Occlusal Caries Depth Measurements Obtained by Five Different Imaging Modalities

Kıvanç Kamburoğlu · Hakan Kurt · Eray Kolsuz · Bengi Öztaş · İlkan Tatar · Hakan Hamdi Çelik

Abstract The study aimed to assess the accuracy and reproducibility of occlusal caries depth measurements obtained from different imaging modalities. The study comprised 21 human mandibular molar teeth with occlusal caries. Teeth were imaged using film, CCD, two different cone-beam computerized tomography (CBCT) units and a microcomputer tomography (micro-CT). Thereafter, each tooth was serially sectioned, and the section with the deepest carious lesion was scanned using a high-resolution scanner. Each image set was separately viewed by three oral radiologists. Images were viewed randomly, and each set was viewed twice. Lesion depth was measured on film images using a digital caliper, on CCD and CBCT images using built-in measurement tools, on micro-CT images using the Mimics software program, and on histological images using AxioVision Rel. 4.7. Intra- and inter-rater reliabilities were assessed according to the Bland/Altman method by calculating Intraclass Correlation Coefficients (ICCs). Mean/median values obtained with intraoral systems were lower than those obtained with 3-D and histological images for all observers and both readings. Intra-observer ICC values for all observers were highest for histology and micro-CT. In addition, intra-observer ICC values were higher for histology and CBCT than for histology and intra-oral methods. Inter-observer ICC values for first and second readings were high for all observers. No differences in repeatability were found between Accuitomo and Iluma CBCT images or between intra-oral film and CCD images. Micro-CT was found to be the best imaging method for the ex vivo measurement of occlusal caries depth. In addition, both CBCT units performed similarly and better than intra-oral modalities.

Keywords Occlusal caries · Depth measurement · CBCT · Micro-CT · Radiography

Introduction

Diagnosis of occlusal caries is an important issue for the clinician since occlusal fissures are the most susceptible sites for primary carious lesions requiring restorative treatment [1, 2]. In order to overcome difficulties during diagnosis and enable better detection of occlusal caries, authors have recommended that traditional methods like visual examination and probing [3] that may cause enamel defects [4] be combined with other diagnostic aids such as radiography, laser or light fluorescence-based methods, or electrical impedance measurements [5–9]. Conventional intraoral film, solid-state detectors and photostimulable phosphor plates are the most commonly preferred and available modalities for diagnosing occlusal caries in conjunction with visual and clinical examination in routine dental practice. These modalities also make it possible to measure caries depth, which can be useful in the diagnosis, treatment planning, management, and follow-up of dental caries. However, because intra-oral systems can only provide two-dimensional information about dental tissue and disease, their ability to measure caries depth is affected by beam angulation, imaging settings, and patient-related

K. Kamburoğlu (✉) · H. Kurt · E. Kolsuz · B. Öztaş
Department of Oral and Maxillofacial Radiology,
Faculty of Dentistry, Ankara University,
Ankara, Turkey
e-mail: kamburogluk@dentistry.ankara.edu.tr

İ. Tatar · H. H. Çelik
Department of Anatomy, Faculty of Medicine,
Hacettepe University,
Ankara, Turkey

factors [10–15]. Cone-beam computerized tomography (CBCT) was introduced in response to the high demand for a technique that could provide three-dimensional data at the tooth level. CBCT offers a number of potential advantages over medical tomography, including easier image acquisition, higher image accuracy, reduced artifacts, lower effective radiation doses, faster scan times, and greater cost-effectiveness [16, 17]. Previous research has examined the effectiveness of CBCT in measuring proximal caries depth using dedicated measurement tools [18] as well as the effectiveness of CBCT in detecting occlusal caries [19] and occlusal caries mixed with proximal caries without the use of measurement tools [20, 21].

While histological evaluation of hard tissue sections is commonly accepted as the gold standard for the detection and measurement of caries lesions [22], microcomputer tomography (micro-CT) represents an innovative and non-invasive technique that offers the possibility of studying human dental tissue without the need to destroy the tissue specimen [23]. High-resolution micro-CT produces three-dimensional reconstructions using cubic voxels and isotropic resolution. While it is technically possible to produce ultra-high resolutions of 1 µm ex vivo, the high radiation dose is incompatible with living organisms [24, 25].

In view of the importance of depth in the diagnosis and treatment of occlusal caries, the present study aimed to assess the accuracy and reproducibility of occlusal caries depth measurements obtained from intraoral film and digital images, CBCT images, and micro-CT images by comparing them to histological measurements.

