, the lesion will most likely be active if cavitation has occurred since bacteria colonize within the cavity and cannot be removed in the case of contacting neighbouring teeth; although non-cavitated lesions may also be infected [13]. If cavitation has developed, preventive treatment to stop the microbiologic activity may, therefore, not be successful. In recent years, treatment strategies have, therefore, changed, with efforts on arresting lesions suspected to have an intact surface sparing operative treatment for cavitated lesions [14]. This treatment strategy leaves a challenge for approximal surfaces in teeth with tightly contacting neighbouring teeth, particularly in the molar regions, where the clinical examination may be incomplete.

Radiographic display of the caries lesion

An additional diagnostic value of radiography compared with merely a visual examination has been reported in several studies over the years for the detection of carious demineralization in approximal surfaces both in adults and children [15–21]. Even though variation among observers' radiographic interpretation of lesions is well-known, radiography is still the most recommended adjunct method available for daily clinical practice in the diagnosis of approximal caries lesions [22].

The demineralization is seen in the radiographic image as a radiolucent zone because the demineralized area of the tooth does not absorb as many photons during exposure as the normal dental hard tissues. The classical shape of the early radiolucent lesion in the enamel is a triangle with its broad base at the tooth surface, but other appearances are common, such as a notch, a dot, a band or thin lines [23]. Lesions involving approximal surfaces are most commonly found in the contact or sub-contact area [24] and the tightness of the contact point may influence caries lesion development [25]. Knowledge of lesion shape and predilection area will usually determine whether the observed radiolucency originates in caries activity. Also, studies have shown that lesion depth can be fairly accurately estimated on radiographs when compared to the depth of the lesion histologically [26,27] and that lesions are not more frequently 'under-scored' than 'over-scored' when compared to lesion depth measurements in histological sections of the tooth (Figure 1) [26].

Unlike the clinical examination, where various signs can determine whether the lesion is active or old/arrested [5], the radiographic image *per se* cannot display whether or not the lesion is presently active. An old inactive lesion will still appear as a demineralized area in the hard tissues, a 'scar', since re-mineralization takes place only in the outermost surface of the lesion [28]. Because the image only mirrors the current extent of demineralization, one radiograph alone cannot determine whether activity is on-going without a valid clinical examination. Only a second image taken at a later time can reveal whether the disease was active in the time period between exposures. In cases where it is decided to monitor the lesion, a follow-up radiograph should be obtained to evaluate whether the lesion is arrested or is progressing. The interval between the radiographic examinations should be determined individually, taking into account previous caries history, age and site of the lesion [29–32].

Conventional radiographic modalities

Intra-oral radiography is the most commonly used imaging modality for detecting carious lesions, whether film-based or based on a digital image receptor [33,34]. The digital receptor may be (1) solid-state sensors (charge-coupled device [CCD] and complementary metal oxide semiconductor technology [CMOS]) with or without a cord that connects the receptor to the computer (in a cordless sensor, the signal is transferred by radio wave to a receiver) or (2) photostimulable storage phosphor (PSP) plate

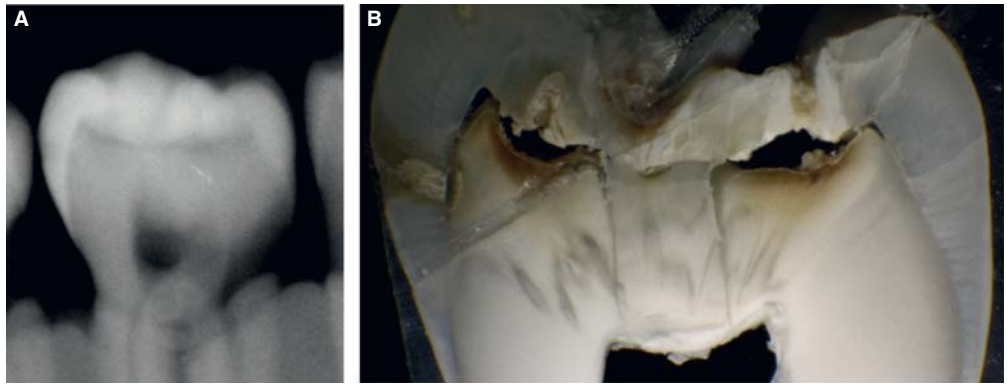

Figure 1. (A) Radiograph of extracted molar with lesion into outer third of dentine in the left surface, (B) histologic section of the same tooth. Depth measurements of the lesion in the two images did not differ (the occlusal lesion was not considered).

systems that use a film-like plate which is processed in a scanner after exposure [35]. Numerous *in vitro* studies have compared film and digital radiography for detection of caries lesions [33,36,37], with the overall finding that no significant differences existed between these modalities. There is a lack of clinical studies that compare film with digital radiography for diagnosis of caries lesions though.

