

RESEARCH ARTICLE

In vitro comparison of high-definition US, CBCT and periapical radiography in the diagnosis of proximal and recurrent caries

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Objective: To assess the *in vitro* performance of high-definition (HD) US, CBCT and periapical radiography for the visibility of proximal and recurrent caries in teeth with and without restoration.

Methods: A total of 240 molar teeth were divided into eight groups each comprised of 30 teeth. Control groups consisted of teeth without caries (Group 1–4; $N = 120$), whereas diseased groups consisted of teeth with proximal caries (Group 5–8; $N = 120$ teeth). Finally, a total of four image sets were obtained as follows: i) PSP periapical radiography, ii) CBCT 0.075 mm voxel size, iii) CBCT 0.2 mm voxel size and iv) HD US images. The image sets were viewed separately by four observers by using a 5-point confidence scale. Intraclass correlation coefficients were calculated. The areas under the ROC curves were compared using chi-square tests. Significance level was set at $\alpha = 0.05$.

Results: Intraobserver agreement for both readings for the four observers ranged between 0.848 and 0.988 for CBCT (0.075 mm) images; 0.658 and 0.952 for CBCT (0.2 mm) images; 0.555 and 0.810 for periapical images; 0.427 and 0.676 for US images. Highest AUC values were found for CBCT (0.075 mm) images and lowest for US images. Statistically significant differences were found among CBCT (0.075 mm) images and US images ($p < 0.001$), CBCT (0.2 mm) images and US images ($p < 0.001$) and periapical images and US images ($p < 0.001$) for the detection of proximal caries.

Conclusion: Periapical and CBCT images outperformed HD US imaging in the detection of proximal dental caries.

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Keywords: Caries diagnosis; Restorative materials; US; Radiography; CBCT; ROC Analysis

Introduction

Today dental caries is among the most common global health problems especially in the developing world. Proximal caries lesions occur between the contacting surfaces of two adjacent teeth. Initially, they appear clinically as opaque regions which occur as a result

of the loss of enamel transparency and as the lesions propagate through the enamel, they take on a triangular form, with the top of the triangle located at the dentine border and pointing towards the pulpal space.¹ Since the proximal surfaces of posterior teeth are large and the mineral loss initially presented by lesions on these surfaces is subtle, proximal caries on posterior teeth are usually difficult to identify on radiographs.² Moreover,

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detection of proximal recurrent carious lesions under restorative materials is also complicated since there is no direct observation possibility for dental tissues under the restoration.³ Accurate and early diagnosis of proximal and recurrent caries is of paramount importance for success and longevity of dental restorations, thereby, preventing extensive tooth loss.⁴ It is suggested that dental restorative materials display radiopacity levels different from dental structures as radiological diagnosis of marginal defects, overhangs and recurrent caries adjacent to these restorations mainly depends on the differentiation of these restorations from carious lesions.⁵ Radiography is the most useful and frequently used method for diagnosing proximal and recurrent caries in conjunction with clinical examination. Digital intraoral sensor systems generally include a solid-state silicon chip or a photostimulable phosphor plate (PSP). Solid-state detectors include a charge-coupled device (CCD), or a complementary metal oxide semiconductor (CMOS). PSP absorbs and stores energy from X-rays and then this contained energy is released as phosphorescent when detected by a photomultiplier.^{6,7} Regardless of the intraoral imaging system used, the two-dimensional (2D) nature of the images limits the information that can be provided, and their value is dependent upon beam angulation, superimposition of anatomical structures and patient-related factors.⁸ Therefore, intraoral periapical techniques may fail to provide enough information in certain cases, such as root fracture, resorption and caries detection.^{8–11} CBCT eliminates most disadvantages of periapical radiography and provides detailed three-dimensional submillimeter accuracy information for dentomaxillofacial diagnosis and treatment planning. CBCT produces high-resolution multiplanar reformatted images of bony structures with lower patient radiation doses than medical computerized tomography (CT).^{12,13} It enables the acquisition of information in a single scan, including 180°–360° rotation around the patient's head by using a cone-shaped X-ray beam and an area detector.¹⁴ However, radiation doses with CBCT is still higher than doses with periapical imaging. Therefore, it is suggested that available CBCT images taken for different tasks such as for implant planning, assessment of impacted third molars or evaluation of pathology and etc., may also be used to detect carious lesions in teeth with or without restorations. CBCT systems offer different sensor types, FOV (field of views) and exposure settings. Beam hardening and metal artifacts that occur in CBCT images are thought to be a limiting factor in detection of recurrent caries under restorations. Voxel size is the term used to define the minimum cube-shaped piece of a CBCT image and may be crucial for the image quality, diagnostic capacity and effective patient doses. Image noise and patient doses may increase with smaller voxel sizes. Thus, selection of optimal voxel size is detrimental for caries diagnosis.^{8–14}