Materials and Method

The present study sample was comprised of 21 human mandibular molar teeth with no restorations and with pit-fissure occlusal caries that were extracted due to periodontal loss or pericoronitis. Informed consent was obtained for the use of all extracted teeth. Teeth were cleaned of calculus and debris, disinfected in 2% sodium hypochlorite solution for 20 min, and stored in distilled water. Each tooth was embedded in a block of silicone impression material. All teeth were imaged using analog X-ray film, CCD digital X-ray, two different CBCT units and a micro-CT unit. Pilot studies were conducted to determine image acquisition exposure parameters, with visibility of the pulpal root canal, dentine, and enamel used as an indication of optimal image quality for all images. Intra-oral radiographs were taken using Size 2 E/F Kodak Insight Film (Eastman Kodak Co, Rochester, NY) and an RVG 5.0 CCD (Trophy, Marne la Valle, France) with a size 1 sensor and 10–15 lp mm spatial resolution. All intra-oral images were exposed under reproducible conditions using an Evaluation X 3000-2C X-Ray unit (New Life Radiology Srl, Grugliasco, Torino, Italy) at 70 kVp, 8 mA, and a focus-receptor distance of 30 cm behind a plexiglass soft-tissue equivalent. Exposure times were 0.4 s for film and 0.1 s for CCD. Films were automatically processed on the same day as exposure using an Extra-x Velopex (Medivance Instruments Ltd., London, England) and fresh chemicals (Hacettepe, Ankara, Turkey) in accordance with the manufacturer's instructions. Intraoral images obtained with RVG Trophy CCD sensor are shown in Fig. 1.

CBCT images were taken using Iluma (3M Imtec, Oklahoma, USA) and 3D Accuitomo 170 (3D Accuitomo; J Morita MFG. Corp, Kyoto, Japan) systems. Iluma images were obtained at 120 kV, 3.8 mA, and an exposure time of 40 s with a 24.4×19.5 cm amorphous silicon flat-panel image detector and reconstructed using a voxel size of 0.2 mm^3. Accuitomo images were obtained at 63 kV, 2 mA, an exposure time of 30.8 s, and a voxel size of 0.125 mm using 6 cm×6 cm field of view (FOV). Axial scans and multiplanar reconstructions were obtained for both CBCT systems, and volumetric data was reconstructed using the systems' own software programs to provide serial coronal and sagittal sections along each tooth plane. CBCT images obtained with Accuitomo 170 unit are shown in Fig. 2.

Micro-CT images of tooth crowns were obtained using a SkyScan 1174 (SkyScan, Kontich, Belgium) at 50 kV, 800 µA and a pixel size of 18-µm. Axial images were exported as bitmap (bmp) files to the Mimics software program (Materialise, Leuven, Belgium) in order to obtain serial coronal and sagittal images. While every scanning procedure, micro-CT system created a .log file which has whole scanning parameters in internationally calibrated metric system. Additionally, when uploading files to Mimics software, we also aligned and adjusted the sections according to parameters displayed in software interface. Micro-CT images obtained with SkyScan 1174 unit are shown in Fig. 3.

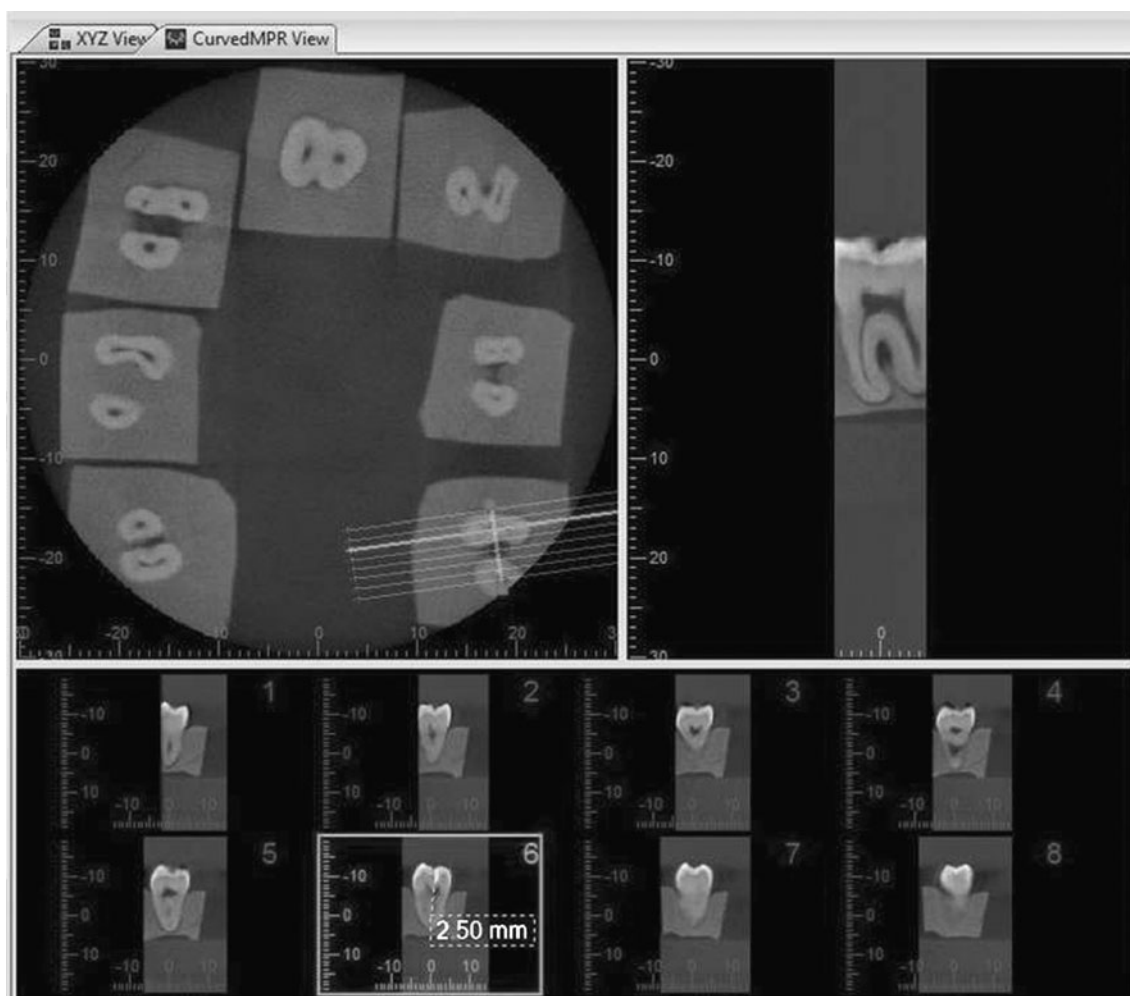Fig. 1 Intraoral images obtained with RVG Trophy CCD sensor

