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Image quality evaluation of eight CMOS (Complementary Metal-Oxide Semiconductor) intraoral digital x-ray sensors

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Image quality evaluation of eight CMOS (Complementary Metal-Oxide Semiconductor) intraoral digital x-ray sensors

Abstract

Purpose: To evaluate the image quality generated by eight commercially available intraoral sensors.

Methods: Eighteen clinicians ranked the quality of a bitewing acquired by means of eight intraoral sensors from one subject. Analytical methods for the evaluation of clinical image quality included the Visual-Grading-Characteristics method, which helps quantify subjective opinions in order to make them suitable for analysis.

Results: The Dexis sensor was ranked significantly better than Sirona and Carestream-Kodak sensors; the image captured with the Carestream-Kodak sensor was ranked significantly worse than those captured with Dexis, Schick and XDR sensors. The EVA sensor image was rated the lowest by all clinicians. Other comparisons resulted in non-significant results.

Conclusions: None of the sensors was considered to generate significantly better quality images than the other sensors tested. Further research should be directed towards determining the clinical significance of the differences in image quality reported in this study.

Key words: Imaging, Oral diagnosis, Digital Sensors, CMOS, Visual-Grading-Characteristics

Introduction

The use of computing and digital technologies is an emerging trend in dentistry. Already in the 1990's, 66.8% of the dentists in the United States used computers in their practice.[1] In 2000, it was estimated that 5% of the practitioners in North America used digital radiography[2], while in 2005, 25% of the surveyed dentists used some form of digital radiography and 18% had planned to purchase digital equipment within one year[3]. The percentage of users was reported to be 30% in 2010 and the expectation is that this trend will continue to increase.[4] Among the digital technologies predicted to be incorporated in practice, digital radiography is quickly becoming the leading imaging technique in dentistry[3]. The most significant factor in deciding whether to include digital imaging in the dental practice is availability and the cost of the computer system. Dentists reported that in addition to the lack of chemicals, lower levels of exposure, image storage and the perceived time saving, improved clinical image is a prime motive for integrating digital imaging in practice.[5,6] Others have asserted that the most significant advantages of digital technologies are image archiving and access, computer-aided image interpretation and tools for image enhancement.[7] Overall, the vast majority of owners of digital imaging systems is satisfied and believes that productivity increased[3].

Intraoral solid-state rigid sensors are based on either the CCD (Charge-Couple Device) or the CMOS (Complementary Metal-Oxide Semiconductor) technologies. There is debate as to which technology is most advantageous; CMOS sensors have lower energy requirements, but both CCD and CMOS sensors are capable of capturing 12 bit images and have clinically acceptable spatial resolution.[3,7] The CMOS technology is currently incorporated in the latest products of several leading manufacturers.

It has already been shown that intraoral digital sensors provide diagnostic images. Early digital systems were useful in evaluating endodontic file lengths up to a size of 15[8]. A recent study determined that the performance in this regard is precise for files up to a sizeof 6[9]. The detection of primary and recurrent caries is similar with digital images and film.[10,11] In addition studies have shown that there is no significant difference in the sensitivity and specificity in the detection of dentinal caries using digital or film based bitewings.[10,11]

The topic of image quality generated by intraoral digital sensors is complex. This is due to the fact that "defining image quality is a complicated process….part of a longer chain of procedures and actions" .[7] As stated "there is a continuous need for the evaluation of new digital intraoral radiography systems that appear on the market, first and foremost for their image quality..."[12] Subjective image quality evaluation was reportedly performed by a small number of evaluators, using several digital systems and usually "in vitro" [13-15] using prefabricated phantoms or cadavers.[16-19]
Image quality also can be affected by placement of the rigid sensor in the mouth, a maneuver that is more challenging than placing regular film.[3] Furthermore, clinicians must adapt to digital images that have a smaller surface than film; for example, the total active area of a size 2 film is 1235 mm^2, whereas similar size digital sensors have active areas in the range of 802-940 mm^2 only.
As with conventional radiography, lighting conditions are important for digital image evaluation[16,20,21], but observers' performance was found to be independent of the visual characteristics of the display monitors[22-24].

In the present study we used a greater number of sensors than previously reported and the image evaluated was captured in-vivo. Images acquired with eight digital intraoral sensors were evaluated by faculty who teach undergraduate dental students. The null hypothesis was that no difference would be found in the clinical image quality between the sensors.