In medicine, ultrasound imaging is a very valuable diagnostic tool in terms of providing onsite immediate assessment without harmful radiation exposure and being applicable to all patient groups. In diagnostic US, high-frequency sound waves are transmitted into the body by use of a transducer and echoes from tissue interface are detected and displayed on a screen. Main disadvantages of US are limited penetration into bone- and gas-filled structures, less spatial resolution at deep tissues and lack of expertise in dentistry. Therefore, its application in dentistry is limited to superficial dento-maxillofacial soft and hard tissue structures since high-resolution, small-sized and intraoral probes were not readily available for dental health.¹⁵ Ultrasound imaging of dental hard tissues and ultrasonographic detection of enamel demineralization were studied previously.^{16–18} The use of ultrasonic waves to identify demineralized lesions is based on the substantial difference in sonic conductivity between sound and demineralized enamel.¹⁹ To the best of our knowledge, no previous study assessed observer ability in the detection of proximal and recurrent caries by using clinically available high-definition US.

Given the clinical importance of proximal caries diagnosis in different circumstances, distinguishing between carious lesions and healthy lesions and restorative materials is crucial. Considering radiation concerns and difficulties in detection of proximal caries under restorations due to the compression of structures in intraoral radiography and occurrence of metal artifacts in CBCT, the goal of this *in vitro* study was to assess the performance of intraoral digital radiography, CBCT with two different voxel sizes and HD US for the visibility of proximal caries in teeth with and without restoration materials in comparison with histological gold standard. Our null hypothesis was that there was no difference between intraoral radiography, CBCT and US systems for the detection of proximal caries lesions.

Methods and materials

Specimen preparation

Institutional Review Board approval was obtained for the present study. Teeth of patients who gave informed consent to donate their teeth for research and teaching purposes were obtained from our collection. A total of 120 molar teeth with proximal dentin caries and 120 molar teeth without caries extracted for periodontal and orthodontic reasons were stored in 1% thymol solution after extraction. All teeth were randomly divided into eight groups each one comprised of 30 teeth. Control groups consisted of teeth (Group 1–4; $N = 120$) without caries, whereas diseased groups consisted of teeth (Group 5–8; $N = 120$ teeth) with proximal caries. Table 1 shows formed groups according to caries status and applied restoration materials. In Group 1, Class 2 cavities were prepared and teeth were restored with traditional glass ionomer base and amalgam. In

Table 1 Applied restoration materials and groups

Groups	Dental caries	Liner	Base	Bonding	Restoration
Group 1	All dental caries were cleaned	Not used	Glass ionomer base	Not used	Amalgam restoration
Group 2	All dental caries cleaned	Not used	Not used	Bonding	Composite restoration
Group 3	All dental caries cleaned	Calcium hydroxide	Glass ionomer base	Bonding	Composite restoration
Group 4	Teeth without carries	Not used	Not used	Not used	Not used
Group 5	Indirect pulp capping	Calcium hydroxide	Glass ionomer base	Not used	Amalgam restoration
Group 6	Indirect pulp capping	Not used	Not used	Bonding	Composite restoration
Group 7	Indirect pulp capping	Calcium hydroxide	Glass ionomer base	Bonding	Composite restoration
Group 8	Teeth with caries	Not used	Not used	Not used	Not used

Group 2, Class 2 cavities were prepared and teeth were restored with universal adhesive and composite. In Group 3, Class 2 cavities were prepared and teeth were restored with calcium hydroxide cement, traditional glass ionomer base, universal adhesive and composite. In Group 4, no cavity was prepared and teeth were used as the control group without caries. In Group 5, Class 2 cavities were prepared and caries were left on the pulpal or axial walls, and the teeth were restored with calcium hydroxide cement, traditional glass ionomer base and amalgam. In Group 6, Class 2 cavities were prepared and caries were left on the pulpal or axial walls, and the teeth were restored with universal adhesive and composite. In Group 7, Class 2 cavities were prepared and caries were left on the pulpal or axial walls, and the teeth were restored with calcium hydroxide cement, conventional glass ionomer base and universal adhesive and composite. In Group 8, proximal carious lesions were left and no restoration was performed.

