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Performance of different diagnostic methods for caries detection: A microtomographic and histological study

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Abstract

Objective: The objective of this study was to compare the performance of visual and imaging macroscopic methods in detecting caries, using histological examination and micro-CT images as the gold standard.

Methods: Under standardized conditions, 20 human teeth with caries lesions, ranging from incipient to severe, were selected. Two examiners, duly trained and calibrated, performed all the analyzes of the study. The teeth were classified according to the ICDAS-II index for the visual macroscopic method. To evaluate the images, periapical, conventional, and digital radiographs of all teeth and Cone Beam Computed Tomography (CBCT) images were acquired, and the examiners classified the presence or absence of caries according to the Ekstrand method (1997). After all the images were taken, the micro-CT and histological methods established the gold standard.

Results: When establishing a response threshold (threshold) restricted to the absence of caries (T0) and the presence of caries in enamel (T1) or dentin (T2), the agreement between examiners ranged from 60 to 75% for all tested methods. The values of Sensitivity (Se), Specificity (Ep), Positive Predictive (PPV), Negative Predictive (NPV) and Accuracy (Ac) for all methods and the two gold standards were evaluated, with CBCT being the one that presented the best performance and conventional radiography the worst.

Conclusion: The diagnosis of caries through imaging methods is a challenge in clinical dental practice, and the choice of examination can significantly interfere with the diagnosis. It was concluded that digital radiographs should be indicated as complementary exams to diagnose caries. Regarding the analysis of the two gold standards, the micro-CT images are more accurate when compared to the histological one, as they can detect minor variations in the density of the tissue method.

Introduction

Dental caries is a dysbiosis caused by a microorganism consortium forming the dental biofilm, working synergistically to initiate and progress carious lesions [1]. If not systematically removed, microbial biofilms produce acids leading to progressive enamel demineralization. In occlusal or interproximal surfaces, the early enamel lesions may represent the greatest diagnostic challenge because mineral loss usually involves dentin when detected in imaging exams [2]. The periapical and interproximal (bite-wings) radiographic techniques are conventionally used in combination with visual examination to establish a treatment plan [3].

Although a consensus exists on the need for radiographic examinations to aid caries detection, it may still be impossible to define which radiographic technique can be considered the gold standard. Previously, conventional radiographic systems were considered more accurate than digital [4]. Recent studies demonstrated that digital systems offered better resolution than conventional methods [5,6]. It is essential to recognize that interpretation may be affected by the insufficient processing time of conventional images, incorrect manipulation of the digital receivers, and errors in the acquisition technique, all of which may interfere with image quality [5,7]. Digital receivers offer advantages compared to conventional films, such as reducing radiation dose, eliminating chemical solutions, and possibly using image enhancement tools to improve caries detection [6,8-10].

Cone-Beam Computed Tomography (CBCT) allows a three-dimensional examination of oral structures and their application in different situations, including pre-surgical evaluation of retained teeth, dental implants, bone, dental fractures, and maxillofacial pathological processes. Some studies, however, have recently focused on its use in diagnosing caries [3,11-13].

Stereomicroscopic examination after sectioning is the preferred method for validating the caries lesions presence [14]. However, during the sectioning process, the area of interest may be damaged or severely compromised [15]. While the stereomicroscopic examination is commonly accepted as the gold standard for the detection of caries lesions, microtomography (micro-CT) represents an innovative, promising, and non-invasive technique with the ability to obtain three-dimensional images and perform detailed analyse mineral density can be used as a gold standard caries detection method [16-19].

Micro-CT may be considered a microscopic version of computed tomography. It also uses X-rays for imaging, in which individual projections (radiographs) can be reconstructed in any plane, and the high-resolution images can be evaluated qualitatively and quantitatively [15,20]. Some studies have already used this technique to evaluate enamel and dentin caries [20,21]. It has been shown to detect caries lesions better than visual, radiographic, and laser fluorescence methods [15]. Despite its superior performance, clinical use of micro-CT is impossible due to the high radiation used during image acquisition. Indeed, it can play a fundamental role as a non-destructive alternative to the stereomicroscopic method [22].

The early detection of dental caries still represents a challenge, recent studies have been committed to evaluating the performance of imaging and visual macroscopic diagnostic methods, testing new technologies, establishing new gold standards [11,12,19,23-25]. The present study aimed to compare the performance of different methods of diagnosing caries, comparing two gold standards, as well as comparing the methods considered the gold standard and evaluating the best option between them.