Material and Methods

Of 12 companies contacted to provide equipment for this evaluation, eight vendors responded and provided size 2 CMOS intraoral sensors-- (XDR-- Cyber Medical Imaging, Los Angeles, CA, USA, RVG 6100-- Carestream Dental LLC, Atlanta, GA, USA, Platinum-- DEXIS LLC., Hatfield, PA, USA, CDR Elite-- Schick Technologies, Long Island City, NY, USA, ProSensor-- Planmeca, Helsinki, Finland, EVA-- ImageWorks, Elmsford, NY, USA, XIOS Plus-- Sirona, Bensheim, Germany, and GXS-700-- Gendex Dental Systems, Hatfield, PA, USA). The Platinum sensor comes in a single size, and is considered to be size 2 since it is used for taking radiographs for posterior teeth and for bitewings. Each sensor was used to capture one left bitewing from the same subject (one of the authors).

IRB approval was sought however, because this is a single-subject study, Case Western Reserve University Institutional Review Board (IRB) concluded that this study does not require further review or approval. The faculty subject (one of the authors) who volunteered, provided verbal consent and was informed about the effective radiation dose of bitewings (total of 10 µSv for eight posterior bitewings)[25].

The volunteer was protected with a lead apron and a protective thyroid collar. Sensors were positioned intraorally with a Rinn kit (model XCP-DS, Dentsply Rinn, Elgin, Il, USA) and the source was a Planmeca Intra x-ray DC machine (Planmeca, Helsinki, Finland) with digital exposure parameters (63 kVp, 8 mA and 0.064 seconds) and rectangular collimation.

The bitewings were taken by one of the authors who is an oral and maxillofacial radiologist (WAR); in total eight bitewings were taken with no retakes necessary.

The same sensors were used to capture the image of an Aluminum phantom (99% pure aluminum, manufactured according to our specs by Bien Air Dental SA, Bienne, Switzerland) sized 1.5 cm. x 1.5 cm. x 1 cm. (w x l x h) (Fig 1). This type of phantom was previously described[16, 19]. The same x-ray machine and settings were used for this purpose. The phantom is divided into 25 squares (3 mm x 3 mm), of which 12 have a round well with a diameter of 1.5 mm and with a depth varying from 0.05 to 0.6 mm, in increments of 0.05 mm. The wells were randomly distributed over the surface of the phantom. All dimensions had a size tolerance of ±0.005 mm.

All sensors were operated with their native software installed on a 15” MacBookPro (Apple Inc., Infinity Loop, CA, USA) with Core 2 Duo processor and 4GB of RAM. The computer was equipped with a 32 bit version of Windows 7 Professional (Microsoft Corporation, Redmond, WA, USA) with the latest updates running under Boot Camp software that enables Apple computers to emulate Windows similar to a PC environment.

The latest version of the software application (at the time of testing) was used to capture radiographs from each sensor: XDR 3.0.5 Beta (XDR sensor), KDI 6.11.7.0 (Kodak RVG 6100), Dexis 9.2 (Dexis Platinum), CDR DICOM 4.5.0.92 (Schick Elite), Romexis 2.3.1.R (Planmeca ProSensor), EVAsoft 1.0 (Imageworks EVA), Sidexis 2.5.2 (Sirona XIOS Plus), VixWin Platinum 2.0 (Gendex GXS-700).

Images were saved in uncompressed TIFF format (Fig 2). For evaluation purposes, the images were displayed on a Dell G2410 monitor at a resolution of 1920 x 1080 in a room without ambient light. Clinical and phantom images were displayed in separate templates created in Adobe Lightroom Ver. 3.5, 64 bit software (Adobe Systems Incorporated, San Jose, CA, USA). When displayed in the Lightroom template, images were not labeled with the name of the sensors (Fig 3). The phantom images were rotated randomly. The templates in Lightroom allowed the images to be displayed side by side, when an image was double clicked, it was enlarged. Double clicking again on the image, returned the display of the template. The evaluators were allowed to enlarge each image as desired, but were not allowed to adjust other parameters such as contrast or brightness.

<u>Image evaluation</u>

Eighteen clinicians evaluated the clinical and the phantom images. All evaluators had at least one year of experience with digital radiography in the undergraduate clinic. For the clinical images, the clinicians were presented with the following instructions: “Arrange the images according to the image clinical quality (best being 1st, worst being 8th). Image quality parameters include but are not limited to clarity, diagnostic value, contrast, sharpness, etc. Please provide your overall evaluation of the clinical quality of the image“. The results of the evaluation were recorded on a separate form for each clinician.