Scotchbond Universal adhesive (3M ESPE, Seefeld, Germany) without prior etching was used as bonding in all composite restoration groups. Calcium hydroxide [Ca(OH)₂] (Dycal, Dentsply De Trey Konstanz, Germany) was used as indirect pulp cupping material in all groups where liner was applied. Conventional glass ionomer base used as the base material was VOCO Ionofil® Molar (Germany). A conventional resin composite (Filtek Z250, Z250/3M ESPE, Seefeld, Germany) was used as a composite restoration material. Gamma-2 free Cavex Avalloy (Cavex Holland BV, Haarlem, Netherlands) amalgam was used as amalgam restoration material.

Imaging procedures

A researcher numbered each group of teeth with a different colour. All the numbered teeth were blended for random selection for the image acquisition process. For imaging procedures, each tooth was placed in the appropriately prepared maxillary and mandibular molar sockets of a dry skull along with its mandible. The dry skull along with its mandible was covered with 2 cm red wax as a soft tissue equivalent material. All teeth were randomly placed in the alveolar sockets in groups of 8 (two molars on left and right hemi-mandibles and hemi-maxillae).

Digital intraoral periapical radiographs were exposed by using an X-ray unit (Gendex Digital Systems, Hatfield, PA, USA) operated at 65 kVp and 7mA with a size two photostimulable phosphor plate (PSP) detector (GXPS-500 PSP, Gendex Digital Systems, Bensheim, Germany). Image recording was set at 64µm (high) pixel size and 32-bit color. *In vitro* imaging was performed using standardized paralleling technique equipment with rectangular collimation (Rinn Manufacturing Company, Elgin, IL, USA) with a focus-receptor distance of 40 cm and an image-exposure time of 0.25 s. Pulpal root canal, dentine and enamel visibility were used as indicators of optimal image quality, determined by consensus.

A CBCT unit (ProMax® 3-D Max; Planmeca, Helsinki, Finland) was used to obtain the CBCT data. The selected voxel sizes were 0.075 mm and 0.2 mm. The imaging parameters for the images obtained at 0.075 mm voxel size were 55 × 50 mm FOV at 96 kVp, 7.1 mA and 15 s with a dose area product (DAP) value of 657 mGy * cm². The imaging parameters for the images obtained at 0.2 mm voxel size were 100 × 59 mm FOV at 96 kVp, 5.6 mA and 12 s with a DAP value of 728 mGy * cm². The observers prepared panoramic and cross-sectional views with a 1 mm section interval and 1 mm thickness.

US examinations were performed by using an ACUSON S 2000 (Siemens, Munich, Germany) high-resolution ultrasonography by the same researchers who conducted CBCT assessments. A 18L6 MHz HD linear probe covered with ultrasonography gel was performed on the transversal plane, with the probe position changed constantly to obtain sufficient cross-sectional images on the monitor. The transducer was positioned perpendicular to alveolar crest in order to enable cross-sectional assessment of the teeth. For the caries evaluation, restorative materials and enamel seen as hyperechogenic with an echogenic shadow was used as the reference for decision-making.

Finally, a total of four image sets were obtained as follows: i) PSP periapical radiography, ii) CBCT 0.075 mm voxel size, iii) CBCT 0.2 mm voxel size and iv) HD US images.