The bitewing technique and projection has been in use for almost a century [38]. As an adjunct diagnostic method to a clinical examination, cost-benefit analyses should follow its use [39,40], however very little has been published on the economic aspects of using bitewing radiography in connection with a clinical examination for diagnosis of caries lesions [41]. One study found that the diagnostic costs, when the aim was to correctly find and treat a lesion, depended on disease prevalence and that a selective radiography strategy saved costs compared to a clinical examination alone or a clinical examination combined with bitewings for all patients [42]. Another study estimated costs for film and digital radiography systems and found that, depending on number of radiographs recorded per year, a dental clinic would benefit from a change to a digital system in 1–3 years [43].

X-radiation is potentially hazardous and dose estimates should be conducted for all radiographic modalities used for diagnostic purposes. Over time, intra-oral receptors have become more radiation sensitive [44–46] and the effective radiation dose to the patient is in the range of 1–8 μSv for one intra-oral exposure [47–49] depending, among other things, on exposure settings, radiation field (collimation) and receptor type. As a consequence of increased sensitivity of the receptors, exposure time has been reduced, minimizing image blur due to patient movement. The use of a film holder with a beam-aiming device has further optimized the bitewing technique in reducing re-exposures due to overlapping contact points; also reducing interpretation errors and facilitating lesion comparison over time [50–52]. The holders available for bitewing examination with PSP plates appear like those for film and universal holders for solid-state sensors are also available. However, there may still be recording problems when solid-state sensors are used for bitewing examination [53]. First, the radiation-sensitive surface area is smaller than the area of a size-2 film, displaying fewer interproximal tooth surfaces per exposure than with film. Second, the stiffness and increased thickness of these sensors is more uncomfortable for the patient [53,54] and may result in more projection errors and retakes [53]. Recently developed sensors with more ergonomic shapes may overcome most positioning problems and patient discomfort though [55]. Care should be taken to reproduce the same image geometry in follow-up images of the same teeth by using standardized film holders to aid the estimate of lesion depth and comparison of images over time [51]. Whether there may be differences between film, PSP systems and solid-state sensors in their ability to compare lesion depth in patient images taken over time seems not to have been studied.

In a summation radiograph (a 2D image of 3D structures), like intra-oral periapical and bitewing images, there is much tissue overlap in broad approximal surfaces and it cannot be determined if cavitation has developed in the outermost surface [56–58]. This may be seen as the major drawback of bitewing radiography for caries diagnosis. Attempts have been made to analyse the grey shade distribution inside the lesion in digital images to distinguish between lesions with and without cavitation [56]. Even though grey shade values were significantly lower (i.e. areas appearing darker in the image) in carious dentine, no differences could be observed between grey values in cavitated and non-cavitated dentinal lesions. One of the advantages with digital receptors is the ability for post-processing, i.e. image enhancement [37]. Image enhancement has been shown, however, to have little effect on the validity of detection of demineralization compared to original un-enhanced images [34], but whether image filtering may improve the detection of cavitation in approximal surfaces has not been studied.

There may, however, be a logical relationship between the depth and extent of the carious demineralization as seen in the bitewing image and the risk for surface breakdown when the surface is no longer supported by the underlying tissues. Pioneer clinical studies from Scandinavian countries were published in the 1980s and 1990s to determine the relationship between radiographic lesion depth observed in bitewing radiographs and cavitation in approximal surfaces (Table I). The clinical state of the surface, cavitated or intact, was in early studies determined during the drilling process for restorative treatment of the tooth in question [59,60]. In these studies involving both children and adults, ~50% of the surfaces with a radiographic lesion extending about half-way into dentine (assessed from the enamel–dentine junction to the pulp) showed surface cavitation [59,60]. An even lower percentage of surface cavitation was reported in a study from the UK, also involving both primary and permanent teeth, since only 40% of surfaces with radiographic lesion depth involving the outer half of the dentine were cavitated [61]. The clinical state of the approximal surface was recorded after temporary separation of neighbouring teeth with orthodontic elastics [62–64] allowing a more direct inspection of the surfaces (Figure 2). The same tooth separation technique was used in a longitudinal study of dental students who at baseline displayed cavitation in 33% of lesions seen in the outer third of dentine [65] and these surfaces were restored. The non-restored surfaces were examined

Table I. Clinical studies on the frequency of cavitated approximal lesions radiographically observed in outer dentine.

