RESEARCH ARTICLE

Beam hardening correction tool improves the diagnosis of incipient caries lesions in Micro-CT images

¹Karla Rovaris, ²Saulo Leonardo Sousa Melo, ¹Polyane Mazucatto Queiroz, ³Carolina Loch, ³Donald R Schwass and ¹Francisco Haiter-Neto

¹Department of Oral Diagnosis, Piracicaba Dental School, University of Campinas, Piracicaba, Brazil; ²Department of Oral Pathology, Radiology and Medicine, College of Dentistry, University of Iowa, Iowa, IA, USA; ³Sir John Walsh Research Institute, Faculty of Dentistry, University of Otago, Dunedin, New Zealand

Objective: To evaluate the effect of Beam Hardening Correction tool (BHC) on Micro-CT images used in the diagnosis of incipient caries lesions.

Methods: Six posterior teeth, with 6 sound proximal surfaces and 6 natural white spot lesions, were scanned using a SkyScan1174 device. Each tooth was imaged 16 times in various acquisition parameters, and reconstructed 3 times applying different levels of BHC (0, 15 and 30%). The 288 datasets were analyzed by three examiners. Gold-standard was obtained by microscopic analyses under polarized light. Area under the ROC curve was obtained for each protocol and the BHC parameter was isolated to individually observe the influence of such parameters of reconstruction.

Results: Microtomographic images were accurate for the diagnosis of incipient caries lesions even when the BHC tool was not applied. Accuracy was perfect in 50 % of the protocols without BHC. When adding the artefact correction, the number of protocols that reached perfect accuracy increased to 81.25%. No difference was found between the protocols that used 15 or 30% BHC. Statistically significant differences were found only in four comparisons, and on those the images that had BHC were more accurate. Two non-BHC protocols reached accuracy scores of 0.653 and 0.881, and were improved to perfect accuracy with BHC application.

Conclusion: The use of the BHC tool should be encouraged when using Micro-CT to detect incipient caries lesions, especially when low-quality parameters aiming less acquisition and processing time are used.

Dentomaxillofacial Radiology (2019) **48**, 20180123. doi: [10.1259/dmfr.20180123](https://doi.org/10.1259/dmfr.20180123)

Cite this article as: Rovaris K, Sousa Melo SL, Queiroz PM, Loch C, Schwass DR, Haiter-Neto F. Beam hardening correction tool improves the diagnosis of incipient caries lesions in Micro-CT images. *Dentomaxillofac Radiol* 2019; **48**: 20180123.

Keywords: X-ray microtomography; dental caries; diagnostic imaging; radiology; dentistry

Introduction

Micro-computed microtomography (Micro-CT) has been validated as a non-destructive three-dimensional *in vitro* method for the assessment of mineralized structures such as trabecular bone¹ and has been expressively used in Dentistry, especially in Endodontics.^{2,3}

Microtomographic technology has also been applied in the detection of caries lesions^{4,5} as a possible

substitute for histological analysis. One study reported a high correlation with no statistical difference between Micro-CT and histology, suggesting Micro-CT as the method of choice for the detection of proximal caries in first molars.⁶ On the other hand, a different group applied similar methodology to evaluate non-cavitated caries lesions using a single scanning and imaging reconstruction protocol, and found that Micro-CT did not establish satisfactory agreement with histological

Correspondence to: RovarisKarla, E-mail: karlarovaris@gmail.com

Received 24 March 2018; revised 02 July 2018; accepted 25 July 2018

Table 1 Parameters used for image acquisition

Scanning		
Filter		
0.5 mm Al		1 mm Al
Rotation step		
0.3°		0.7°
Frame		
1		3
Voxel size		
14.1 µm		
Rotation		
180°		360°

analysis. They concluded that Micro-CT was not an effective alternative for the detection of proximal caries lesions.⁷

The polychromatic nature of the X rays is inherently linked to beam hardening. This phenomenon is due to the absorption of some photons by the surface of the material while more penetrating photons continue the route through it. Given that the less penetrating photons are being blocked by the material, the average energy of the beam increases, *i.e.* the beam becomes harder and more penetrating. This behavior may result in images presenting an area of greater radiopacity at its periphery, even when the material presents homogeneous density.^{8–11}

The effects of beam-hardening artifacts on *in vitro* caries models have been quantitatively tested.¹⁰ There are two main ways to reduce the generation and effects of beam hardening: (1) by using physical filters; or (2) by applying specific artifact-reduction algorithms [*e.g.* the Beam Hardening Correction (BHC) tool]. Single (Al) and combined (Al/Cu) component filters have been individually used in research but, to the best of our knowledge, have never been confronted.^{12,13} Energy acquisition parameters, filters and BHC were tested on the improvement of image quality in an attempt to validate Micro-CT when using transverse microradiography (TMR) as the gold standard. The 0.5 mm-Al filter

and non-application of BHC were associated to worse results, and were not correlated to TMR, unlike other protocols.¹⁴