Material and methods

Study design and ethical aspects

The Local Research Ethics Committee duly approved this cross-sectional, ex-vivo observational study under opinion N°1.329.168.

Sample selection and eligibility criteria

Twenty permanent human teeth were selected and stored in individual containers. All teeth were disinfected in 2% glutaraldehyde for approximately 2 hours and then kept hydrated in distilled water. Each tooth had its root covered with utility wax and mounted on a Styrofoam base to facilitate handling and simulate implantation conditions in the alveolus. Single or multi-rooted teeth with the absence or presence of carious lesions were included, and those with crowns partially (2/3 or more) or wholly destroyed were excluded.

Two trained and calibrated examiners assessed every sample (n=20). All methods were evaluated on two occasions, with an interval of 15 days between evaluations to verify reproducibility and agreement.

Assessment methods

Four methods were used to detect the presence of carious lesions: macroscopic visual, conventional radiography, digital radiography, and cone-beam tomography (Figure 1).

Figure 1: Caries detection methods tested. **(A)** Macroscopic visual; **(B)** Conventional radiography; **(C)** Digital radiography; **(D)** Cone-beam tomography.

Macroscopic visual

The examiners independently classified the presence or absence of caries according to the ICDAS-II index, with scores ranging from 0 to 6, where: 0 = absence of caries; 1 = first visual change in enamel; 2 = distinct visual change in enamel; 3 = darkened shading located at the enamel-dentin junction; 4 = darkened shading originating in dentin; 5 = cavity with visible dentin; 6 = extensive cavity with visible dentin. The teeth were examined dry and by direct vision [26].

Radiographic and tomographic

Periapical, conventional, and digital radiographs were taken using a single Instrumentarium Intraoral Focus™ X-ray device (Instrumentarium Imaging, Tuusula, Finland), operating at 70 kVp and 7 mA, varying only the image receptor and exposure time. For the conventional images, F film (Kodak, Eastman Kodak Company, Rochester, NY, USA) was used, with an exposure time of 0.3 seconds and manually processed according to the temperature/time method. The radiographs were digitized and exported in .jpeg format for further analysis.

For the digital images, a phosphor plate-type receiver (PSP), size 2 (Express®, Instrumentarium Imaging, Tuusula, Finland) was used, with an exposure time of 0.2 seconds and visualization in the CliniView™ program (Instrumentarium Imaging, Tuusula, Finland).

Next, Cone-Beam Computed Tomography (CBCT) images were taken of each tooth, using the KODAK K9500™ CT scanner (Carestream Health, Rochester, USA), with the parameters 10 mAs, 90 kVp, FOV (Field of View) of 9 .5 x 15 cm, 0.2 mm³ voxel and scanning time of 10.8 seconds, with 360º rotation.

Both images were randomly organized in templates to be later evaluated. The use of post-processing tools to visualize the images was not allowed. The evaluators should classify the possible lesions according to the depth of the radiolucency according to the scores assigned by Ekstrand, 1997 [27] (modified), as follows: 0 – no radiolucency; 1 – visible radiolucency in enamel; 2-visible radiolucency in the external half of the dentin; 3 – Visible radiolucency in the inner half of the dentin.

The visualization program used for tomographic images was Carestream 3D™ (Carestream Health, Rochester, USA), and the same scoring system was used (Ekstrand, 1997 [27] - modified).

Establishing the gold standard

Two experienced examiners, a Pathologist, and an Oral Radiologist, who did not participate in the sample evaluation process, established the gold standard.

To obtain the pattern by micro-CT, the teeth were scanned using the SkyScan 1173™ device (SkyScan, 1173; Bruker-microCT, Kontich, Belgium). The acquisition parameters were 70 kV, 114 x 114 μA, 14.6 mm spatial resolution, 1 mm aluminum filter, 250 ms exposure time, 0.5° rotation step, and an average of 5 and 360° rotation turns. The isotropic voxel was 14.25 μm. Images were evaluated continuously in a low-light environment using a 23 inch monitor. The scores were the same as those of the previously described imaging methods (Ekstrand, 1997 [27] - modified) (Figure 2).

Figure 2: Gold standard: Microtomographic images. **(A)** No radiolucency; **(B)** Radiolucency visible in the enamel; **(C)** Visible radiolucency in the external half of the dentin; **(D)** Radiolucency in the inner half of the dentin.