A specific calibration session by using three images, which were not included in the study, was conducted prior to the assessment process. The image sets were viewed separately by four blinded and calibrated

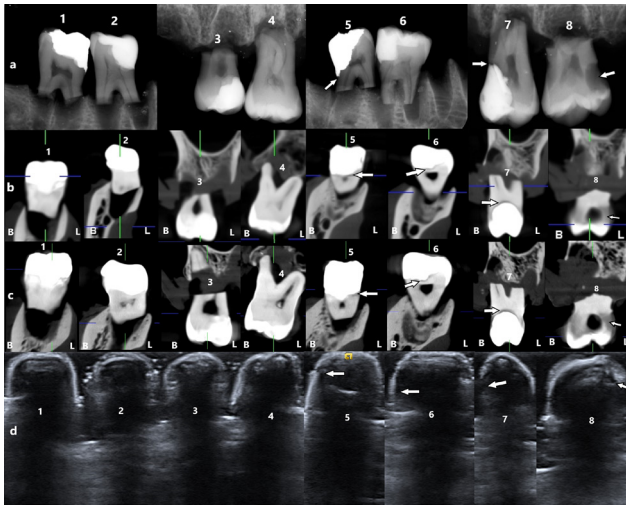


Figure 1 a) Representative periapical radiographic images for Groups 1–8; b) CBCT images obtained from mesial or distal aspects obtained at 0.075mm voxel size for Groups 1–8; c) CBCT images obtained from mesial or distal aspects obtained at 0.2mm voxel size for Groups 1–8; d) High-definition US images of teeth for Groups 1–8. Groups: 1) Traditional glass ionomer base and amalgam restoration; 2) Universal adhesive and composite restoration; 3) Calcium hydroxide cement, traditional glass ionomer base, universal adhesive and composite; 4) Sound tooth; 5) Calcium hydroxide cement, traditional glass ionomer base, universal adhesive and composite restoration with residual caries; 6) Universal adhesive and composite restoration with residual caries; 7) Calcium hydroxide cement, traditional glass ionomer base, universal adhesive and composite restoration with residual caries; 8) Proximal carious lesion, without restoration. White arrow shows radiolucent residual caries in periapical radiography and CBCT images. In high-definition ultrasonography images, white arrow shows anechoic carious lesion and continuous loss of enamel tissue.

observers (between 5 and 10 years of experience in dental and caries imaging) in a dimly lit room with no time restrictions. The image sets were viewed at one-week intervals, and evaluations of each image set were repeated one week after the initial viewings. All the images were randomized within each imaging protocol. For periapical and CBCT images, the observers were asked to assess the presence or absence of proximal caries on a 22" monitor (MD213MG LCD; NEC, Tokyo, Japan) with a screen resolution of 2048×1536 pixels and 32-bit color depth. The teeth were assessed by using the Gendex Imaging Software for periapical images and Planmeca Romexis Software for CBCT images on a medical diagnostic monitor (NEC, Tokyo, Japan) that had a 21.3" screen and 2048×1536 resolution. US assessments were conducted by using Siemens system's own software and monitor. When ultrasound bounces between two interfaces with high acoustic impedance, it moves forward and backward between these interfaces. Tissues may be categorized as either echogenic or anechogenic, with echogenic, or hyper-echogenic, tissue reflected with high intensity to produce light screen images, such as restorative materials and dental hard tissue and anechogenic, or hypoechoic, tissue reflected with low intensity to produce dark screen images such as caries. For all image types, caries was

diagnosed according to a 5-point confidence rating. The rating scale expressed the presence or absence of caries as: (1) almost definitely present, (2) probably present, (3) unsure, (4) probably not present and (5) almost definitely not present. Figure 1 shows representative periapical radiographic images, CBCT images and HD US for Groups 1–8.

Histological validation of the status of caries was performed by serially sectioning each tooth mesiodistally in parallel to the long axis of the crown. Both sides of each section were examined under a stereomicroscope (610) (Stemi 2000; Carl Zeiss, Jena, Germany) by one of the present study's authors, who recorded each tooth as either sound or as having a carious lesion, which was defined as a demineralized white or yellowish-brown discoloured area in the dentine. A histological examination of the 120 proximal tooth surfaces revealed no caries and 120 proximal tooth surfaces showed dentine caries.

Statistical analysis

Intraclass correlation coefficients were calculated to assess the intra- and interobserver agreement for each image type according to the following criteria: <0.40 = poor agreement; 0.40 – 0.59 = fair agreement; 0.60 – 0.74 = good agreement; 0.75 – 1.0 = excellent agreement.²⁰ The estimated ICC values were based on absolute agreement, two-way mixed effects model. Obtained scores from four different image types and four different caries types were compared with the gold standard by using the receiver operating characteristic (ROC) analysis in order to evaluate the observers' ability to differentiate between teeth with and without caries. The areas under the ROC curves (AUC - Area Under Curve - values) were calculated and the tests for the equality of AUCs for each image type and restoration material and were compared using chi-square tests. Significance level was set at $\alpha = 0.05$. The significance probability was adjusted for the effect of multiple comparisons by using Bonferroni correction. All calculations were carried out using the STATA 12.1/MP4 statistical software.