The diagnostic value of Micro-CT for the non-destructive evaluation of caries lesions has already been investigated, but there is a gap on how scanning and reconstruction settings may affect image quality. The correction of beam hardening is of paramount importance in studies that deal with incipient caries lesions since it impairs the density of the outermost enamel layer. Due to the need for testing these parameters, the present study aimed to evaluate the effect of a BHC on Micro-CT images used in the diagnosis of incipient caries lesions.

Methods and materials

Sample preparation

Institutional review board approval was obtained for this study. Six extracted human posterior teeth (*i.e.* 12 surfaces—6 sound surfaces and 6 presenting natural white spot lesions) were collected and subjected to clinical and radiographic inspection to be included in this study. Exclusion criteria consisted of teeth with cavitated caries lesions and restorations. Periapical radiographs were obtained with the paralleling technique, using the dental intraoral digital system VistaScan (Dürr Dental, Beitigheim-Bissingen, Germany) and the images were acquired at 7 mA, 70 kVp and 0.06 s.

Image acquisition

Micro-CT scans were performed in the Skyscan 1174 (Bruker, Kontich, Belgium) at 50 kV and 800 µA. The parameters used to acquire the images are shown in Table 1.

Each of the 6 teeth was scanned using 16 different parameters combinations, resulting in a total of 96 scans. Data were reconstructed 3 times—without applying BHC and using 15 and 30% of BHC (Figure 1)—resulting in 288 sets of images. The ring artefact correction (RAC) value was maintained constant for all datasets. The protocols used are shown in Table 2.

Image assessment

Images were randomized and different positions were adopted for the same tooth to minimize memorization of the lesions by the evaluators. These variations were accomplished after reconstruction of the images, using DataView software (Bruker, Kontich, Belgium). No variation of position was adopted during the scanning process.

Three oral radiologists with more than 5 years of experience in diagnostic imaging independently evaluated the images. Evaluators were calibrated through demonstrative training on the use of DataView software (Bruker, Kontich, Belgium). The evaluation was conducted 3 times per week, only 30 sets each time, to

Figure 1 Axial reconstructions, without BHC (A) and with 30% BHC (B), evidencing the difference in visibility of the existing incipient caries lesion.

Table 2 Studied protocols resulting from different acquisition and reconstruction parameter combinations

Protocol	Frame	Rot step	Rotation	Al filter (mm)	BHC
P 1A	1	0.3°	180°	0.5	0
P 1B	1	0.3°	180°	0.5	15
P 1C	1	0.3°	180°	0.5	30
P 2A	1	0.3°	360°	0.5	0
P 2B	1	0.3°	360°	0.5	15
P 2C	1	0.3°	360°	0.5	30
P 3A	3	0.3°	180°	0.5	0
P 3B	3	0.3°	180°	0.5	15
P 3C	3	0.3°	180°	0.5	30
P 4A	3	0.3°	360°	0.5	0
P 4B	3	0.3°	360°	0.5	15
P 4C	3	0.3°	360°	0.5	30
P 5A	1	0.7°	180°	0.5	0
P 5B	1	0.7°	180°	0.5	15
P 5C	1	0.7°	180°	0.5	30
P 6A	1	0.7°	360°	0.5	0
P 6B	1	0.7°	360°	0.5	15
P 6C	1	0.7°	360°	0.5	30
P 7A	3	0.7°	180°	0.5	0
P 7B	3	0.7°	180°	0.5	15
P 7C	3	0.7°	180°	0.5	30
P 8A	3	0.7°	360°	0.5	0
P 8B	3	0.7°	360°	0.5	15
P 8C	3	0.7°	360°	0.5	30
P 9A	1	0.3°	180°	1.0	0
P 9B	1	0.3°	180°	1.0	15
P 9C	1	0.3°	180°	1.0	30
P 10A	1	0.3°	360°	1.0	0
P 10B	1	0.3°	360°	1.0	15
P 10C	1	0.3°	360°	1.0	30
P 11A	3	0.3°	180°	1.0	0
P 11B	3	0.3°	180°	1.0	15
P 11C	3	0.3°	180°	1.0	30
P 12A	3	0.3°	360°	1.0	0
P 12B	3	0.3°	360°	1.0	15
P 12C	3	0.3°	360°	1.0	30
P 13A	1	0.7°	180°	1.0	0
P 13B	1	0.7°	180°	1.0	15
P 13C	1	0.7°	180°	1.0	30
P 14A	1	0.7°	360°	1.0	0
P 14B	1	0.7°	360°	1.0	15
P 14C	1	0.7°	360°	1.0	30
P 15A	3	0.7°	180°	1.0	0
P 15B	3	0.7°	180°	1.0	15
P 15C	3	0.7°	180°	1.0	30
P 16A	3	0.7°	360°	1.0	0
P 16B	3	0.7°	360°	1.0	15
P 16C	3	0.7°	360°	1.0	30