Fig. 2 CBCT images obtained with Accuitomo 170 unit

Following imaging, teeth were embedded in acrylic and serially sectioned mesio-distally in parallel to the long axis using a water-cooled diamond saw at low speed. For each tooth, the section with the deepest carious lesion was scanned using a high-resolution scanner (Epson Perfection V750-M Pro Scanner) at 600 dpi resolution and ×15 magnification and viewed using the AxioVision Rel. 4.7 image software (Carl Zeiss Imaging Solutions, Göttingen, Germany). Histological sections obtained from the teeth are shown in Fig. 4.

Images were evaluated separately by three oral radiologists experienced in image interpretation. Each image set (film, CCD, Iluma CBCT, Accuitomo CBCT, micro-CT, and histology) was viewed in a random order in a different session at 1-week intervals. Intra-observer agreement was assessed by having each observer view all image sets twice, with a 7-week interval between viewing to eliminate memory bias. Conventional film radiographs were evaluated using a light box and magnifier (×2), and a digital caliper (Absolute Digimatic, Mitutoyo Corp., Kawasaki, Japan) was

used to measure lesion depth, defined as the distance from the enamel surface to the innermost part of the lesion. Digital 2-D and 3-D images were viewed on a 22" LG Flatron monitor (LG, Seoul, South Korea) at a $1,440 \times 900$ pixel screen resolution and 32-bit color depth. CCD and CBCT measurements of the largest dimensions of occlusal caries lesions were performed using the built-in measurement tools provided by the imaging software. Micro-CT measurements were obtained from the available sections using the Mimics software measurement tools, and histological measurements were performed using the AxioVision Rel. 4.7 imaging software.

Intra- and inter-rater reliability was assessed with the Bland/Altman method by calculating Intraclass Correlation Coefficients from residual variances of one-way ANOVA (with reading as the main variable) and two-way ANOVA (with the variables reading, observer and the interaction between the two). One-way ANOVA for each observer was also used to calculate a within-variability for each of them. Statistical analysis was performed using SAS 9.0 (PROC
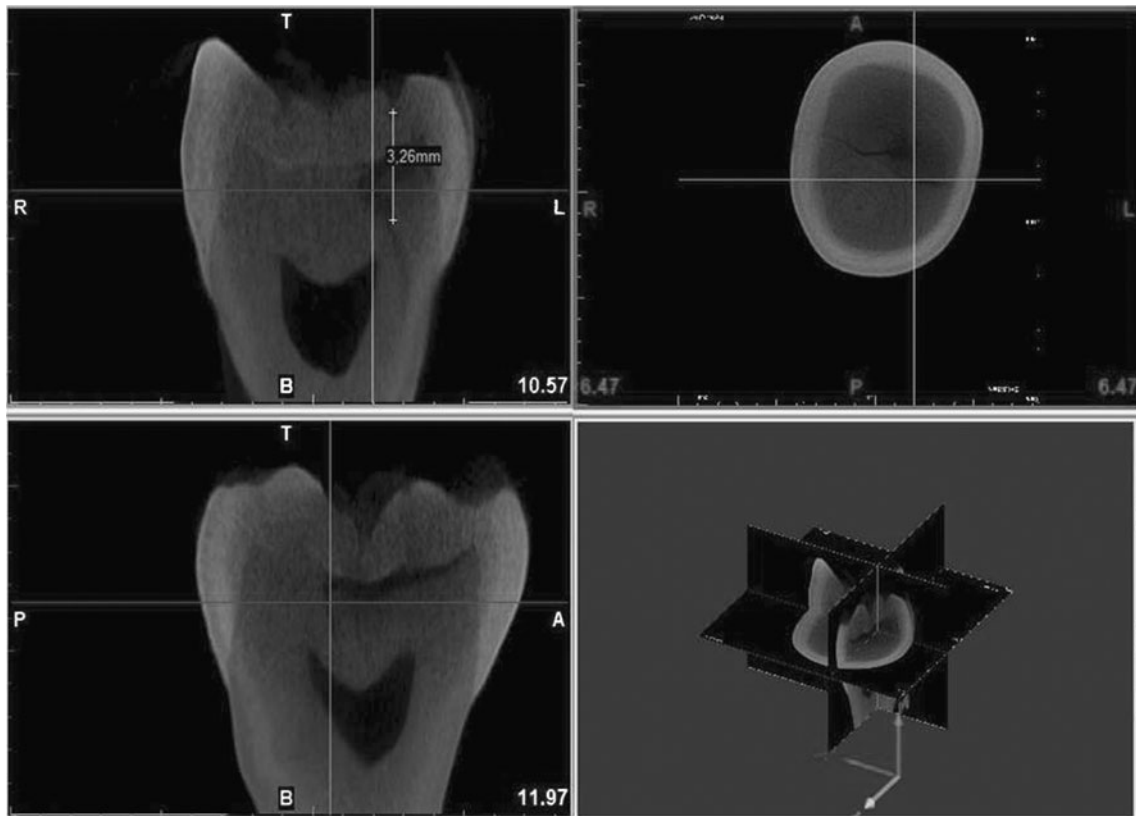
Fig. 3 Micro-CT images obtained with SkyScan 1174 unit