Results

Intraclass correlation coefficients (ICC) for intraobserver and interobserver agreement were calculated. Intraobserver agreement for both readings for the four observers ranged between 0.848 and 0.988 for CBCT (0.075mm) images; 0.658 and 0.952 for CBCT (0.2mm) images; 0.555 and 0.810 for periapical images; 0.427 and 0.676 for US images. Higher ICCs were calculated for CBCT images in comparison with periapical radiography and US images for intraobserver agreement. In general, good and excellent ICCs were calculated for CBCT images and fair and good agreement for periapical images for intraobserver agreement. Lowest ICCs were found for US images suggesting in general

Table 2 Diagnostic performance shown as area under curve for each image type and group

Group	Image Type	N	AUC	Std. Err.	95% Confidence Interval	
					Lower bound	Upper bound
Teeth	CBCT 0.075 mm	60	0.9995	0.0002	0.9411	0.9998
	CBCT 0.2 mm	60	0.9911	0.0092	0.9730	0.9999
	Periapical	60	0.9672	0.0323	0.8938	0.9998
	Ultrasound	60	0.7989	0.0574	0.6865	0.9113
Amalgam	CBCT 0.075 mm	60	0.950	0.0246	0.9017	0.9982
	CBCT 0.2 mm	60	0.9411	0.0332	0.8761	0.9991
	Periapical	60	0.9022	0.0413	0.8213	0.9832
	Ultrasound	60	0.7006	0.0682	0.5667	0.8342
Composite	CBCT 0.075 mm	60	0.9994	0.0008	0.9971	0.9998
	CBCT 0.2 mm	60	0.9998	0.0003	0.9959	1
	Periapical	60	0.9572	0.018	0.9318	1
	Ultrasound	60	0.7194	0.0673	0.5875	0.8513
Composite (Dycal)	CBCT 0.075 mm	60	0.9967	0.0035	0.9898	1
	CBCT 0.2 mm	60	0.9933	0.0058	0.9819	1
	Periapical	60	0.9594	0.0199	0.9304	0.9935
	Ultrasound	60	0.6994	0.0695	0.5632	0.8356

fair agreement. For interobserver agreement among four observers, for both readings, ICCs ranged between 0.879 and 0.981 for CBCT (0.075mm) images; 0.841 and 0.959 for CBCT (0.2mm) images; 0.854 and 0.957 for periapical images; 0.696 and 0.854 for US images. In general, good to excellent agreement were found among the observers.

Table 2 shows the diagnostic performance as area under curve (AUC) for each image type and group. In

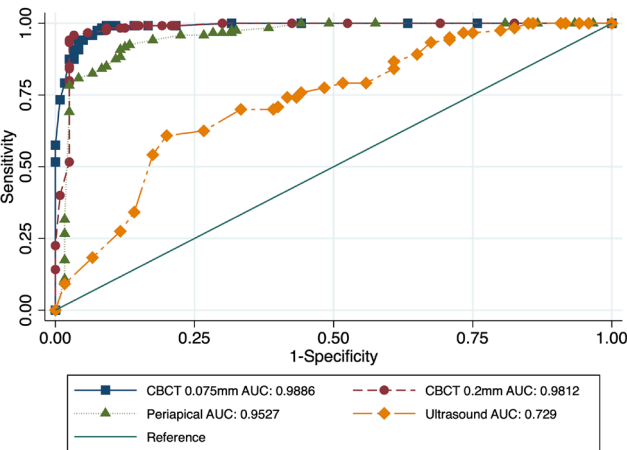


Figure 2 Receiver operating characteristic (ROC) curves for all image sets and overall groups. PA: Periapical radiography; CBCT 1: 0.075 mm voxel size data; CBCT 2: 0.2 mm voxel size data, US: High-definition ultrasonography.

