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ABSTRACT:
Objective: To assess and compare the image quality of four CBCT systems for their clinical practicality using a quality assurance (QA) phantom, and to aid in the decision-making process by providing objective choices for the selection of an appropriate platform based on speciality-specifics.

Methods: The four CBCT systems evaluated were: Carestream CS 9300, KAVO Kerr i-CAT FLX, Morita Accuitomo 80 and Planmeca ProMax Max. All CBCT volumes were imaged with the QUART DVT_KP phantom. QA parameters such as Nyquist Frequency (NF), contrast, noise, contrast-to-noise ratio (CNR), and homogeneity and noise were assessed. QA data were statistically analyzed using one-way ANOVAs and Tukey-Kramer HSD post hoc tests (alpha = 0.05).

Results: Carestream CS 9300 had the highest contrast ($p < 0.0001$) for the small, medium, and large fields of view (FOV) in comparison with the other CBCT systems, but also had the greatest level of noise for the small and large FOVs. For the small and medium FOVs (e.g., < 10 cm diameter x 10 cm height), Morita Accuitomo 80 had the lowest noise ($p < 0.0001$) than the other three CBCT systems. NF was determined to be inversely related to voxel size; a smaller voxel results in a higher NF, and a larger voxel results in a lower NF. A similar relationship exists between noise and FOV; low noise is asociated with a larger FOV, whereas high noise is asociated with a smaller FOV. A linear relationship was observed between FOV and CNR. CNR differences in small FOV for the four CBCT systems evaluted were not statistically significant.

Conclusions: No single CBCT system excelled on all QA parameters evaluated. High contrast may be more desirable for endodontic evaluation, but low noise is preferential for 3D model fabrication, and consistency in homogeneity may be more desireable when assessing bone quality. Therefore, selection of a CBCT system is imaging task dependent.

INTRODUCTION

When considering a cone beam computed tomography (CBCT) unit for a dental office, few studies exist that methodically evaluate CBCT systems. Current, available scientific literature may be difficult to understand and are written with engineering or research terms unfamiliar to the average dental clinician [1,2,3,4,5]. As result most dental practitioners will purchase a CBCT scanner from a product line they are familiar with, while a few others will seek out new marketing material for different CBCT systems. Reading and understanding CBCT marketing information is challenging and complicated by the lack of standards necessary to evaluate and compare various systems. Some CBCT manufacturers provide features that are not available on other systems, such as choosing the number of basis images, choosing the arc of rotation, the ability to stitch or bring together two or more smaller CBCT volumes into a larger CBCT volume, the ability to scan models, the ability to create surface renderings in conjunction with a CBCT volume and the ability to combine a visible light surface scan with the CBCT scan volume. The dental practitioner unfamiliar with CBCT technology is left hesistant thinking that they must have all these features.

Further the marketing information can be deceiving and complicated enough with non-standardized terminology and marketing jargon to confuse a dental practitioner. An example of non-standardized terminology to refer to same or similar CBCT feature is “metal artifact reduction.” Planmeca refers to this function as ARA (artifact removal algorithm) [6]. Carestream Dental describes it as “Advanced Second-Generation Metal Artifact Reduction” [7]. The same function is called MARS (metal artifact reduction sequence) by Dentsply Sirona [8]. The manufacturer, Acteon refers to “dynamic artifact reduction,” and Genoray has labeled it SMARF (Smart Metal Artifact Reduction Function) [9]. This function can be applied at different times during CBCT acquisition -- in some cases during the radiographic acquisition and in other cases after the CBCT volume has been acquired.

All CBCT systems are acceptance tested after installation and before clinical use with a Quality Assurance (QA) phantom supplied in accordance with Food and Drug Administration requirements [10]. The QA evaluation is meant to ensure that the system is functioning as designed and is in compliance with regulations. If these QA measurements could somehow be extrapolated to other CBCT systems, it would provide a method to compare the performance of different CBCT systems. However, most CBCT manufacturers provide QA phantoms that are proprietary and suitable for use on its system only.

Fortunately, there are several independent companies that manufacture CBCT QA phantoms suitable for use with all dental CBCT scanners. The use of such a universal QA phantom would allow some comparison of CBCT performance among CBCT systems. A universal CBCT QA phantom has been used in other studies to assess image quality [11, 12, 13]. In this paper we will discuss the parameters of one such CBCT QA phantom, and translate them into common terms, to provide better understanding about how to select a CBCT system to meet your dental office needs.