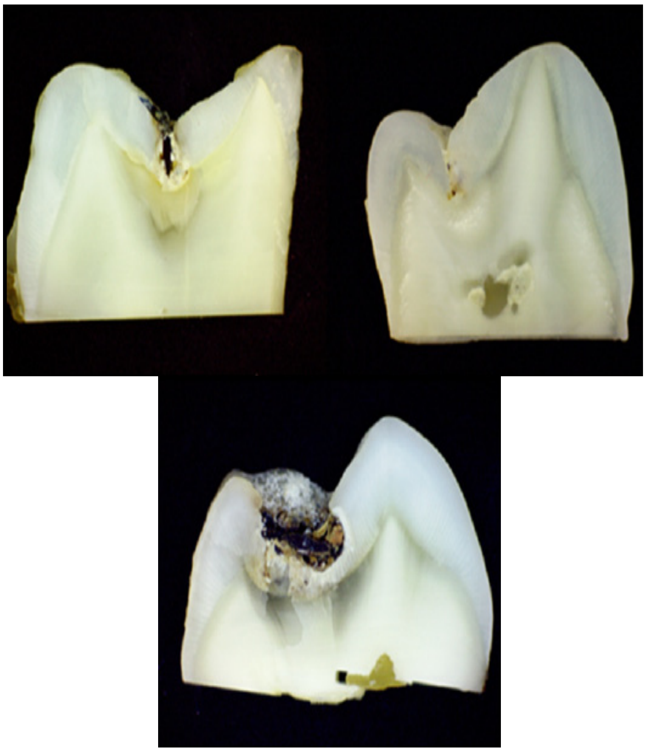
Figure 3: Gold standard: Stereomicroscopy images of the tooth sections.

For the histological gold standard, after the acquisition of all images, the teeth were sectioned into 700 μm thick sections in the mesiodistal direction using a 200 μm water-cooled diamond disc (Isomet™, Buehler, Lake Bluff, IL, USA). The evaluation was performed using a stereoscopic microscope, with a magnification of 10-20x, under reflected light (Olympus SZ61, Tokyo, Japan) (Figure 3). The presence or absence of caries was defined according to the criteria of Ekstrand, 1997 [27], being: 0 = without demineralization; E1 = demineralization extending to the outer half of the Enamel; E2 = demineralization extending to the inner half of the Enamel; D1 = demineralization at the dentinal-enamel junction, without evident propagation into the dentin; D2 = demineralization extending to the outer half of the dentine; D3 = demineralization extending to the inner half of the dentine.

Statistical analysis

A descriptive analysis of the tested variables was performed, with categorical variables represented by absolute and relative frequencies. Quantitative variables were represented by mean and standard deviation, median and interquartile intervals [quartile 1; quartile 3], and minimum and maximum values.

The agreement's Kappa or Pabak (adjusted Kappa) coefficient was analyzed. The degree of agreement can vary from 0 to 1 and can be classified, according to Landis and Kock, 1977 [28] as less than zero (poor), from 0 to 0.20 (low), from 0.21 to 0.40 (regular), from 0.41 to 0.60 (moderate), from 0.61 to 0.80 (substantial) and from 0.81 to 1.00 (almost perfect). The significance level adopted was 0.05. Analyzes were performed using SPSS (Statistical Package for Social Sciences), version 23 (SPSS Inc., Chicago, IL, USA).

The correlation between the tested methods and the gold standard and the values of sensitivity, specificity, positive and negative predictors, and accuracy were determined. To increase the statistical power of the sample and equalize the tested scores, similar values were grouped into thresholds called "thresholds", namely T0 (Absence of caries), T1 (caries in enamel), and T2 (caries in dentin) [20]. The combination of scores according to the similarity of responses is described in Table 1.

Table 1: Scores assigned to thresholds determined for joining similar values.

T0 = Absence of caries	**All scores 0**
T1 = enamel caries	Clinical appearance (1 = first visual change in enamel; 2 = distinct visual change in enamel; 3 = localized at dentinal-enamel junction). Imaging methods (1 – visible radiolucency in enamel). Histological (E1 = demineralization extending into the outer enamel half; E2 = demineralization extending into the interior half of the Enamel; D1 = demineralization at the dentin-enamel junction without prominent propagation into the dentine).
T2 = dentin caries	Clinical appearance (4 = darkened shading originating from dentin; 5 = cavity with visible dentin; 6 = extensive cavity with visible dentin). Imaging methods (2 - visible radiolucency in the outer half of the dentin; 3 - radiolucency in the inner half of the dentin). Histological (D2 = demineralization extending into the outer half of the dentin; D3 = demineralization extending into the inner half of the dentin).