GLM), and Bland/Altman plots were drawn with the limits of agreement using MedCalc.

Results

Occlusal caries depth measurements by modality, observer and reading are given in Table 1. In general, mean/median values were lower for intra-oral systems than for 3-D modalities and histology for all observers and both readings. ICC values for each observer are given in Table 2. Intra-observer ICC values for all observers were highest for histology and micro-CT. In addition, intra-observer ICC values were higher for histology and CBCT than for histology and intra-oral methods. Inter-observer ICC values for first and second readings were high for all observers (Tables 3 and 4).
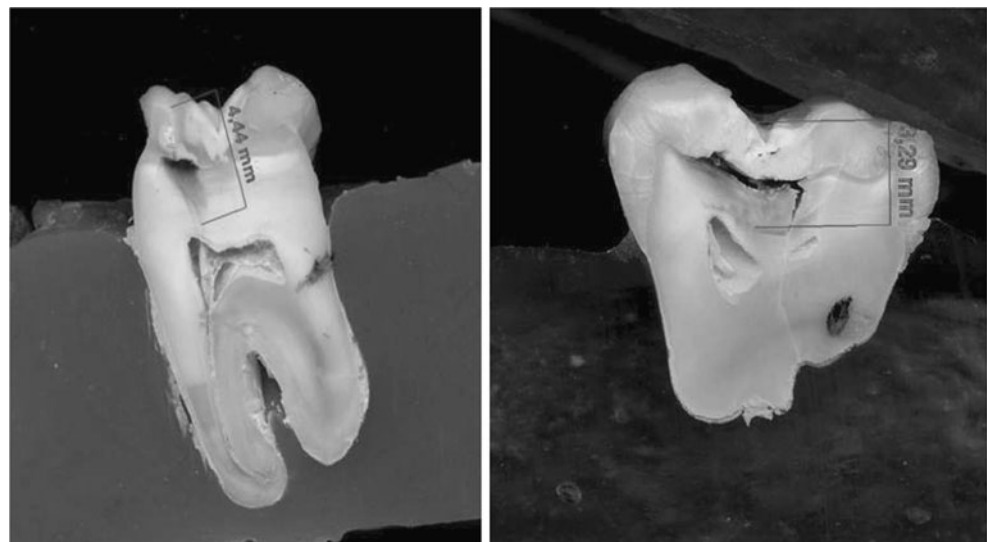
Fig. 4 Histological sections obtained from the teeth

Table 1 Descriptive statistics for caries depth measurements obtained using different methods are given in millimeters