The null hypothesis of the study is that there will be no difference in the performance between these four CBCT systems as determined with a universal QA phantom. The alternative hypothesis is there will be differences between the CBCT systems as determined by a universal QA phantom which could then provide an effective means to aid in the selection of a CBCT systems best suited for your office.

METHODS AND MATERIALS

CBCT Systems

Four clinical CBCT systems were evaluated Carestream CS 9300 (Atlanta, GA), KAVO Kerr i-CAT FLX (Brea, CA), Morita Accuitomo 80 (Irvine, CA), and Planmeca ProMax 3D Max (Hoffman Estates, IL) (Table 1) with the universal QA phantom. The following image parameters Nyquist Frequency, contrast, noise, contrast-to-noise ratio (CNR), Modulation Transfer Function (MTF), and homogeneity were evaluated and compared.

Although the CBCT scanners were not new, each system was calibrated by either a trained biomedical technician or medical physicist performing the required manufacturer's specified QA tests within one month of the research data acquisition.

The Carestream CS9300 CBCT scanner is a flexible FOV device offering hybrid capabilities of CBCT imaging along with panoramic and cephalometric imaging capabilities. The CS9300 has a pulsed radiation beam to reduce radiation dose. This CBCT device marketed by the Carestream Dental group to all dental providers as a versatile and flexible product suitable for all imaging needs. As such it is intended to be used with the patient standing in the CBCT scanner but a small stool can be used if required to stabilize the patient during image acquisition, and also available for wheelchair access. In terms of CBCT imaging, the FOV ranges from 50 x 50 to 170 x 140 mm FOV [7]. (Note the first numerical value indicates the diameter of the volume and the second value represents the height of the volume).

The i-CAT FLX CBCT scanner offers a seated positioning for the patient during CBCT scanning. This CBCT has the ability to provide CBCT volumes and a panoramic radiograph only. The radiation from the i-CAT FLX CBCT is pulsed to reduce patient exposure. This scanner also offers a radiation dose saving mode with a shorter exposure time. This CBCT scanner is also capable of offering several flexible FOVs from 80 x 50 to 230 x 170 mm [14].

The Morita Accuitomo 80 scanner has a seated position during CBCT scanning. The chair height adjusts to center the patient within the FOV. This CBCT device marketed by J. Morita Corp. for endodontists and periodontists. This CBCT offers only three sizes: 40 x 40, 60 x 60, and 80 x 80 mm. The Morita Accuitomo 80 is a dedicated CBCT scanner only, and their unique One Data Viewer program that doesn't have implant planning capability [15].

The Planmeca ProMax 3D Max utilizes an upright position for scanning, but a seating position can be used for patient stability or wheelchair access. This is a dedicated 3D imaging device. However, it offers multiple different sizes ranging from 50 x 55 to 230 x 260 mm. The Planmeca ProMax 3D Max is marketed by Planmeca for use in all general dentist and specialty practices [6].

In this study, we selected three of the FOVs from each CBCT system to represent small, medium and large FOVs for ease of comparison to the other CBCT systems and to correlate with clinical needs.

CBCT Phantom

The universal quality assurance (QA) phantom (QUART DVT_KP, QUART GmbH, Zorneding, Germany) was utilized for the assessment of Nyquist Frequency, contrast, noise, contrast-to-noise ratio, MTF, and homogeneity [16]. This phantom is made up of two large discs of clear polymethylmethacrylate (PMMA)(160 mm diameter x 20 mm height) containing test objects for quality control as well as positioning tools for reproducible placement. Within the upper PMMA disc in the central portion, a region of polyvinvylchloride, air, and a centering aide are located. The centering aid is for aligning the disc with the laser guide in the CBCT system. A round liquid filled bubble level is located off to the side of the PMMA disc. The lower disc has a threaded hole to allow the phantom to be screwed onto a customized holder from the manufacturer, however neither the fixation aid nor the customized holder were not used in this study (Figure 1).

A custom platform to fit into the chin support mechanism of each CBCT scanner was fabricated to support the phantom. These custom-printed holders were attached to ½ inch thick sheet of clear PMMA with nylon screws to create the customized platform (Figure 2). To centrally position the phantom within the correct height in the FOV, a small 5 cm diameter clear PMMA cylinder was used to elevate the QA phantom (Figure 2C). To ensure all required test components of the phantom were imaged properly, scout scans were utilized to to position the phantom both horizontally and verticallywithin the FOV.