Reference	Country	Subjects	*n* surfaces	Validation method	*n* lesions in outer dentine	% cavitation of lesions in outer dentine
Bille and Thylstrup [59]	Denmark	6–15 years	158 surfaces	clinical assessment during cavity preparation (7 operators)	58	52
Mejàre et al. [69]	Sweden	teenagers	24 surfaces	direct visual inspection after orthodontic extraction	6	100
Thylstrup et al. [60]	Denmark	children and adults	1080 surfaces	clinical assessment during cavity preparation (263 operators)	330	52
Mejàre and Malmgren [68]	Sweden	7–18 years	60 surfaces	clinical assessment during cavity preparation after tooth separation	32	78
de Araujo et al. [72]	Brazil	high school students	77 surfaces	direct visual inspection after tooth separation	19	90
Pitts and Rimmer [61]	UK	children ≤16 years	1468 perm surf 756 prim surf	direct visual inspection after tooth separation	22 134	41 28
Akpata et al. [73]	Saudi Arabia	17–48 years	216 surfaces	direct visual inspection after tooth separation (2 observers)	43	80
Lunder and von der Fehr [70]	Norway	17–18 years	46 surfaces	cavity recorded after tooth separation, impression and stone die	23	65
Hintze et al. [65]	Denmark	dental students mean age 24 years	115 surfaces	direct visual inspection after tooth separation	61	33
Ratledge et al. [13]	U.K.	Adults	60 surfaces	cavity recorded in impression after tooth separation	54	85
Sansare et al. [74]	India	18–58 years	126 surfaces	direct visual inspection after tooth separation	29–45	83–100

every 6 months and the rate of new cavitations was 20–44% at every examination up to 1.5 years after baseline. Thereafter, no more cavities developed in the surfaces. Based on the same baseline data of dental students (i.e. a highly motivated patient group), it was concluded in another report that correct decision for operative treatment (i.e. when the surface was cavitated) was more reliably determined from a mere clinical examination of the surface than from the radiographic appearance of a lesion extending just into dentine [66]. In opposition, a study of approximal surfaces in primary molars found that the detection rate for cavitation was much higher using radiography than with visual inspection [67].

Other previous and some more recent clinical studies (Table I) have not been able to reproduce the low rate of surface cavitation connected with a radiographic lesion seen in the outer dentine. In early studies of Swedish child and teenager populations, a cavitation rate of 78% was reported for radiographically observed lesions in the outer half of the dentine [68] and in another study by the same authors it was found that all radiolucencies extending into dentine (although a small number) were cavitated [69]. In

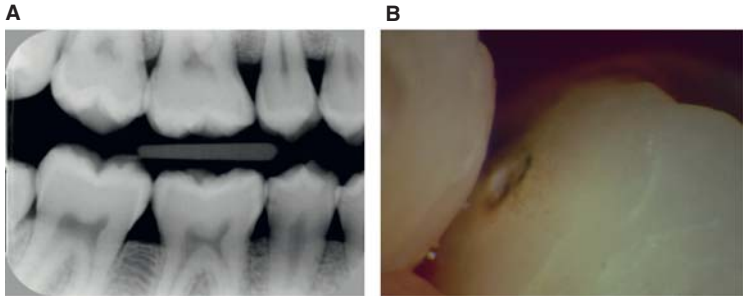

Figure 2. (A) Bitewing radiograph of patient showing a caries lesion into outer third of dentine in the distal surface of 45, (B) cavity in the same surface observed after tooth separation.

Norwegian 17–18 year-olds, surface cavitation was determined after tooth separation with orthodontic rubber rings, impression and stone die of the impression. Surfaces with a demineralization of ~1 mm into dentine in the bitewing image were cavitated in 65% of the cases. The risk for cavitation was higher in a caries-active group than in a moderate-caries group [70]. In adult patients from the UK, 85% of surfaces with lesions extending more than 0.5 mm into dentine had cavitation recorded in an impression of the lesion after tooth separation [13]. One study found that only 50% of the cavitated surfaces would be observed if the threshold was a radiographic lesion into dentine, since the other half of the cavitated surfaces had more shallow radiographic lesions [71]. Three studies from non-western countries (Brazil, Saudi Arabia and India) reported between 80–100% of surfaces with radiographically observed lesions in the outer one-third of dentine to be cavitated [72–74]. The methods of evaluation and the definition of a surface cavitation will surely have an impact on the prevalence of cavitated surfaces reported in clinical studies of the relation between radiographic lesion depth and surface cavitation. An *in vitro* study found that 95% of surfaces with a radiographically observed lesion in the outer half of dentine had cavities that were seen with the naked eye, while all surfaces were cavitated if electron microscopy was used [75]. How this fact would influence lesion progression in the clinical situation was not estimated. Moreover, few studies have reported on the variation in observers' ability to detect a cavity after tooth separation [12,74].