avoid the memorization of the teeth by the examiners and visual fatigue.

In order to classify the presence and absence of caries lesions, the evaluators used a 5-point scale: (1) absent, (2) probably absent, (3) uncertain, (4) probably present, and (5) present. 30% of the images were re-evaluated, 1 month after the first evaluation, in order to calculate the intra- and inter-examiner agreements.

Table 3 Area under the ROC curve for each protocol tested

Protocols	Area under ROC		
	A 0% BHC	B 15% BHC	C 30% BHC
P1	1	1	1
P2	0.972	1	1
P3	0.969	1	1
P4	1	1	1
P5	0.653 ^a	0.969	1
P6	0.972	1	1
P7	0.881 ^a	1	1
P8	0.969	1	1
P9	1	1	0.972
P10	1	0.998	0.969
P11	1	1	1
P12	1	0.972	1
P13	1	0.972	1
P14	0.972	1	0.998
P15	1	1	1
P16	0.972	0.972	1

^aStatistically significant different from all other values ($p < 0,05$).

Histological preparation and examination

Samples were cleaned with ethanol and individually embedded in epoxy resin (Epofix Cold Setting Embedding Resin, Struers, Copenhagen, Denmark). After sitting for 24 h, blocks were serially sectioned into 1000 μm thick sections in the mesio-distal direction, using a 300 μm watered diamond blade. The tooth sections were polished under irrigation to reach the approximate

Figure 2 Receiver operating characteristic (ROC) curves of the different values described in Table 3. Note: X-axis represents the false positive rate (1 – specificity). Y-axis represents the true positive rate (sensitivity). The line of no-discrimination – diagonal line from the left bottom to the top right corners – represents a completely random guess.

Table 4 Kappa index of intra- and inter-rater agreement for the diagnosis of caries lesions

Examiner	E1	E2	E3
E1	0.894	0.883	0.881
E2	–	0.935	0.875
E3	–	–	0.928

thickness of 100 μm . During this process, slices were constantly checked under the microscope to avoid over-grinding and loss of the carious lesion tissue. Sections were ultrasonically cleaned and slices were mounted using transparent varnish. Two experienced and pre-calibrated observers examined the sections using a Leica DMLP light microscope (Leica Microsystems Inc., Wetzlar, Germany) under polarized light. A two-point scale was used to identify the presence or absence of caries lesions: (0) absence, and (1) presence.

Statistical analysis

Data were tabulated and the area under the ROC curve, representing the relationship between sensitivity and specificity, was obtained by pooling together the recorded observations based on the 5-point scale for each protocol. The BHC parameter was isolated to observe its influence on the image individually and ANOVA was used to compare protocols. Pairwise comparisons of values of two different protocols at a time were performed using post-hoc Tukey test. The significance level was set at 5%. The software used for statistical analysis was the MedCalc 15.8 (MedCalc Software, Ostend, Belgium).

Results

Micro-CT images were accurate for the diagnosis of incipient caries lesions even without using the BHC tool. In 50% of the protocols with 0% BHC, accuracy was perfect in relation to histology. When adding BHC the number of protocols that reached perfect accuracy rose to 81.25%.

Although an improvement of accuracy with the application of the correction was noted, statistically significant differences were found only in two of the comparisons within the same protocol between those without and with the BHC correction (Table 3). In those cases (protocols 5 and 7), the accuracy scores of 0.653 and 0.881 changed to perfect accuracy with the BHC correction.

In general, there was no statistically significant difference among protocols; except in protocols P5A and P7A that were statistically significantly different from each other and from all other protocols (Figure 2).

Table 4 summarizes the Kappa index values for intra- and inter-examiner agreement for the detection of caries lesion. According to Landis & Kock (1977),¹⁵

our evaluators achieved an almost perfect intra- and inter-examiner agreement.