For the phantom images, the clinicians were presented with a form with a grid of 5 x 5 squares, representing the phantom. The evaluators were requested to identify the presence of the wells on a grid of 25 possible locations and to mark the results on the form. The results of the identification were used to determine if any of the evaluators had a level of false results that would lead to the clinician being an outlier; if a clinician was determined to be an outlier, the protocol stated that the scores generated by that evaluator for the clinical images, would be discarded from the analysis.

Analytical methods.

In order to detect outliers, the frequency and the distribution of false positive responses of the evaluators for the phantom images were computed. A 95% confidence interval of the total sample of the evaluators was also computed for the total sample of the evaluators.

For the clinical images evaluation, a Visual Grading Characteristics (VGC) analysis was performed.[26,27] This method was designed to determine the difference in image quality between two modalities in cases of ordinal multiple rating. In the current study, the data consisted of multiple ratings for each image on an ordinal scale. For each of the images to be compared the frequency of the ratings provided by the evaluators, for each level of the scale, was calculated. These frequencies were then transformed into cumulative proportions for each level of the evaluation scale and served as a basis for generating VGC curves.
The "Area Under the Curve" (AUC) was utilized as a single measure of the difference in image quality between two modalities compared, i.e., each pair of sensors.[26] The AUC represented the difference in overall rankings between the two images for which the VGC curve was generated (an area which significantly differed by 50% represented a significant difference between the rankings of the two images).

The VGC curves and the corresponding AUC values for each pair of sensors were calculated using the ROCKIT software, ver. 0.9.1 Beta downloaded from http://metz-roc.uchicago.edu/MetzROC/software. [28] All other statistics were generated in SPSS for Windows ver. 20 (IBM, Armonk, NY, USA).

Results

Eighteen faculty clinicians (evaluators) who teach in the undergraduate clinic at Case Western Reserve University School of Dental Medicine (CWRU) evaluated the clinical and phantom images. The average evaluator's time since graduation was 25.12 years (SD 8.13) with a range of 11 to 39 years.

In the detection of outliers, from a total of 15 false positives, 9 were attributed to a one clinician (four other clinicians had one false positive each and another clinician had two false positives). The mean of true positives ("hits") for the first clinician (1.92) was not within the 95% confidence interval limits of the total sample of the evaluators (3.23-4.07). In light of these results, the evaluations reported by this clinician were considered outliers and were not included in the analysis of the clinical images. Consequently, all the results reported reflect the evaluations provided by only 17 clinicians.

In order to calculate the reliability of the rankings of the clinical images by the remaining 17 evaluators, we calculated the inter-rater reliability reflected by the Intraclass Correlation Coeffiicent (ICC), based on the random effects assumption. The ICC was calculated using an assumption of absolute agreement, i.e., we expected the exact same ranking from all of the evaluators. For this sample, we received an ICC of 0.92 (95% confidence interval: 0.80- 0.98).

The ranking provided by the evaluators of each sensor was compared between all possible sensor pairs using the VGC method. [26,27]Table 1 presents the frequency of each rank (1=best, 8=worst) and the cumulative proportions for each level of the evaluation scale. The EVA sensor was not included in the analysis since it was consistently ranked 8 (worst) by all the evaluators. Therefore, since no other sensor except Eva was ranked 8, the analysis included only seven levels of ranking. We calculated the AUC for each pair of the seven sensors (a total of 21 pairs) and the 95% confidence interval for the calculated AUC (Table 2). The AUC is the area under the ROC curve that was generated for each pair of sensors, as illustrated in Figure 4. Significance ($p<0.05$) is determined when the confidence interval does not include the 0.5 value. In other words if the calculated area under the curve is significantly different, 50% or more, there is a significant difference between the rankings of the two sensors under consideration.
The results show that the clinical image acquired with the Platinum-Dexis sensor was ranked significantly better than that captured with the XIOS Plus-Sirona and the RVG 6100-Carestream (Kodak) sensors; the image captured with the RVG 6100-Carestream (Kodak) sensor was ranked significantly worse than the images captured with the Platinum-Dexis, CDR Elite-Schick and XDR-Cyber Medical Imaging. All other comparisons resulted in non-significant results.