Table 3 Diagnostic performance was shown as area under curve for each image type for overall groups along with pairwise comparisons

Image Type	N	AUC	Std. Err.	95% Confidence Interval	
				Lower bound	Upper bound
CBCT 0.075 mm	240	0.9886	0.0048	0.9793	0.9981
CBCT 0.2 mm	240	0.9812	0.0089	0.9638	0.9992
Periapical	240	0.9527	0.0141	0.9251	0.9803
Ultrasound	240	0.7290	0.0324	0.6655	0.7925
P-values of pairwise comparisons					
	CBCT 0.075 mm	CBCT 0.2 mm	Periapical	Ultrasound	
CBCT 0.075 mm					
CBCT 0.2 mm	0.4591				
Periapical	0.0157	0.0872			
Ultrasound	<0.001	<0.001	<0.001		

general, highest AUC values were calculated for teeth without restoration followed by teeth with composite restorations and teeth with amalgam restorations. Table 3 shows diagnostic performance as AUC for each image type for overall groups along with pairwise comparisons. Highest AUC values were found for CBCT (0.075 mm) images and lowest AUC values were found for US images. Statistically significant differences were found among CBCT images and US images ($p < 0.001$) and periapical images and US images ($p < 0.001$) for the detection of proximal caries. Figure 2 shows receiver operating characteristic (ROC) curves for all image sets and overall groups.

Discussion

To our knowledge, the present study was the first to compare proximal and recurrent caries lesions by using clinically available HD ultrasonography in comparison with periapical and CBCT in an *in vitro* setting. Accurate assessment of proximal caries lesions is important for the clinician in terms of providing immediate and appropriate dental intervention and preventing extensive dental tissue damage and pain. We evaluated the diagnostic potential of HD ultrasound that provided real-time rapid images, at a low cost and without ionizing radiation in assessing proximal caries lesions in teeth and under various restorations. Although, there were certain limitations in the detection of proximal lesions by US, such as shadowing behind different materials and practical difficulties, our study showed promising results. In US imaging, sound waves are transmitted, attenuated and/or scattered when they interact with a medium. Acoustic impedance defines the resistance of a material to propagation of ultrasound waves, and it is determined by the density of the material. Bones and dental hard tissues reflect more sound waves than fluid and they produce white and bright images. Since

ultrasound waves cannot transmit through compact structures, a black acoustic shadow occurs behind them. In the present study, lower intra- and interobserver reliability along with lower Az values obtained from US images may be attributable to this phenomenon. Therefore, in assessing ultrasound findings, it is important to consider that ultrasound is an operator- and technique-dependent imaging modality. In ultrasound imaging, the borders of the caries lesions may differ according to tissue thickness and continuity and acoustic impedance. Anechogenic or hypoechogenic poorly defined caries lesion and loss of enamel tissue should be considered for caries diagnosis. Further studies with larger sample sizes are needed to better understand the factors influencing the versatility and accuracy of ultrasound to assess caries lesions.

Observation and detection of proximal and recurrent caries are clinically difficult and these carious lesions are mostly diagnosed by using radiographic techniques in combination with clinical examination. Intraoral radiographic techniques are the most commonly used methods for the detection of proximal lesions; however, these techniques are two-dimensional in nature and have relatively low sensitivity and specificity due to superimposition and projection geometry issues.^{21–23} In previous studies, wax was used to simulate secondary caries around restorations for the assessment of sensitivity and specificity of different radiographic systems.²⁴ In the current study, we evaluated the effectiveness of different diagnostic methods caries diagnostic ability under composite or amalgam fillings, with natural caries, with or without the application of capping materials, in order to better simulate actual clinical conditions.

During diagnostic imaging and assessment, the radiopacity of composite resins, dentin bonding agents, amalgams, liners and base materials plays a critical role in the ability of clinicians to distinguish restorations from both tooth structures and secondary caries. In real clinical situations, diagnostic challenges arise when radiographic images present barely discernible radiopacity differences between dental tissues and restorative material.²⁵ Excessive radiopacity has been reported to have a negative impact that may reduce the ability to diagnose recurrent caries and other defects.^{26,27} A previous study suggested that CBCT examination should not be used to determine the presence or absence of caries when amalgam fillings are present in direct contact with an area being diagnosed.²⁸ Another study found no significant difference in the diagnostic performance of CBCT images and classical radiographs.²⁹ In the present study, although beam hardening artefacts were frequently detected by the observers, our trained observers performed better with CBCT images when compared to other modalities utilized. However, in general, we found highest AUC values for teeth without restoration followed by teeth with composite restorations and teeth with amalgam restorations. This result might be due to negative effects

of beam-hardening artefacts with CBCT and acoustic impedance with US.