Results

The agreement between examiners was considered substantial, ranging from 60% to 75% for the methods tested in general, with the lowest agreement for conventional radiography and the highest for CBCT.

Taking into account the gold standard obtained by micro-CT, 10% (n=2) of the images of dental crowns did not show radiolucency, 55% (n=11) showed visible radiolucency in enamel, 10% (n=2) visible in the outer half of the dentin and 25% (n=5) in the inner half of the dentin. The agreement of imaging methods concerning the micro-CT gold standard ranged from 25 to 50%, with the lowest for conventional radiography and the highest for CBCT.

According to the histological gold standard analysis, 35% (n=7) of the tooth surfaces were sound without demineralization. 20% (n=4) had a carious lesion on the outer half of the enamel, 5% (n=1) on the inside of the enamel, 10% (n=2) on the enamel-dentin junction, without propagation to the dentin, 15% (n=3) had caries lesions propagated in the outer dentin and 15% (n=3) in the inner half of the dentin. The concordance between the visual macroscopic method and the histological gold standard ranged from 30% to 40%.

When a response threshold (threshold) was established, restricted to the absence of caries (T0) and the presence of caries in Enamel (T1) or dentin (T2), the agreement between examiners ranged from 60 to 75% for all tested methods. Threshold analysis for the visual macroscopic method compared to the histological gold standard ranged from 45 to 55%, and imaging methods for the micro-CT gold standard ranged from 25 to 60%. Regarding the two gold standards, the agreement was 33% when the response thresholds were established, with a significant difference between them, as seen in Table 2.

Table 2: Agreement between the two methods is considered the gold standard after establishing response thresholds.

		MICRO-CT				
		T0	**T1**	**T2**	PABAK	*p*
Histological		n (%)	n (%)	n (%)		
	T0	2 (10)	4 (20)	1 (5)	0.33	0.04*
	T1	0 (0)	5 (25)	2 (10)		
	T2	0 (0)	2 (10)	4 (20)		

Table 3: Sensitivity (Se), specificity (Ep), positive predictive (PPV), negative predictive (NPV) and accuracy (Ac) values for the gold standards.

		MICRO-TC						
		T2	**T0+T1**	**Se**	**Ep**	**VPP**	**VPN**	**Ac**
Histológico		n (%)	n (%)	[IC95%]	[IC95%]	[IC95%]	[IC95%]	(%)
	T2	11 (55)	3 (15)	78,6	66,7	84,6	57,1	75
	T0+T1	2 (10)	4 (20)	[60.4; 89.8]	[34.5; 88.4]	[57.8; 95.7]	[25.1; 84.2]	

The confidence interval adopted is 95%.

The values of Sensitivity (Se), Specificity (Ep), Positive Predictive (PPV), Negative Predictive (NPV), and accuracy (Ac) for all methods and the two gold standards were evaluated in two different situations, namely: T0 versus T1+T2 and T2 versus T0+T1. Regarding the gold standards, for the situation where only the Absence (T0) or presence of caries (T1+T2) was observed, the accuracy was 75%, and it was impossible to establish the other values. As for the situation in which dentin caries were isolated, the description is found in Table 3.

Regarding the evaluated methods, micro-CT was the most sensitive in both situations T0 x T1+T2 (70.6%) and T2 x T0 + T1 (85.7%). Regarding specificity, the CBCT method showed higher values for T0 x T1+T2 (71.4%), while the micro-CT was more specific for T2 x T1+T0 (83.3%). In both situations, analogue radiography was the least sensitive (38.5; 64.3%) and specific (28.6; 33.3%) method.

The visual macroscopic method showed good sensitivity (92.3%) compared to the micro-CT gold standard for the situation where T2 was observed in isolation. However, it showed lower values at T0 x T1+T2 (50%). Likewise, the digital radiographic method showed the highest sensitivity values when T2 was isolated (92.3%).

At T0 x T1+T2, the accuracy of the methods ranged from 50-65% compared to the histological gold standard and from 45-95% compared to the micro-CT gold standard. When dentin caries was evaluated in isolation (T2 x T1+T0), the accuracy ranged from 55-90% compared to histological and 70-95% compared to micro-CT.

Discussion

Clinical detection of early caries lesions remains a challenge. For this reason, the present study evaluated commonly used methods for diagnosing caries lesions in the general population [29]. In disagreement with previous studies [15,16,29] that showed a strong correlation between clinical and histological methods, our results showed only a regular correlation between these (ranging from 30% to 40%).