Even with the drawbacks of the summation radiograph, the depth of the approximal carious lesion displayed in the bitewing image seems nevertheless at current to be one of the estimates used to determine cavitation risk and, thus, treatment decision in situations where the surface is clinically inaccessible and when only one radiograph is available. Early studies from western countries reported that most dentists decided on restorative treatment when the lesion appeared in the radiograph restricted to the enamel [76–79], while a minor fraction of the dentists considered the enamel–dentine junction [78,79] or a shallow dentinal lesion as the threshold for the decision on restorative treatment in low caries-active patients [80,81]. Also, more recent results suggest that dentists still advocate filling therapy for lesions seen in enamel or at the enamel–dentine junction in many parts of the world [82–86]. However, from Scandinavia it has been shown that treatment strategies have changed over 25 years, particularly among younger dentists, in that very few would restore lesions confined to enamel [87,88]. It appears that the dentists' opinion on when cavity formation has occurred and their belief that the radiograph underestimates lesion depth were decisive factors for suggesting operative treatment [76,78,86,89].

It may be concluded from existing studies that the deeper the lesion has penetrated into dentine observed in the radiograph, the more likely it is cavitated, and dentinal lesions extending more than halfway to the pulp are most likely cavitated. Previous results on the risk for cavitation in surfaces with a

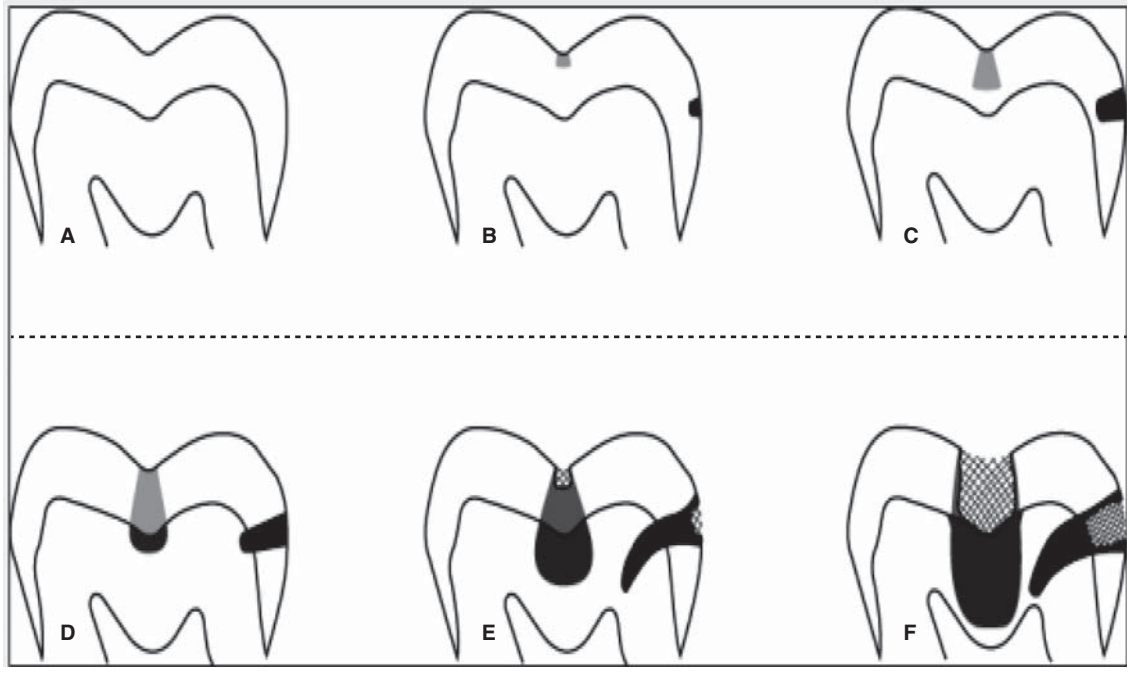

Figure 3. Schematic drawing of caries lesion development. Guidelines for treatment decision: Operative treatment is suggested at radiographic depth stages *e* and *f* (with permission from: Ekstrand KR, et al. Caries diagnostics and risk assessment in dental practice for adults. Danish Dent J 2013;3:212–223 [91]).

Table II. Studies on detection of approximal caries demineralization, lesion depth and surface cavitation (last three rows) comparing CBCT and intra-oral systems.