Authors found no statistically significant difference between bonding systems and periapical imaging modalities assessed for the visibility of secondary caries. Furthermore, false-positive rate for periapical imaging techniques and adhesive systems were found to be high. Therefore, authors suggested that since bonding systems used under composite restorations may mimic secondary caries, they should have adequate radiopacity in order to compensate projection geometry issues.³⁰ Similar results were also found in a study which compared inspection, film, PSP and CBCT for the detection of proximal caries in unrestored teeth.¹ We found higher AUC values for 0.075 mm voxel size CBCT images when compared to CBCT with 0.2 mm voxel size, PSP and US, in the detection of proximal and proximal recurrent caries. Although clinical use of CBCT in the diagnosis of recurrent proximal caries is not applicable in every patient due to radiation concerns and it is known that artifacts may negatively affect the image quality, it is our belief that available CBCT images taken for other purposes may be used for caries diagnosis as a supplementary tool.

A previous study found CBCT to outperform intraoral periapical imaging in the detection of recurrent caries under composite restorations. Authors aimed to compare the diagnostic accuracy of conventional and digital intraoral radiography and CBCT for detection of artificial recurrent caries around mesio-occluso-distal composite restorations.³¹ Accuracy of CBCT was significantly higher than that of digital and conventional intraoral radiography ($p < 0.05$). The accuracy was 0.83, 0.78, 0.55 and 0.49 for CBCT Cranex 3D, CBCT NewTom 3G, conventional and digital intraoral radiography, respectively.³¹ Authors compared CBCT, PSP and F-speed film in assessing the depth of interproximal carious lesions. The correlation between the measurements of the two observers was 0.977 for film, 0.997 for image plate system and 0.998 for CBCT similar to our findings. Bland-Altman plots revealed that CBCT agreed highly with the gold standard while the agreement between the periapical images was moderate. Authors concluded that CBCT was a promising tool for detection and monitoring of proximal carious lesions.³² Measurement of caries lesions was out of the scope of our research. Better visibility of proximal caries with CBCT might be attributable to the possibility of assessing lesions in axial, coronal and cross-sectional views by using reformatted multiplanar reconstructed images. System and software capability, observer experience and sample selection are all important factors in assessing recurrent caries with CBCT.

Authors of a previous study³³ assessed the *in vitro* diagnostic ability of CBCT images by using seven different display types in the detection of occlusal and proximal recurrent caries under different types of restorations. Teeth were imaged using 100 × 90 mm field of

view at three different voxel sizes of a CBCT unit (Planmeca ProMax[®] 3D; Planmeca, Helsinki, Finland). Authors found poor and moderate agreements. Higher Az values were observed with medical monitors when used with dedicated software in comparison with other display types which performed similarly in the diagnosis of recurrent caries under restorations. In general, no difference was found among three different voxel sizes ($p > 0.05$). In addition, observers performed better in the detection of recurrent caries when assessing composite restorations than amalgams. In general, higher Az values were obtained for composite restorations than for amalgam restorations for all observers.³³ Authors of another study evaluated the *ex vivo* diagnostic ability of nine different CBCT settings in the detection of recurrent caries under amalgam restorations in primary teeth. Variations in tube voltage and tube current did not affect the detection of recurrent caries under amalgam restorations in primary teeth.³⁴ In the present study, we used medical monitor along with Planmeca CBCT taken at 96 kVp, 7.1 mA and dedicated software by using 0.075 mm and 0.2 mm voxel sizes and we found that CBCT images outperformed HD US in the detection of proximal caries *in vitro*.