Observer	Reading			Histology	Micro CT	CBCT (Iluma)	CBCT (Accuitomo)	Film	CCD (Rvg)
1	1								
			Mean	3.5257	3.4905	3.4714	3.4875	3.0014	3.0448
			Median	3.5000	3.4100	3.6400	3.2550	2.8000	2.8100
			SD	1.25313	1.23278	1.09188	1.12962	.98717	1.07908
			Minimum	1.54	1.81	1.90	1.95	1.51	1.66
			Maximum	5.84	5.86	5.37	5.15	5.94	6.50
1	2								
			Mean	3.5748	3.5090	3.4862	3.5065	2.9629	2.9900
			Median	3.3300	3.4000	3.5600	3.6000	2.8000	2.7000
			SD	1.25116	1.23745	1.11685	1.16207	1.03450	1.04113
			Minimum	1.80	1.79	1.80	1.90	1.50	1.60
			Maximum	5.90	5.86	5.45	5.25	6.00	6.10
2	1								
			Mean	3.6095	3.5176	3.4929	3.4329	3.0376	3.0510
			Median	3.7800	3.3400	3.4000	3.2000	2.9000	2.8700
			SD	1.15680	1.12881	1.06354	1.07624	1.01788	1.02167
			Minimum	1.90	1.84	1.90	1.90	1.60	1.70
			Maximum	5.95	5.90	5.39	5.19	5.99	6.00
2	2								
			Mean	3.6333	3.6048	3.4429	3.4700	2.9195	2.9476
			Median	3.5000	3.4800	3.5500	3.7000	2.8900	2.8700
			SD	1.19814	1.16154	1.05910	1.05714	.93118	1.03974
			Minimum	1.76	1.80	1.70	1.80	1.50	1.40
			Maximum	5.89	5.90	5.01	5.08	5.00	5.80
3	1								
			Mean	3.5581	3.5705	3.4900	3.5029	2.8129	2.9062
			Median	3.8000	3.8000	3.2000	3.3000	2.8000	2.8000
			SD	1.23774	1.23973	1.08835	1.07052	.95900	1.08435
			Minimum	1.50	1.40	2.00	2.20	1.40	1.35
			Maximum	5.90	5.99	5.80	5.78	5.00	6.00
3	2								
			Mean	3.5667	3.5443	3.3748	3.3995	2.9910	2.9524
			Median	3.5000	3.5000	3.0000	3.2500	2.8000	2.8000
			SD	1.23077	1.23520	1.02609	1.01945	1.19872	1.16860
			Minimum	1.80	1.80	1.90	2.00	1.60	1.60
			Maximum	5.90	5.90	5.24	5.25	6.20	6.00

Table 2 ICC values for intra-observer variability

Method	Observer 1	Observer 2	Observer 3
Histology and micro-CT	0.989	0.982	0.997
Histology and CBCT (Iluma)	0.823	0.734	0.639
Histology and Accuitomo	0.882	0.794	0.669
Histology and film	0.431	0.317	0.254
Histology and CCD (Rvg)	0.440	0.296	0.294

Table 3 ICC values for inter-observer variability for first readings

Method	Obs1–obs2	Obs1–obs3	Obs2–obs3
Histology	0.942	0.958	0.920
Micro-CT	0.952	0.937	0.914
CBCT (Iluma)	0.963	0.910	0.916
CBCT (Accuitomo)	0.965	0.912	0.892
Film	0.959	0.895	0.932
CCD (Rvg)	0.950	0.918	0.956

Bland-Altman plots (Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14) showed very close agreement between micro-CT and histological measurements. (Given the high inter-observer ICC values for both readings, Bland/Altman plots were drawn for observer 1 only.) Repeatability of measurements for each modality is given in Table 5. No differences in repeatability were found between Accuitomo CBCT and Iluma CBCT images or between intra-oral film and CCD images.

Discussion

The present research mainly focused on observers' measurement reliability conducted on images obtained by using different X-ray systems. Observers performed occlusal caries measurements which were defined in millimeters. There are also various diagnostic tests for occlusal caries detection which are of clinical interest. DIAGNOdent (KaVo, Biberach, Germany), a quantitative laser fluorescence (LF) unit, is currently used as an aid in the diagnosis of occlusal carious lesions. LF was found to be capable of monitoring de-/re-mineralization process in early caries lesions in situ [26]. Electrical resistance measurement (ERM) which is proposed for occlusal caries detection uses a probe with a coaxial airflow and depends on the permeability changes due to caries demineralization of the tissues [27]. A study

Table 4 ICC values for inter-observer variability for second readings

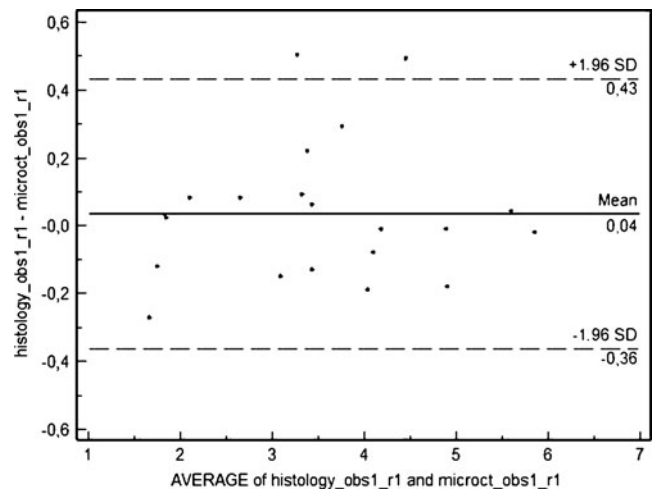| Method	Obs1–obs2	Obs1–obs3	Obs2–obs3
Histology	0.964	0.962	0.920
Micro-CT	0.969	0.971	0.935
CBCT (Iluma)	0.975	0.956	0.948
CBCT (Accuitomo)	0.970	0.947	0.944
Film	0.968	0.932	0.896
CCD (Rvg)	0.979	0.912	0.926