Discussion

Histological examination, which can illustrate the true anatomical-pathological condition of the tissue, is the gold standard for *ex vivo* diagnosis of caries lesions.¹⁶ Despite its proven superiority, this method also presents some deficiencies, such as: (1) possible damage to the carious tissue during the sectioning of the tooth; (2) the true depth of the lesion may be lost between histological sections; and (3) the amount of time needed to process the samples.^{17,18}

Ideally, destruction (*e.g.* sectioning) of a sample just to collect the gold-standard assessment should be avoided. New, non-destructive methods, after being validated against reference methods could serve as a gold standard.¹⁹ Micro-CT offers an innovative way of quantitatively and qualitatively assessing of hard tissues *in vitro* without the need of destroying the specimen.⁴

The present study evaluated Micro-CT images reconstructed with and without applying BHC in the diagnosis of incipient caries lesions. The intra- and inter-examiner agreement showed values close to perfection.¹⁵ Micro-CT was consistent even in the detection of incipient lesions such as white spots without evidence of cavitation. In fact, all the studied protocols but two (P5A and P7A) provided highly accurate images. Those two protocols (P5A and P7A) with lower accuracy (0.653 and 0.881) were acquired with poor scanning parameters, resulting in images of doubtful quality for the diagnosis of incipient caries lesions. The application of BHC in those cases demonstrated to improve the diagnostic performance of the images. Previous studies emphasized the importance of quality of images and placed it as a very important factor to make the method accurate.²⁰

After an appropriate correction of beam hardening, the effect this artefact should disappear.¹⁰ A pilot study was performed to choose the level of correction to be used in this study. Given that corrections over 30% worsened the images, the levels of 15 and 30% were chosen. The use of BHC, even without being the tested parameter, has already been recommended in other studies that used samples of sound and/or demineralized dental tissues.^{21,22} In the present study, BHC was able to improve the images of the worst protocols to the point of obtaining a perfect accuracy. A previous *in vitro* caries model compared the effect of BHC on the images of a polychromatic Micro-CT, using a monochromatic source as gold standard. Those authors stated that the diagnostic error index of the two groups of images (polychromatic and monochromatic) was equal, showing the efficiency of the tool in correcting the effects of the beam hardening artefact.¹⁰ Other study of similar methodology also found a worse performance when the BHC was not employed.¹¹

The majority of previous Micro-CT studies for evaluation of caries lesions used devices that reached about 100 kVp.^{5-7,10,11,20,22,23} In a previous study devices capable of generating 50 and 100 kVp were compared and no differences were found between them. In fact, the 50 kVp device performed better, which justified the use of images of this device for the BHC test. The findings

of the present study support the use of lower energy devices with satisfactory and perfectly accurate results.

In conclusion, based on our results, the use of the BHC tool should be encouraged when using Micro-CT to detect incipient caries lesions, especially when low-quality parameters aiming less acquisition and processing time are used.