As with any device there are limitations, this QUART DVT_KP phantom did not provide a means of evaluating detector type, dose reporting, arc of rotation, scan mode, focal spot, milliampere, seconds and kilovoltage peak; therefore, these CBCT features will not be discussed in the paper.

CBCT Data Collection

Each CBCT system has many different FOV selections, voxel size, kVP, mA, and exposure time (see Table 1). To manage the multitude of exposure parameters and variables from the different CBCT, it was decided to group the CBCT systems based on FOV. The FOVs selected for this study were a small, medium and large on each CBCT device as much as possible. Small FOVs included 50 x 50 to 80 x 50 mm, medium included 100 x 55 to 80 x 80 mm, and large FOV extended from 170 x 135 to 230 x 260 mm (see Table 2). Pre-programmed clinical settings were used in obtaining the images with no changes made to the default voxel, kV, mA or exposure time. The FOV selected for each of the CBCT scanners was based upon both the physical dimensions of the FOV and the voxel size. For example, the iCAT FLX 80 x 80 mm and 0.120 mm voxel combined was classifed as a small FOV. Dose saving protocols were not utilized as the reduction in radiation dose may affect many of the QA test parameters of Nyquist Frequency (NF), contrast, noise, contrast-to-noise ratio (CNR), homogeneity and Modulation Transfer Function (MTF).

To minimize artifacts and bias, the Quart DVT_KP phantom was placed in the isocenter of each CBCT scanner such that equivalent exposure by the photon beam was made. This was confirmed with a scout scan such that there was equidistant measurements on all sides of the phantom.

The study involved the collection of 5 CBCT scans of small, medium and large for each CBCT scanner for a total of 55 CBCT scans to allow for better comparison of the results. DB was responsible for acquiring the CBCT scans on all the 4 CBCT scanners and different FOVs after a trial run of acquiring the CBCT data with all the researchers.

Three FOVs were chosen on the Carestream CS 9300, the KAVO Kerr i-CAT FLX and the Planmeca Pro Max Max. In the case of the of Morita Accuitomo 80, the smallest FOV 40 x 40 mm was too small to capture the contrasting PMMA/PVC/Air elements within the upper disc of the phantom and this FOV was excluded from this study. Therefore the 60 x 60 mm FOV was utilized as the small FOV. Accordingly the 80 x 80 mm FOV was selected as the medium size FOV in this study and there is no large FOV scan for this device (See Table 2).

To ensure accuracy and minimize the effects of photon flux and detector inefficiencies, 5 CBCT volumes were captured of each FOV for all 4 CBCT scanners. The images were acquired in each device manufacturers own proprietary software, reconstructed to create the CBCT volume and then exported in DICOM format in the axial orientation. In total 55 CBCT scans were obtained since there was no large FOV with the Morita Accuitomo 80 CBCT scanner.

Data Analysis

The CBCT volumes were exported in DICOM format and imported into NIH ImageJ version 1.52a software (National Institute of Health, Bethesda, MD) for analysis. Each scan was viewed in ImageJ using axial slice orientation. Using Image J, each image slice was examined and the authors (DB is a resident in a postgraduate Advanced Education in General Dentistry Program with 6 years experience; PM is a board certified Oral and Maxillofacial Radiologist; TR is board certified in Oral and Maxillofacial Radiology; and WL is a dentist with 18 years experience and 6 years as a medical physicist) reached a consensus as to which was the top and bottom slices of the upper disc, and the middle slice was determined using this information. The middle image slice of the upper disc, and the middle image slice of the lower disc were selected for analysis using the QUART DVT Pro software.

Locating the middle slice of each disc was important to minimize any unintended influences from other objects shadow or materials of different attenuation level being cast upon the test area. This was repeated for each of the 5 scans of each FOV selected on each CBCT. The middle slice from the center of the upper and lower PMMA discs were analyzed using QUART DVT_pro software.

Image Quality Parameters

Standard image quality parameters of NF, contrast, noise, CNR, MTF and homogeneity were used to compare image quality among the CBCT scanners. Data was collected from all 4 CBCT scanners and the data for each of the 5 CBCT scans of small, medium and large for each CBCT scanner was amalgamated and plotted in Figure 4 of the results.