Fig. 5 Difference versus average of values measured by micro-CT and histology with 95% limits of agreement for the first reading of observer 1

evaluated the performance of four observers by using ERM adjunct to visual inspection in diagnosing small dentinal lesions at one site per occlusal surface and the performance of ERM was also compared with that of radiographic examination. The ERM had the highest sensitivity, and visual inspection had the highest specificity. ROC analysis showed no statistically significant differences between the performance of the observers when using visual inspection and ERM ($P>0.05$). One examiner performed statistically significantly better by measuring the electrical resistance of enamel than by radiographic examination ($P<0.05$) [28]. Another in vitro
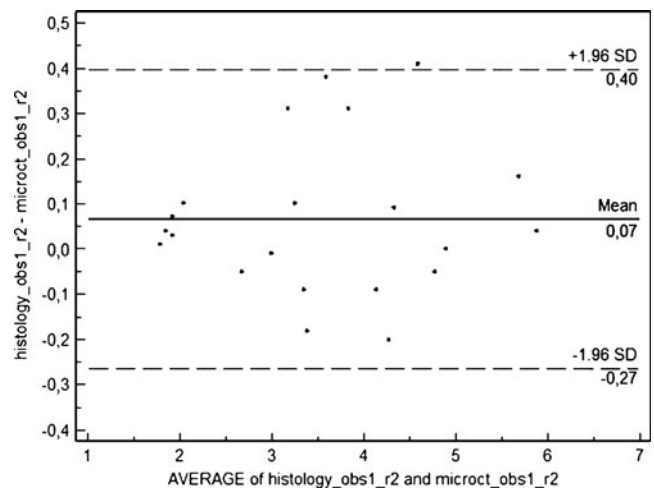

Fig. 6 Difference versus average of values measured by micro-CT and histology with 95% limits of agreement for the second reading of observer 1
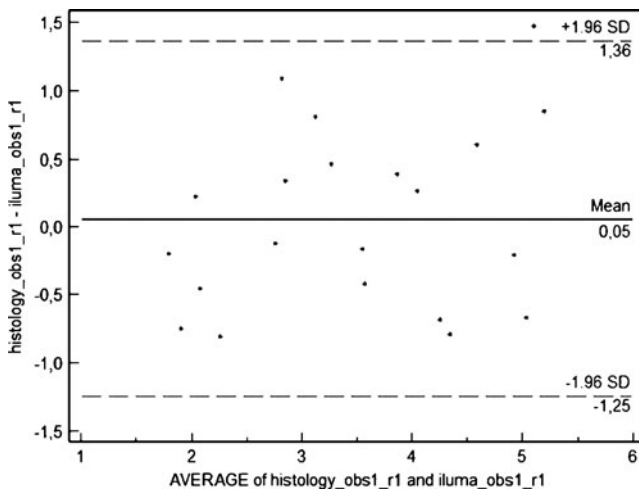
Fig. 7 Difference versus average of values measured by Iluma and histology with 95% limits of agreement for the first reading of observer 1
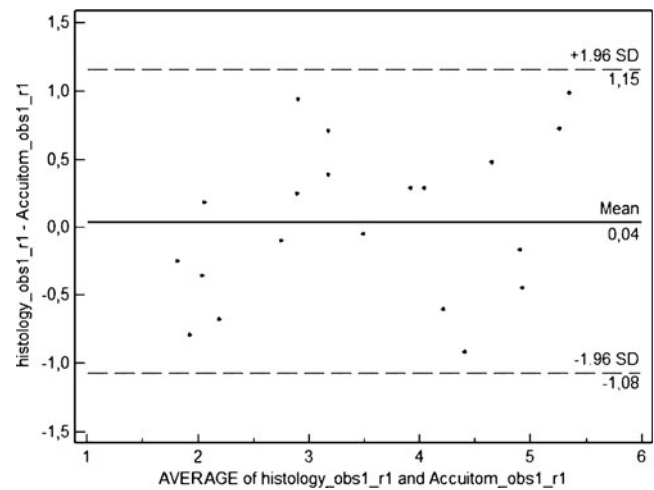

Fig. 9 Difference versus average of values measured by Accuitomo and histology with 95% limits of agreement for the first reading of observer 1

study [27] compared two methods of ERM and found CRM (cariometer) prototype to perform similarly compared with ECM (electronic caries monitor). CRM (cariometer) prototype was proposed as a candidate for further development, owing to its simplicity and ease of usage [27]. In addition, thermal imaging was shown to be a promising technology for occlusal caries detection [29].

According to the findings of the present study, micro-CT and histological measurements of occlusal caries depth are highly comparable, suggesting that micro-CT may be used as a non-destructive ex vivo imaging modality. Previous studies by the authors found similarly favorable results in

the ex-vivo imaging and assessment of teeth and teeth pathology using micro-CT images [24, 25]. However, while micro-CT has been established as an accurate gold standard for determining the presence or absence of caries [21], its effectiveness in caries depth measurement had not been previously assessed.