Discussion

Intraoral solid-state sensors have been tested in different settings. Nonetheless, such studies tested a small number of sensors that generated images that were evaluated by a relatively small number of clinicians.[13-15,29] This study demonstrates greater validity over previous studies, all of which used fewer types of sensors, fewer evaluators or a combination of both. Moreover, our study utilized images generated from a single human subject from the same area of the mouth, which enabled us to standardize the clinical conditions while testing a broad range of available products.

Since the correlation between physical measures that can be determined by the use of phantoms and clinical image quality is poor, there is no justification for extrapolating such measurements to clinical performance of the sensor.[15,27,30] However, use of phantoms such as the aluminum block used in this project, provides valuable information regarding quality control and standardization.[31]

In the present study the clinicians were not limited to evaluating a single clinical parameter such as the presence of caries, the quality of a restoration, etc., but were instructed to rank the overall quality of an image. Subjective quality estimations can serve as the baseline for objective quality methodology as long as there is no perfect model that would apply to a complex situation such as the quality of an x-ray image[32]. This approach is consistent with image quality defined as the degree to which the image satisfies the requirements imposed on it, thus relevant to the end user.[33] Image quality evaluation is considered to be a high-level interpretative process of perception that cannot be dissected by analyzing only “low-level” physical image characteristics such as sharpness, noisiness, brightness and contrast.[32,34] In this context, only a weak relationship was reported between image fidelity (the ability to discriminate between two images based on the physical characteristics) and image quality (the preference for one image over another).[35]

The VGC method used in this study is a relatively easy way to quantify subjective opinions and make them suitable for analysis, while providing the opportunity to use the AUC as a single measure to quantify differences in image quality between two compared modalities.[26,27] Results show that the Platinum-Dexis sensor image was ranked significantly better than two other sensors (XIOS Plus-Sirona and RVG 6100-Carestream), but in a comparison of other sensors with Platinum-Dexis no significant differences were found. For example, the image generated by the Planmeca sensor was not found to be statistically significantly different than either the

Platinum-Dexis or the RVG 6100-Carestream images. This finding indicates that even differences that have been found to be statistically significant may be so subtle to the degree that their clinical significance is unclear.

In this study many parameters were standardized as much as possible, such as using a single clinical subject, capturing the image from the same area of the mouth with each sensor, using a device that aligns the x-ray machine with the sensor, standardized evaluation conditions and the profile of the evaluators. We are aware of the fact that the sample size of the evaluators may be a limitation in this study. Using a single subject in this study and exposing one area of the mouth not only contributed to standardization but also enabled the authors to keep the ALARA (As Low As Reasonably Achievable) principle of minimizing radiation exposure. Although ALARA principles were carefully observed and implemented and the amount of exposure was kept to an absolute minimum, researchers using this kind of single-subject survey should carefully weigh the benefits versus radiation hazards. However this standardization might lead to a limitation as in a recurrent similar exercise on other subjects (of different sizes, ages, ethnicities, systemic bone pathologies, etc.) and different mouth areas, imaging may lead to different results. Another potential limitation is that the clinicians were not required to justify the image ratings, thus we could not analyze whether there is one perceived single factor that had a major influence on the image quality. Despite the fact that a positioning device to align the X Ray source with the sensor was used, the subject may bite on it with various forces each time and the alignment may be subject to minor variations. It is also clear that because not all sensors have the same dimension and/or physical configurations, different bitewing images may depict more or less of the crestal bone. One should also consider that using a standardized exposure from one machine may affect the image quality of some sensors because the chosen parameters may not fall within the optimal dynamic range of these devices. Finally another possible shortcoming lies in the fact that intra-rater reliability over time was not assessed, therefore it is possible that the raters' results will be different if re-tested.

In conclusion, the null hypothesis was rejected because there were statistically significant differences between the images captured with different sensors. Clearly the EVA—ImageWorks sensor generated an image that was consistently rated worst by all clinicians; whereas on the other side of the spectrum, no sensor could be identified as generating better quality images than the other sensors tested. Further research should be directed towards determining the clinical significance of the differences in image quality found in this study.

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Figures Legends

Figure 1: Aluminum Phantom with 12 wells with a diameter of 1.5 mm and with a depth varying from 0.05 to 0.6 mm, in increments of 0.05 mm.