Authors assessed intraoral images and two CBCT systems for detection of artificial buccal recurrent caries like lesions created by placing wax under restorations. Higher interobserver agreement was obtained from the CBCT images compared with the intraoral images. The Az values of both readings of all three observers were highest for the Veraviewepocs 3D followed by Kodak 9000 except for the second reading of the third observer. CBCT outperformed intraoral radiography in detection of artificial buccal recurrent caries under restorations.³⁵ While artificial caries like buccal recurrent caries was evaluated in the mentioned study, we evaluated observer performance in the detection of natural proximal caries under restorations by using CBCT, periapical imaging and HD US. Furthermore, in the evaluation of recurrent proximal caries, the properties of the restoration materials are as important as the differences in imaging systems. Snergy, Ice, Filtek Silorane, Filtek Z250, Clearfil Majesty Posterior, Herculite Classic, Spectrum Tph and Natural Look composite materials exhibited higher radiopacity than dentin, and all dentin bonding agents tested exhibited lower radiopacity than enamel or dentine. In addition, excellent linear correlation was found between film and phosphor plates for both composite resins and binding agents.³⁶ In our study, since only one composite system and bonding system were used, no comparison was made between products.

Our study was the first to assess observer performance in the detection of proximal caries *in vitro* by using clinically available HD ultrasound, CBCT and periapical radiography. Authors of a previous study³⁷ evaluated an ultrasonic caries detector, consisting of a PC-controlled ultrasonic pulse receiver along with a probe. Ultrasonic caries detector sensitivity was 0.82 compared with 0.75

for bite-wing radiographs when the threshold was determined as radiolucency in inner enamel and dentin, and 0.49 when the threshold of radiolucency was in dentin. The specificity of ultrasonic caries detector was 0.75 vs 0.9 for radiographs. The ultrasonic detector exhibited a higher sensitivity than the radiographs at the cost of lower specificity. Unlike our study, ultrasonic caries detector used in the mentioned study was not able to display images of the teeth and caries but the signal appearing on the screen showed the acoustic reflection obtained from proximal carious lesion.³⁷

Authors developed a biomicroscopic experimental system with a single-element transducer for the acquisition of three-dimensional ultrasound echo signals from *ex vivo* human dental samples. The press-focused high-frequency ultrasound transducer had a centre frequency of 40 MHz and -6dB bandwidths of 67%. Authors investigated the ability of this desktop system to detect early dental caries and compared the results obtained with a conventional ultrasound imaging system (Sonix-Touch Q+; BK Ultrasound).³⁸ The conventional ultrasound imaging system was a linear array system with a linear array transducer (L14-5/38; BK Ultrasound), allowing the acquisition of ultrasound echo signals at a centre frequency of 13.3 MHz in two-dimension. Their results showed that high-frequency ultrasound had the potential to detect white spot lesions with better contrast and resolution than conventional ultrasound imaging. Also, the invasion depths of lesions obtained with the developed system had good agreement with those obtained with the micro-CT images. Authors suggested that studied desktop system might offer information on the depth and shape of the caries lesion. High-frequency US imaging gave similar results when compared to microcomputed tomography imaging in the detection of white spot lesions, while eliminating the risk of radiation.³⁸ However, mentioned device is not clinically available and cannot be used in routine dental practice. Conventional ultrasonography system that was used for the mentioned study showed lower performance than high frequency ultrasound and gold standard micro-CT.³⁸ We used a two-dimensional 18L6 MHz HD linear probe ultrasound that facilitated better visibility of dental structures and restorations. With the ultrasound system utilized in the present research, we found less successful results when compared to CBCT and periapical images when detecting proximal caries lesions. Further innovative approach is essential to improve image quality in terms of frequency and three-dimensional reconstructive capacity of clinically applicable ultrasound systems in order to improve observer performance. The development and improvement of such devices are extremely important for both clinicians and patients in the dental sector. Recently, there has been much interest in the development of non-invasive and non-ionizing techniques in caries diagnosis. Future work will also encompass the transformation of the ultrasound systems so that attenuation and reflection

measurements can be performed and combined with two- and three-dimensional imaging systems, which will be used to assess healthy and carious tooth samples.

Conclusion

CBCCT images and periapical radiography images outperformed HD US in the detection of proximal caries *in vitro*. However, HD clinical US may provide supplementary information without ionized radiation but it is not a substitute for X-ray imaging techniques. Specific attention should be directed towards developing dental

ultrasound probes in order to detect subtle changes in teeth.

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Disclosure

The authors declare that they have no conflict of interest.

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