This study found intra-oral analog X-ray film and digital X-ray modalities performed similarly in the detection of occlusal caries depth. Accuracy of both intra-oral analog X-ray film and digital X-ray sensor measurements is limited by the two-dimensional nature of the technology, the superimposition of anatomical structures and patient-
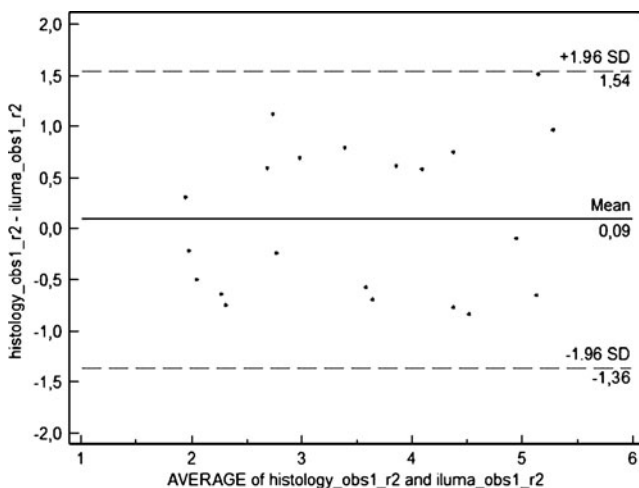

Fig. 8 Difference versus average of values measured by Iluma and histology with 95% limits of agreement for the second reading of observer 1
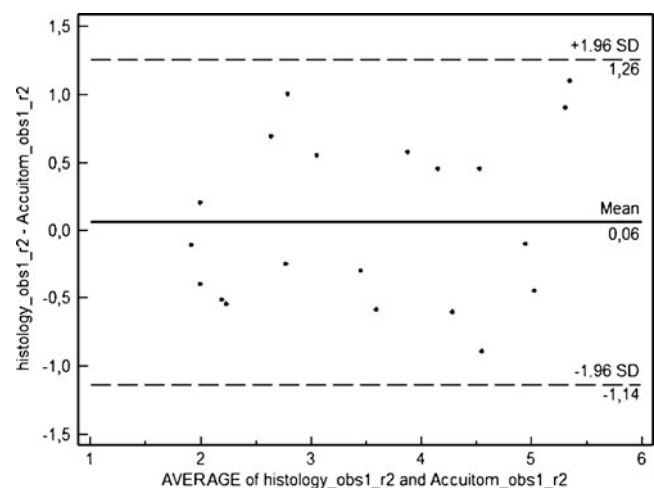

Fig. 10 Difference versus average of values measured by Accuitomo and histology with 95% limits of agreement for the second reading of observer 1
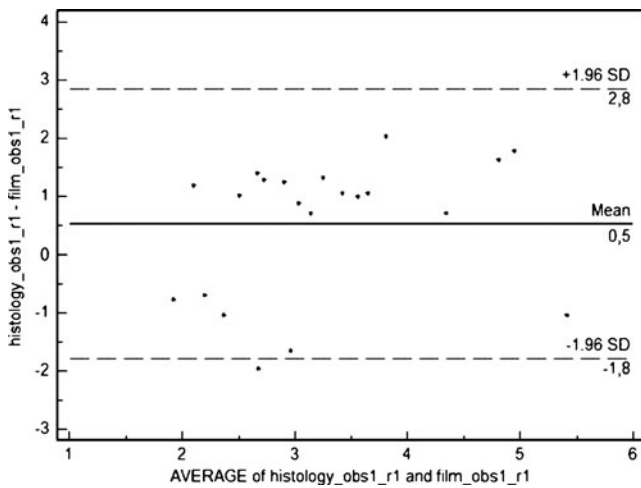
Fig. 11 Difference versus average of values measured by film and histology with 95% limits of agreement for the first reading of observer 1
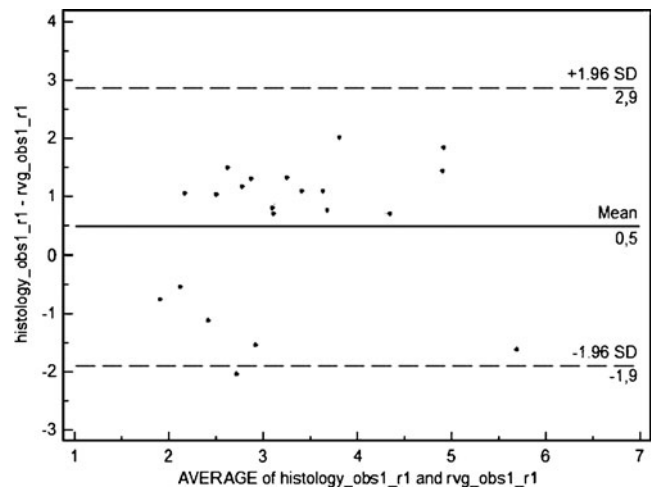

Fig. 13 Difference versus average of values measured by RVG and histology with 95% limits of agreement for the first reading of observer 1

related factors; however, because of the lower radiation doses associated with intra-oral sensors and the built-in measurement tools of digital systems, digital is preferable to film technology. In the present study, calibration of intra-oral images through inclusion of an object with a known diameter within the image was not performed. Occlusal caries depth measurements from intra-oral images were lower when compared with histological assessment, suggesting that clinicians must be cautious when assessing caries depth using intra-oral radiography in routine clinical practice. However, micro-CT images were calibrated during importing process to Mimics software.