Figure 2: Clinical images acquired with the tested intraoral digital sensors

Figure 3: Clinical images displayed in Adobe Lightroom for evaluation

Figure 4: Example of VGC curve comparing the RVG 6100-Carestream (Kodak) and Platinum-Dexis. The empty square boxes represent the operating points corresponding to the evaluators' ranking of the sensor.

Tables Legend:

Table 1: Frequency and cumulative proportions (by sensor) of clinical image quality ranking

Table 2: Visual Grading Characteristics (VGC) results for clinical images ranking. Each box displays the AUC, SD and 95% confidence intervals. Significant differences between pairs are denoted by an asterisk ($p<0.05$)

Rank	Frequency **Platinum**-- DEXIS	Cumulative Proportion **Platinum**	Frequency **EVA**-- Image Works	Cumulative Proportion **EVA**	Frequency **GXS-700**-- Gendex	Cumulative Proportion **GXS-700**	Frequency **RVG 6100**-- Carestream (Kodak)	Cumulative Proportion **RVG 6100**
1	3	1	0	1	2	1	0	1
2	5	0.82352941	0	1	3	0.882352941	0	1
3	4	0.52941176	0	1	2	0.705882353	3	1
4	1	0.29411765	0	1	0	0.588235294	5	0.82352941
5	2	0.23529412	0	1	3	0.588235294	1	0.52941176
6	1	0.11764706	0	1	3	0.411764706	4	0.47058824
7	1	0.05882353	0	1	4	0.235294118	4	0.23529412
8	0	0	17	1	0	0	0	0
Total →	17		17		17		17	

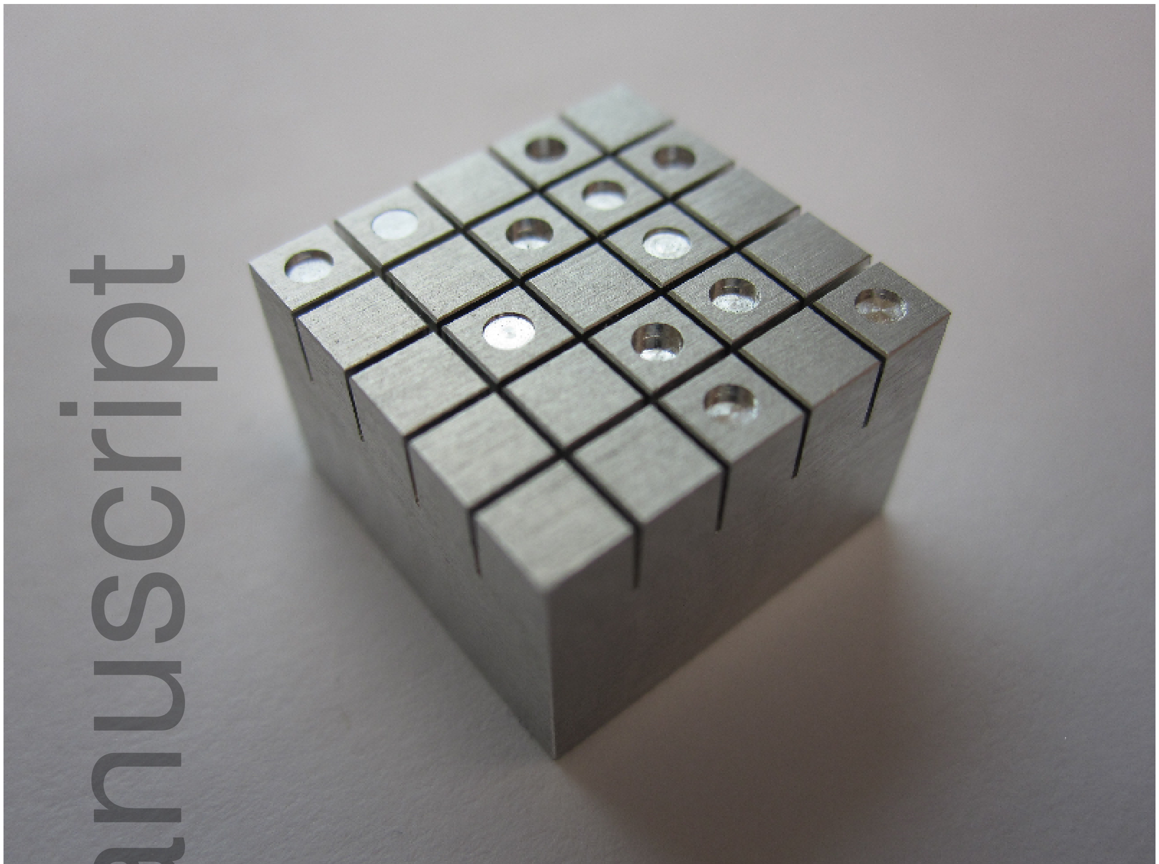
Rank	Frequency **ProSensor**-- Planmeca	Cumulative Proportion **ProSensor**	Frequency **CDR Elite**-- Schick	Cumulative Proportion **CDR Elite**	Frequency **XIOS Plus**-- Sirona	Cumulative Proportion **XIOS plus**	Frequency **XDR**-- Cyber Medical Imaging	Cumulative Proportion **XDR**
1	3	1	2	1	2	1	5	1
2	2	0.82352941	3	0.882352941	0	0.882352941	4	0.70588235
3	3	0.70588235	1	0.705882353	2	0.882352941	2	0.47058824
4	0	0.52941176	5	0.647058824	5	0.764705882	1	0.35294118
5	2	0.52941176	3	0.352941176	4	0.470588235	2	0.29411765
6	4	0.41176471	3	0.176470588	2	0.235294118	0	0.17647059