Reference	CBCT systems	Intra-oral systems	Study outcome	Validation method	*n* surfaces	Findings
Akdeniz et al. [109]	Accuitomo 3DX	PSP + film	Demineralization lesion depth	*In vitro* histology	41	CBCT more correct for lesion depth than intra-oral systems
Tsuchida et al. [105]	Accuitomo 3D	Film	demineralization	*In vitro* micro CT	100	No significant difference between modalities
Kalathingal et al. [104]	Local CT	CCD sensor	Demineralization lesion depth	*In vitro* histology	48	No significant difference for detection LCT more correct for lesion depth
Young et al. [110]	Accuitomo 3DX	CCD sensor	Demineralization	*In vitro* micro CT	100	CBCT higher sensitivity for dentinal lesions
Haiter-Neto et al. [103]	Accuitomo 3DX + NewTom 3G	PSP + film	Demineralization	*In vitro* histology	200	Accuitomo/intra-oral: no significant difference between modalities NewTom lower accuracy than others
Şenel et al. [102]	ILUMA	PSP + CCD Sensor + film	Demineralization	*In vitro* histology	276	No significant difference between modalities
Zhang et al. [107]	ProMax 3D KODAK 9000 3D	Film + PSP	Demineralization	*In vitro* histology	78	No significant difference between modalities
Qu et al. [108]	NewTom 9000 Accuitomo 3DX KODAK 9000 3D ProMax 3D, DCTPro	—	Demineralization	*In vitro* histology	78	No significant difference among CBCT units, nor for FOV
Kayipmaz et al. [106]	Kodak 9500	Film + PSP	Demineralization	*In vitro* histology	72	No significant difference between modalities
Haak et al. [111]	Galileos	CCD sensor	Surface cavitation	*In vitro* surface inspection	112	higher sens. and spec. with CBCT than intra-oral for cavitation
Wenzel et al. [57]	Accuitomo 3DX	PSP + CCD sensor	Surface cavitation	*In vitro* surface inspection	257	20–50% increased sens. for CBCT compared with intra-oral receptors; spec. no significant difference
Sansare et al. [58]	Kodak 9000 3D	Film	Surface cavitation	Clinical temporary tooth separation	79	33% increased sens. for CBCT compared with intra-oral film; spec. no significant difference

radiographic lesion depth extending into the outer third/half of dentine have been contradictory; guidelines have, however, been suggested for western populations as to when to offer operative treatment to an approximal surface with a carious lesion observed in the radiograph [90,91]. A schematic drawing of these guidelines published in the *Danish Dental Journal* illustrates the suggested threshold for operative treatment (Figure 3) [91]. The radiographic lesion illustrated as stage *d* has penetrated less than one third into the dentine with a reported 'small' risk of cavitation and stages *b–d* are, therefore, determined superficial caries, while at stage *e* the lesion has progressed two-thirds into dentine and the risk for cavitation of the surface is high. It is not totally clear from the figure, however, how dentinal lesion depths between stages *d* and *e* should be treated, thus the threshold for operative treatment may be left to individual interpretation.

Further evidence for the suggested radiographic threshold for operative treatment may be found in longitudinal prospective studies of lesion behaviour. There have been a large number of studies on progression of caries lesions over time, particularly in children and adolescents, although few have focused directly on the behaviour of lesions present in the outer dentine. Focusing particularly on studies assessing progression of lesions observed radiographically in dentine, the survival rate of lesions extending into the outer third of dentine was 42% over a median

Table III. Effective dose (μSv) by small FOV CBCT scanning estimated using International Commission on Radiological Protection, ICRP (2007) recommendations.

References	CBCT unit	FOV cm	μSv
Rottke et al. [116]	3D Accuitomo FP, depending on FOV	4 × 4, 8 × 8	47–314
	Kodak 9000 3D, depending on FOV	5 × 3.7, 7.8 × 3.7	25–48
	ProMax 3D, depending on FOV	3.2 × 4.2, 8 × 8	23–357
	Orthophos XG 3D, depending on FOV	8 × 5.5, 8 × 8	43–176
	Scanora 3D	6 × 6	40
	PaX-Duo3D	5 × 5	19
Schilling and Geibel [117]	KaVo 3D eXam, depending on resolution	8 × 8	62–122
	KaVo eXam Plus 3D, depending on FOV	6 × 4, 6.4 × 7.7	40–184
Al-Okshi et al. [118]	Veraviewepocs 3De, depending on region	4 × 4	21–22
	ProMax 3D	4 × 5	10
	NewTom VGi, depending on resolution	8 × 8	45–129
Morant et al. [119]	i-Cat (Next Generation), depending on rotation (full/half)	8 × 8	18–29
Qu et al. [120]	ProMax 3D, depending on FOV	5 × 4, 5 × 8, 8 × 8	102–298
Suomalainen et al. [121]	3D Accuitomo, depending on FOV	4 × 3, 6 × 6	27–166
	ProMax 3D	8 × 8	674
	Scanora 3D	6 × 6	91
Okano et al. [122]	3D Accuitomo, depending on FOV	3 × 4, 4 × 4, 6 × 6	30–101
Hirsch et al. [123]	Veraviewepocs 3D, depending on FOV	4 × 4, 8 × 4	30–40
	3D Accuitomo, depending on FOV	4 × 4, 6 × 6	20–43
Ludlow and Ivanovic [115]	Promax 3D, depending on patient size	8 × 8	488–652
	PreXion 3D, depending on resolution	8 × 7.6	189–388
Lofthag-Hansen et al. [124]	3D Accuitomo/ 3D Accuitomo FPD, depending on FOV	3 × 4, 4 × 4, 6 × 6	11–17