Our study found both CBCT units performed similarly and better than both intra-oral modalities in measuring occlusal caries depth. These results are analogous to those of a previous study that found CBCT performed better than intra-oral modalities in millimetric proximal caries depth measurement [18]. Another recent study found CBCT to be superior to intra-oral imaging in the detection of deep enamel occlusal caries, superficial dentine caries and deep dentine caries, but found no differences between modalities in the detection of superficial enamel occlusal caries or healthy subjects [19]. The present study included dentine caries lesions only.
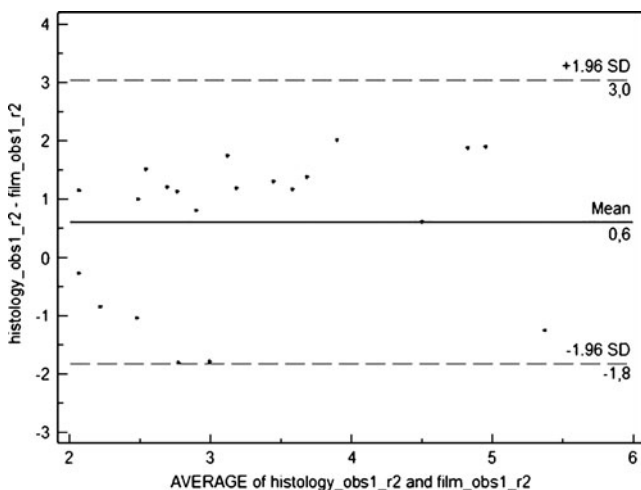

Fig. 12 Difference versus average of values measured by film and histology with 95% limits of agreement for the second reading of observer 1
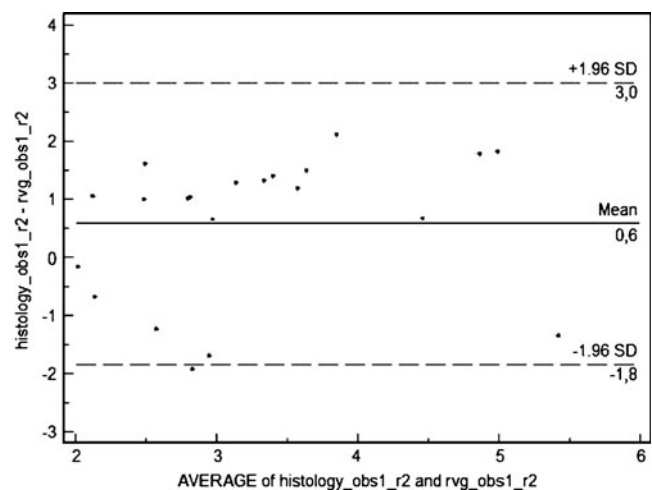

Fig. 14 Difference versus average of values measured by RVG and histology with 95% limits of agreement for the second reading of observer 1

Table 5 Repeatability for each method

Method	Obs1	Obs2	Obs3
Histology	0.30	1.05	1.00
Micro-CT	0.20	0.81	0.90
CBCT (Iluma)	0.36	0.73	1.28
CBCT (Accuitomo)	0.43	0.79	1.24
Film	0.25	0.71	1.25
CCD (Rvg)	0.33	0.61	1.25

CBCT systems offer a variety of different image acquisition settings. In this study, the Accuitomo 170 CBCT images were acquired at 6×6 cm (0.125 mm^3 voxel resolution), and the Iluma CBCT images were reconstructed using a voxel size of 0.2 mm^3, since they are more applicable in routine applications in terms of reconstruction times. It is possible that measurement accuracy would have increased by using the smallest voxel sizes available (4×4 FOV/0.08 mm^3 voxel resolution with the Accuitomo CBCT system and 0.1 mm^3 voxel size with the Iluma CBCT system).

In clinical situations, the quality of CBCT images can be seriously affected by patient motion and by beam hardening and scatter caused by metallic restorations; however, neither of these issues were factors in the present study, which was conducted ex vivo and did not include teeth with restorations.

CBCT is not considered suitable for use in routine clinical dental practice because of the high effective radiation doses. A recent study reported effective doses for the Accuitomo CBCT to vary between 11 and 77 μSv, depending on FOV, exposure parameters, and region examined [30]. According to ICRP 2007 tissue weights, Iluma CBCT images acquired at 120 kVp and 3.8 mA (as in the present study) result in an effective dose of 498 μSv [31]. Current research is being directed towards offering higher-definition 3-D images with similar or lower effective doses than film. Although micro-CT is an innovative device offering high-definition dental images, the ultra-high radiation dose, high cost, and long scanning and image reconstruction times associated with micro-CT make it unsuitable for clinical use. However, in view of the results of the present study, it can be recommended as a non-destructive ex vivo method for dental caries depth measurement.

Conclusion

This study found micro-CT to be the best imaging method for use in the ex vivo measurement of occlusal caries depth. In addition, CBCT units were found to perform similarly and better than intra-oral modalities.

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