7	3	0.17647059	0	0	2	0.117647059	3	0.17647059
8	0	0	0	0	0	0	0	0
Total →	17		17		17		17	

Table 1 – Frequency and cumulative proportions (by sensor) of clinical image quality ranking

AUC **SD** **95% CI**	Platinum--DEXIS	GXS-700--Gendex	RVG 6100--Carestream (Kodak)	ProSensor--Planmeca	CDR Elite--Schick	XIOS Plus--Sirona
GXS-700--Gendex	0.67 0.094 0.475-0.83					
RVG 6100--Carestream (Kodak)	0.8279 0.0756 0.642-0.937*	0.595 0.104 0.389-0.778				
ProSensor--Planmeca	0.6315 0.097 0.433-0.80	0.463 0.101 0.277-0.658	0.36 0.100 0.189-0.566			
CDR Elite--Schick	0.6041 0.097 0.408-0.776	0.373 0.098 0.202-0.574	0.267 0.086 0.128-0.456*	0.41 0.102 0.232-0.615		
XIOS Plus--Sirona	0.699 0.0895 0.507-0.847*	0.46 0.100 0.278-0.657	0.38 0.097 0.214-0.581	0509 0.101 0.318-0.699	0.598 0.098 0.403-0.772	
XDR--Cyber Medical Imaging	0.478 0.103 0.287-0.674	0.347 0.096 0.183-0.546	0.246 0.094 0.102-0.460*	0.383 0.098 0.250-1.446	0.416 0.101 0.236-0.616	0.343 0.096 0.180-0.543

Table 2 - Visual Grading Characteristics (VGC) results for clinical images ranking. Each box displays the AUC, SD and the confidence intervals at 95%. Significant differences between pairs are denoted by an asterisk ($p<0.05$)



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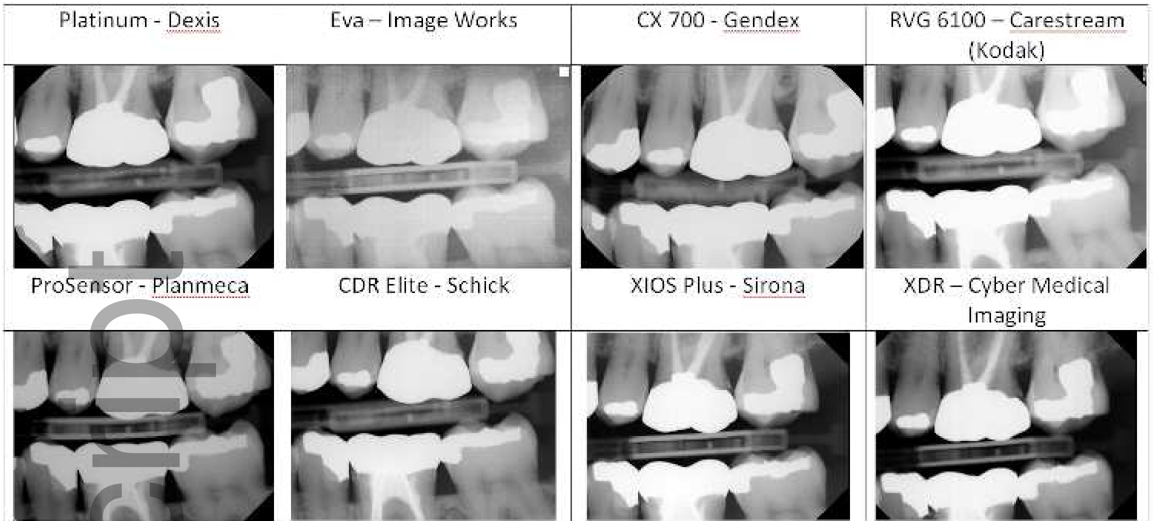