References

- Müller R, Van Campenhout H, Van Damme B, Van Der Perre G, Dequeker J, Hildebrand T, et al. Morphometric analysis of human bone biopsies: a quantitative structural comparison of histological sections and micro-computed tomography. *Bone* 1998; **23**: 59–66. doi: [https://doi.org/10.1016/S8756-3282\(98\)00068-4](https://doi.org/10.1016/S8756-3282(98)00068-4)
- Paqué F, Boessler C, Zehnder M. Accumulated hard tissue debris levels in mesial roots of mandibular molars after sequential irrigation steps. *Int Endod J* 2011; **44**: 148–53. doi: <https://doi.org/10.1111/j.1365-2591.2010.01823.x>
- Peters OA, Paqué F. Root canal preparation of maxillary molars with the self-adjusting file: a micro-computed tomography study. *J Endod* 2011; **37**: 53–7. doi: <https://doi.org/10.1016/j.joen.2010.08.047>
- Schwass DR, Swain MV, Purton DG, Leichter JW. A system of calibrating microtomography for use in caries research. *Caries Res* 2009; **43**: 314–21. doi: <https://doi.org/10.1159/000226230>
- Cochrane NJ, Anderson P, Davis GR, Adams GG, Stacey MA, Reynolds EC. An X-ray microtomographic study of natural white-spot enamel lesions. *J Dent Res* 2012; **91**: 185–91. doi: <https://doi.org/10.1177/0022034511429570>
- Soviero VM, Leal SC, Silva RC, Azevedo RB. Validity of Micro-CT for in vitro detection of proximal carious lesions in primary molars. *J Dent* 2012; **40**: 35–40. doi: <https://doi.org/10.1016/j.jdent.2011.09.002>
- Mitropoulos P, Rahiotis C, Stamatakis H, Kakaboura A. Diagnostic performance of the visual caries classification system ICDAS II versus radiography and micro-computed tomography for proximal caries detection: an in vitro study. *J Dent* 2010; **38**: 859–67. doi: <https://doi.org/10.1016/j.jdent.2010.07.005>
- Zou W, Hunter N, Swain MV. Application of polychromatic μ CT for mineral density determination. *J Dent Res* 2011; **90**: 18–30. doi: <https://doi.org/10.1177/0022034510378429>
- Mulder L, Koolstra JH, Van Eijden TM. Accuracy of Micro-CT in the quantitative determination of the degree and distribution of mineralization in developing bone. *Acta Radiol* 2004; **45**: 769–77. doi: <https://doi.org/10.1080/02841850410008171>
- Kovács M, Danyi R, Erdélyi M, Fejérdy P, Dobó-Nagy C. Distortional effect of beam-hardening artefacts on Micro-CT: a simulation study based on an in vitro caries model. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **108**: 591–9. doi: <https://doi.org/10.1016/j.tripleo.2009.06.009>
- Hamba H, Nikaido T, Inoue G, Sadr A, Tagami J. Effects of CPP-ACP with sodium fluoride on inhibition of bovine enamel demineralization: a quantitative assessment using micro-computed tomography. *J Dent* 2011; **39**: 405–13. doi: <https://doi.org/10.1016/j.jdent.2011.03.005>
- Lo EC, Zhi QH, Itthagarun A. Comparing two quantitative methods for studying remineralization of artificial caries. *J Dent* 2010; **38**: 352–9. doi: <https://doi.org/10.1016/j.jdent.2010.01.001>
- Neves AdeA, Coutinho E, Vivan Cardoso M, Jaecques SV, Van Meerbeek B. Micro-CT based quantitative evaluation of caries excavation. *Dent Mater* 2010; **26**: 579–88. doi: <https://doi.org/10.1016/j.dental.2010.01.012>
- Hamba H, Nikaido T, Sadr A, Nakashima S, Tagami J. Enamel lesion parameter correlation between polychromatic Micro-CT and TMR. *J Dent Res* 2012; **91**: 586–91. doi: <https://doi.org/10.1177/0022034512444127>
- Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; **33**: 159–74. doi: <https://doi.org/10.2307/2529310>
- Hintze H, Wenzel A. Influence of the validation method on diagnostic accuracy for caries. A comparison of six digital and two conventional radiographic systems. *Dentomaxillofac Radiol* 2002; **31**: 44–9. doi: <https://doi.org/10.1038/sj.dmf.4600645>
- Jablonski-Momeni A, Stachniss V, Ricketts DN, Heinzel-Gutenbrunner M, Pieper K. Reproducibility and accuracy of the ICDAS-II for detection of occlusal caries in vitro. *Caries Res* 2008; **42**: 79–87. doi: <https://doi.org/10.1159/000113160>
- Haite Neto F, dos Anjos Pontual A, Frydenberg M, Wenzel A. Detection of non-cavitated approximal caries lesions in digital images from seven solid-state receptors with particular focus on task-specific enhancement filters. An ex vivo study in human teeth. *Clin Oral Investig* 2008; **12**: 217–23. doi: <https://doi.org/10.1007/s00784-007-0173-5>
- Anderson P, Elliott JC, Bose U, Jones SJ. A comparison of the mineral content of enamel and dentine in human premolars and enamel pearls measured by X-ray microtomography. *Arch Oral Biol* 1996; **41**: 281–90. doi: [https://doi.org/10.1016/0003-9969\(95\)00122-0](https://doi.org/10.1016/0003-9969(95)00122-0)
- Taylor AM, Satterthwaite JD, Ellwood RP, Pretty IA. An automated assessment algorithm for micro-CT images of occlusal caries. *Surgeon* 2010; **8**: 334–40. doi: <https://doi.org/10.1016/j.surge.2010.06.007>
- Clementino-Luedemann TN, Kunzelmann KH. Mineral concentration of natural human teeth by a commercial micro-CT. *Dent Mater J* 2006; **25**: 113–9. doi: <https://doi.org/10.4012/dmj.25.113>
- Neves A de A, Coutinho E, Vivan Cardoso M, Jaecques SV, Van Meerbeek B. Micro-CT based quantitative evaluation of caries excavation. *Dent Mater* 2010; **26**: 579–88.
- Schwass DR, Leichter JW, Purton DG, Swain MV. Evaluating the efficiency of caries removal using an Er: YAG laser driven by fluorescence feedback control. *Arch Oral Biol* 2013; **58**: 603–10. doi: <https://doi.org/10.1016/j.archoralbio.2012.09.017>