survival time of ~3 years in the mixed dentition [92]. The median survival time of similar lesions in other reports was 3.1 years [93] and 3.4 years [94] in young populations studied over more than 10 years. It seems that children who at a young age display lesions in approximal surfaces will be prone to manifest dentinal lesions a number of years later [95,96]. Few studies seem to have been conducted in adults. In one study, lesions extending up to 1 mm into the dentine progressed at various speeds (30% had progressed after 8 months, 56% after 20 months and 70% after 36 months), thus only 30% did not progress during the 3-year follow-up period [97]. The deeper the dentine lesion, the more likely it progressed. The majority of lesions also progressed in 20-year-olds even when there was focus on their oral habits during the study period [98]. There seems, thus, to be a lack of observational population studies with the aim of following the behaviour of radiographically displayed dentinal lesions, which can support the strategy that such lesions should be spared operative treatment.

Most of the above cited studies on the relationship between radiographic lesion depth and surface cavitation are between 12–30 years old and only a few of them actually support that the majority of surfaces where lesion depth is one-third into dentine are non-cavitated. There seems, thus, to be a need for new studies in present day child and adult populations on the relationship between radiographic lesion depth and surface cavitation for the guidelines to be validated. There is also a lack of data regarding the relationship between radiographic lesion depth and cavitation in populations from developing countries, where the caries activity, access to a dental healthcare and availability of fluorides in drinking water or toothpastes may be quite different from that of industrialized countries. Moreover, there seems to be few studies on the behaviour of radiographic dentinal lesions over time, particularly in adults.

Advanced radiographic modalities

An advanced digital 3-dimensional radiographic modality, cone beam computed tomography (CBCT), has recently entered the dental clinic [99]. The basic principle in CBCT volumetric tomography is that tomographic sections in a given pixel resolution are obtained, which mathematically are

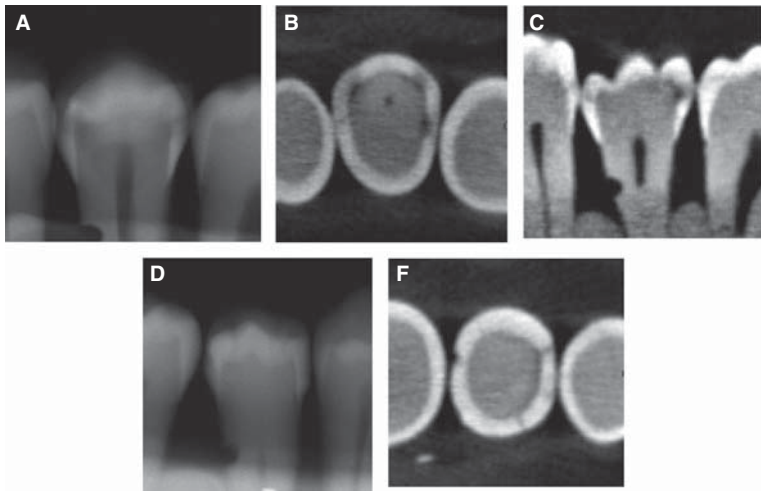

Figure 4. (A) bitewing-like radiograph of extracted premolar with deep lesions in both approximal surfaces; lesions scored as cavitated, (B, C) axial and sagittal CBCT sections of the same tooth showing the deepest demineralized area; lesions scored as non-cavitated. The lesion was clinically not cavitated. (D) bitewing-like radiograph of extracted premolar with shallow lesions in both approximal surfaces; lesions scored as non-cavitated, (E, F) axial and sagittal CBCT sections of the same tooth displaying cavitation in the left surface. This lesion was clinically cavitated.

joined together to form so-called voxels (a cubic pixel) that constitute the examined tissue cylinder. The size of the tissue cylinder is selected prior to the examination, the so-called field-of-view (FOV). The patient sits/stands/lies still and an exposure, usually in a 360° rotation around the patient, constitutes the examination. The imaged tissue volume can subsequently be sectioned in all directions, based in the coronal (frontal), sagittal (lateral) and axial (horizontal) planes.

Most often larger FOVs are related to lower voxel resolution in the subsequent images and *vice versa*. This means that, theoretically, more details are distinguishable in high resolution, small FOV examinations. Moreover, large FOVs are generally related to higher effective dose to the patient than smaller FOV, although this relationship may not be linear [100]. Imaging protocols concerning FOV and voxel resolution for various diagnostic tasks have only sparsely been evaluated [101], although this is recommended in order to keep the dose as low as reasonably achievable in every CBCT examination (ALARA principle) [99].