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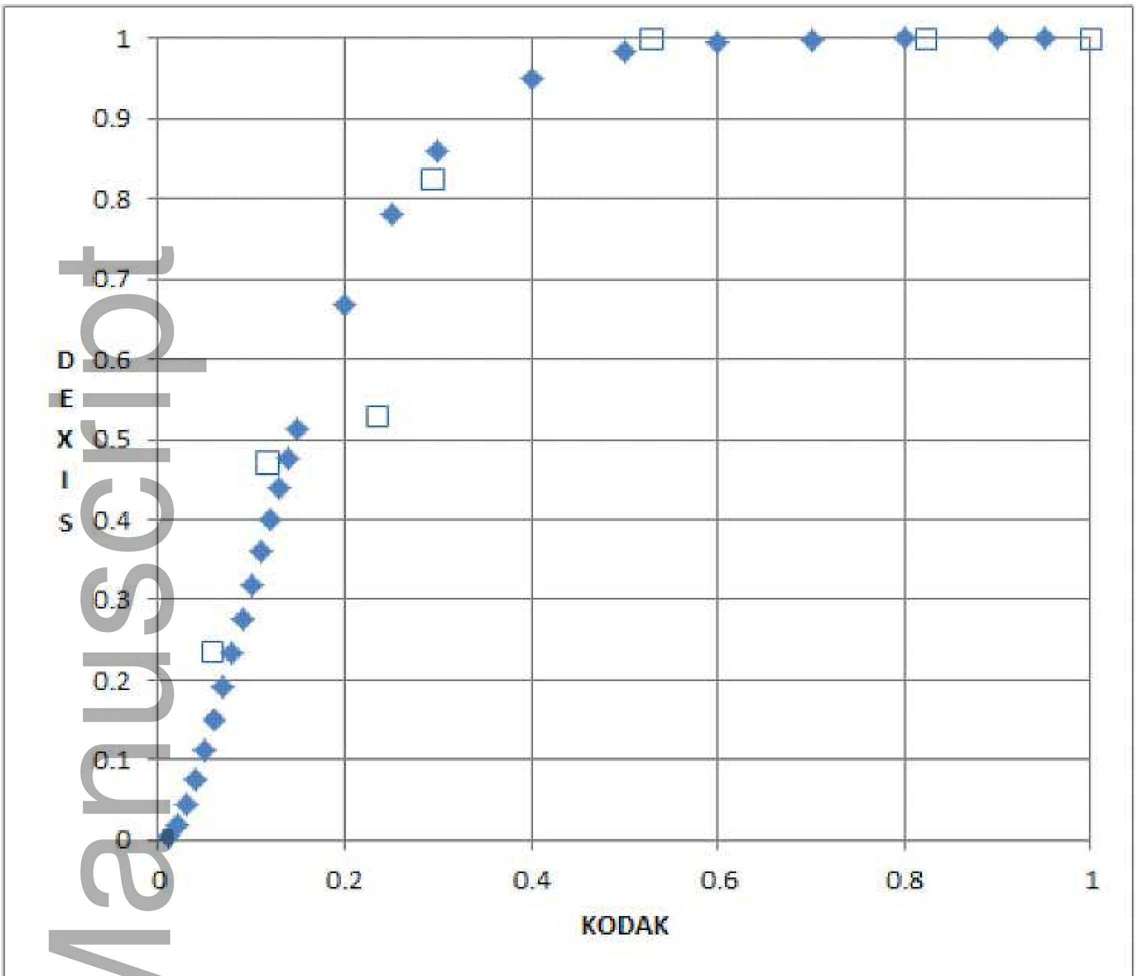

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