The histological method is well established in the literature as the gold standard for *in vitro* studies and has been widely used [16,13,15,22]. However, due to its destructive nature, micro-CT has been tested as a gold standard for investigating the extension of carious lesions [19,20,21,30]. Our results showed a regular (33%) agreement between the two methods, suggesting that each method significantly differs in defining carious lesions. However, the correlation of the imaging methods with micro-CT was higher than with the histological method. Such information may indicate that micro-CT could be more appropriate to relate to clinical methods of caries diagnosis.

Micro-CT allows a more accurate evaluation of the extent of a caries lesion, compared with histological sections, to determine the degree of mineral loss because it can be considered a direct indicator of demineralization [21]. In addition, micro-CT does not damage the sample and allows a complete volumetric evaluation of the tooth [19-21]. The present study showed a high inter-examiner concordance for the micro-CT gold standard (ranging from 65% to 90%). The performance of the imaging methods demonstrated a 25% agreement for conventional radiography and 55% for digital radiography when compared with the micro-CT gold standard. The possible reason is generally attributed to a deficiency in radiographic detection of early signs of demineralization [15]. The micro-CT method was the most sensitive for caries detection in enamel and dentin. Micro-CT was more accurate than the histological gold standard, in disagreement with Soviero et al., 2012 [15] previously reported results.

The accuracy of conventional and digital radiographic methods in carious lesion evaluation has previously shown high inter-examiner agreement (89.25%) [5]. In the present study, the inter-examiner agreement for all the methods tested ranged from 60% to 75%. This can be justified by the number of methods tested, creating a broad spectrum to be evaluated and resulting in lower agreement. Establishing a threshold (T0, T1, and T2) was an attempt to reduce the scores and propose more practical criteria for lesion evaluation. It showed high inter-examiner agreement with previously published studies [15]. On this basis, higher scores can lead to doubt and, consequently, errors in the evaluation for caries diagnosis.

In the present study, the most sensitive method to detect caries in enamel was the micro-CT (85.7%), followed by the digital and CBCT methods, with 71.4% sensitivity. However, all values observed (Se, Ep, Ac, VPP, and VPN) were higher when dentin caries were considered. The values decrease when only the enamel lesions are considered. This result corroborates previous studies showing that for the threshold T1, radiographic evaluation usually produces a poor result [6,10,15,20,31,32].

Although the accuracy of two-dimensional systems is well established in the literature, they may be limited by their two-dimensional nature [32-34]. In the present study, the accuracy of the two-dimensional systems ranged from 35% to 80% (more minor in the conventional method and higher in the digital method). Digital images have advantages over conventional ones, mainly because they offer the possibility of improvements in the image quality, such as modulation of contrast and density, which increases diagnostic precision [6,10].

In the present study, when compared with the micro-CT gold standard, the performance of CBCT in caries detection ranged from 40% to 50%, and that of digital radiography, from 50% to 55%, in disagreement with others [35], showed a high concordance of CBCT in comparison with radiographic methods. On the other hand, others showed that CBCT images offer advantages in evaluating caries through the digital radiographic method [36,37]. This can be explained by the difference in lesion distribution since both used a sample in which most lesions were limited to the enamel. In the present study, when the evaluation was performed on dentin caries (T2), all methods showed higher accuracy and sensitivity, including CBCT (85.7; 80%).

It is well established that the greater precision of the tomographic systems in the evaluation of all dental surfaces in the different planes contributes to the detection of caries lesions [13]. Although the CBCT does not have many of the disadvantages of two-dimensional examinations, the dose of radiation emitted to the patient is considerably higher, and according to our results, the sensitivity and accuracy did not demonstrate higher values than the digital radiographic method. The SEDENTEXCT guidelines [38] do not recommend CBCT for caries diagnosis mainly because of the higher radiation dose when compared to intraoral radiography.

On the other hand, other studies recommend using CBCT in situations where two-dimensional radiographic methods are ineffective [33,35].

In summary, the diagnosis of caries by imaging methods remains a challenge in dental practice, and the choice of examination method can interfere significantly with the diagnosis. According to our results and in agreement with previously published works, the digital radiographic method is the most accurate.

The limitations found in the present study relate to the large number of scores used and the non-association between the methods. Further studies are needed to test the combined use of diagnostic methods and to use only the thresholds to improve the diagnosis of caries, especially those involving only enamel.

Conclusion

Micro-CT images were more accurate than the histological method since they could detect minor variations in the density of dental tissues. Our results suggest that digital radiographs should be indicated as complementary examinations in the diagnosis of caries.

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