Previous *in vitro* studies have assessed the validity of CBCT imaging for detection of carious lesions (Table II). In such studies, teeth were positioned in plaster in a row simulating the posterior parts of the jaws and CBCT sections were performed in the mesio-distal (which in the clinical situation would equal the sagittal) and axial planes of the teeth. The majority of studies compared a CBCT system using a small FOV with one or more intra-oral radiographic receptors with histological sectioning of the teeth as gold standard. In most studies it was found that CBCT was no more accurate than intra-oral film, solid-state sensors or PSP systems for overall detection of demineralization in approximal surfaces [102–107]. Also, no significant differences were observed among several CBCT units and FOVs [108]. Two studies showed that CBCT was somewhat more accurate than intra-oral receptors for measuring lesion depth [104,109]. One study found that CBCT had higher sensitivity for detecting dentinal lesions than a CCD sensor [110]. One CBCT unit using large voxel size was less accurate than a unit with smaller voxel size [103]. On the basis of these findings it may be generally concluded that little is gained by using CBCT for detection of carious demineralization compared with the traditional intra-oral radiographic receptors.

On the other hand, the ability for thin sectioning of the tissue volume in all planes might enable the display of a break-down/cavity in approximal surfaces with CBCT. Few studies have yet explored the accuracy of CBCT imaging in detecting surface cavitation (Table III, last three rows). Two *in vitro* studies compared CBCT in small FOV with intra-oral systems in a bitewing-like projection for detection of cavitated approximal surfaces in non-filled extracted human permanent premolars and molars [57,111] (Figure 4). Very high sensitivities and specificities were obtained with CBCT (Galileos unit) [111]. Significantly higher sensitivities were obtained in another study with CBCT (Accuitomo unit) than with the intra-oral receptors, which were not compromised by lower specificities [57]. The difference in sensitivity between CBCT and the intra-oral receptors was between 20–50% and interpreted as clinically relevant [57]. One clinical study has been conducted in teeth without restorations [58]. Adult patients suspected to have carious lesions after a visual clinical and a bitewing examination participated in a CBCT examination (Kodak 9000 unit). Radiographic assessment recording lesions with or without cavitation was

performed by two observers in bitewings and CBCT sections. Orthodontic separators were placed interdentally between the lesion-suspected surfaces. The separator was removed after 3 days and the surfaces recorded as cavitated or intact. For both observers, sensitivity was significantly higher for CBCT than for bitewings (average difference 33%), while specificity was not significantly different between the methods [58]. It may be concluded from these studies that CBCT in high voxel resolution, so far as the only radiographic method, was fairly accurate in determining whether or not clinical cavitation existed in approximal tooth surfaces and much more accurate than intra-oral receptors.

This raises the question of whether CBCT should then be used prior to the decision for operative treatment of caries lesions. The major considerations to take into account before this can be advised should be costs/resources, radiation dose and, moreover, imaging artefacts.

It is of the utmost importance that socio-economic considerations are part of the evaluation of a new diagnostic method [39,40]. CBCT units are costly; therefore, it may be evident that resources connected with an examination should be estimated. While there are numerous studies on the accuracy of CBCT for various diagnostic tasks, very few seem to have assessed cost-benefits or even just costs related to a CBCT exam [112]. One recent health-economy study calculated direct and indirect costs for a CBCT exam to be ~4-times that of a panoramic image [113]. Little documentation exists on cost-effectiveness for radiography in connection with caries diagnosis, but, since a CBCT unit may be more than 50-times the price of a dental x-ray unit and maintenance of the unit and time spent in interpreting the images would also be much less for a bitewing radiograph, it may be self-evident that the costs for CBCT will heavily exceed those for a bitewing examination.

CBCT may further be the radiographic method which provides the highest effective dose to the patient of available dental radiographic equipment [114,115], although the variation between units and between FOVs is large. The biological effect of radiation depends on several factors, among others the irradiated tissues, the body volume and the exposure settings. In order to compare risks after various radiation exposures, the so-called effective dose is often estimated [48], which is measured in the unit Sievert.

For caries lesion detection the use of small FOVs would apply, which may be defined as a tissue volume ranging between 4 × 4 and 8 × 8 cm. Table III illustrates effective doses in μSv for small FOVs calculated for various CBCT units [115–124] after ICRP 2007 [49]. The range is 10 μSv to 650 μSv depending on CBCT unit, FOV, region, voxel resolution and patient parameters. The effective dose for one intra-oral exposure has been reported to be in the range of 1–8 μSv [49] and 5 μSv for a posterior 4-image bitewing examination with rectangular collimation using PSP or F-speed film [48]. The average effective dose for one bitewing exposure with a rectangular collimation has been calculated to 1.3 μSv [49]. Roughly, it may thus be concluded that a small FOV CBCT examination provides 10–100-times the radiation dose of a single bitewing image. It must be noted that there are units that do not provide very small FOVs; however, a FOV that just covers the diagnostic task in question should always be selected. There is no lower limit or 'safety zone' for ionizing radiation exposure in diagnostic radiography, where no harm can be guaranteed [125], and children are in general three times more susceptible to radiation than adults [126].

Artefacts of various sources are seen in CBCT images [127]. Beam hardening artefacts originate in errors in the mathematical reconstruction of the images [128]. These artefacts may have strong effects on image quality, inducing 'cupping' effects and streaks over areas of the image, which means that a square item may appear concave and that grey values will be altered and unevenly distributed in the beam direction [127,129,130]. A major source of beam hardening artefacts is the presence of metal in the imaged volume, producing dark streaks in the reconstructed volume [127]. Such artefacts have been shown to be present in the proximity of titanium implants [130–132] and titanium and lead rods [133]. Attempts have been made to reduce artefacts with post-processing software and an algorithm was shown to be useful in re-gaining grey values in a phantom [134,135]. The same authors on the other hand showed that detection of fractures in root-filled teeth was less accurate when an artefact-reducing algorithm was used than without this feature [136]. Older restorative dental materials such as amalgam may also affect image quality, and even plast and glass-ionomer materials may contain barium, lead or zinc to lend radiopacity in bitewing radiographs, which may disturb correct CBCT image reconstruction.

It must be born in mind that the studies on CBCT detection of approximal caries lesions and cavitation were conducted in teeth without fillings. In the clinical study [58], some of the neighbouring teeth had restorations. It may be questionable whether approximal cavities can be reliably detected in a dentition with metal- or other radiopaque-material restorations. It has been shown in studies of occlusal caries lesion detection by CBCT that enamel density is also capable of inducing beam hardening effects [110]. This fact presumably resulted in many false positive recordings of occlusal lesions, deeming CBCT inaccurate for radiographic occlusal caries demineralization diagnosis [110].

Any imaging modality will suffer if the patient moves during the exposure and, obviously, children

Table IV. Search strings used to achieve publications examined for the review.

A		B		C		D		E	
1: Approximal OR proximal	2 078	1: Approximal OR proximal	2 078	1: Cone-beam computed tomography OR cone beam CT	1 208	1: Cone-beam computed tomography OR cone beam CT	1208	1: Cone-beam computed tomography OR cone beam CT	1208
2: Caries OR carious	11 008	2: Caries OR carious	11 008	2: Caries OR carious	11 008	2: Radiation dose	421	2: Artifact OR artefact	107
3: Cavity OR cavitation OR cavitated	6 091	3: Longitudinal OR prospective OR follow-up	13 439						
4: Radiograph* OR image	14 993	4: Radiograph* OR image	14 993						
1+2+3+4	48	1+2+3+4	127	1+2	14	1+2	72	1+2	18

are more prone to move during the examination than adults. The image acquisition time for CBCT examinations is ~6–20 s and the higher the voxel resolution, the smaller the movement necessary to produce an incorrect reconstruction and, thus, motion artefacts [127]. Motion artefacts may be seen in the reconstructed image sections in various shapes and severity depending on the type and magnitude of head movement [137,138], but double contours and stripe-like artefacts have been found to be the most common [138,139]. The artefacts deteriorated the images to various extents depending on which part of the FOV was examined [138]. One survey estimated that, for a broad range of patients, 0.5% of CBCT images possessed artefacts using a CBCT unit with 20 s acquisition time while, for children and elderly patients, artefacts were seen in 11–22% of cases [139].

Conclusion

In conclusion, due to the relatively high radiation dose, costs and imaging artefacts, CBCT examination cannot be advocated at current as a primary radiographic examination to distinguish cavitated carious lesions from lesions in still intact approximal surfaces, although its accuracy seems to exceed that of conventional modalities in non-restored teeth. However, teeth without restorations included in a CBCT examination performed for other diagnostic tasks (e.g. before removal of a lower third molar) should be assessed also for approximal surface demineralization and cavitation. Bitewing radiography is, thus, still state-of-the-art as an adjunct in diagnosing carious lesions in clinically inaccessible approximal surfaces, despite its inability to accurately distinguish between cavitated and non-cavitated lesions. The risk for cavitation is related to radiographic lesion depth; however, there is a need for new studies in both child and adult populations to validate currently suggested thresholds for operative treatment decision based on the radiographic lesion depth.

Appendix

For the present review, a search for scientific documentation was made for the following topics: radiography and caries lesion cavitation; radiography and caries lesion behaviour; CBCT and caries lesions; CBCT and radiation dose; and CBCT and artefacts. In the search for studies (Table IV), the following search criteria and filters were used: PubMed database, English language, title/abstract, human studies and dental journals. Searches were conducted 28–30 July 2013. The search strings and results are seen in Table IV. Further, a hand search was made from selected journals and abstracts. For search A and C, both *in vivo* and *in vitro* studies were included. For search D, only original articles estimating effective dose (μSv) were included.

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