NF refers to the sampling rate at which data points are collected. The Nyquist frequency is one-half of the sampling rate of a discrete signal processing system. To create an image using x-ray photons, sufficient samples must be recorded to capture the peaks and trough of the original x-ray beam. Each set of peaks and trough of the original x-ray beam is a discrete unit. NF is important in CBCT imaging because the sampling rate determines the amount of small detail that can be captured and recorded to form the 3D CBCT volume. Fine details, such as trabecular bone patterns and presence or absence of a fracture might not be recorded if the NF is too infrequent. NF was evaluated using an axial slice through the PVC portion of the upper disc in the QUART DVT_KP phantom.

Contrast refers to the noticeable differences in gray level instensity between adjacent regions of a radiographic image and is a subjective visual observation. It is simply a measurement of gray scale differencesbetween two regions of known attenuation properties. The QUART DVT_pro software measures the difference between the mean of pixel gray levels in a pixel line of PVC and the mean of pixel gray levels in a pixel line of PMMA contained in the upper disc of the phantom as a contrast value. This pixel line of the PVC and PMMA are from the same middle axial image slice as used for the NF evaluation.

Noise is simply an unwanted signal that is recorded on the image receptor. Noise is undesirable because it degrades the quality of the CBCT image. Image noise refers to the fluctuations in pixel values in the image that can mask lesions or structures of interest, interfering with diagnostic tasks. There are many forms of noise in CBCT imaging but for purposes of QA it can be reduced to the mean of all standard deviations of pixel values or signal intensities on the image receptor. Noise was recorded as the mean of all standard deviations of pixel values in PVC and PMMA from the middle axial image slice in the upper disc of the phantom. Since these two materials are assumed to be homogeneous and the x-ray photon beam is assumed to be uniform, this noise determination can be inferred by the mean of all standard deviations of pixel values in PVC and PMMA.

CNR refers to the ratio of contrast to noise. CNR is the difference in signal intensity between different tissues, divided by the background noise. CNR offers an insight into how well a region can be discerned from the background noise. This is important in CBCT imaging to allow the detection of subtle differences in grey level intensities from what may be otherwise seen as noise. In the case of the QUART DVT_KP phantom, CNR is the ratio of contrast between PVC and PMMA and the corresponding mean image noise.

MTF is utilized to show how effective a signal in this case x-ray photons is transferred or recorded by the image receptor. A high MTF value would indicate greater efficiency and a more accurate representation of the signal. The MTF although not directly related to spatial resolution may be an indication of how well an imaging system is able to display small details in the imaged object. Therefore MTF evaluations need to occur along an edge or border of an object where there is a rapid change in signal intensity. The MTF was measured using the same middle slice of the CBCT scan selected by positioning ROI over the PVC/Air boundary where the largest signal drop off would be present in the upper disc of the QUART DVT_KP phantom (Figure 3B).

Homogeneity is a measure used to validate consistency across an image receptor [17]. For this QA test parameter, the axial slice of clear PMMA portion in the lower disc of the QUART DVT_KP phantom was analyzed. A homogeneous object such as the clear PMMA material should display the same grey scale values if the image detector were recording the grey scale intensities accurately. A defective or malfunctioning detector may not display consistent grey level intensities nor accurately display the differential attenuation in different densities when differences in attenuation of the imaged object are present. Homogeneity using this phantom is defined as a relation between a measured basic contrast and a measure of background change within a homogenous slice. Ideally, mean grey scale or pixel values for a ROI in the homogenous disc of the phantom are constant, i.e. their deviation is zero. Five ROIs are automatically positioned by the QA software and analyzed (Figure 3).

Statistical Analysis

The data from each of the parameter tests were analyzed with an ANOVA and Tukey-Kramer HSD post-hoc test (alpha = 0.05), using statistical software (JMP, SAS, Cary, NC).

RESULTS

The results are presented in Table 3 according to the predetermined FOV classification of small, medium and large used in this study. A small FOV ranged from 50 x 50 to 80 x 80 mm depending on the CBCT scanner, medium from 100 x 55 to 160 x 60 mm and large from 170 x 135 to 230 x 260mm as shown in Table 2.

The data of all 5 CBCT scans for each FOV size have been aggregated and are an overview of the data in each plot of the QA parameters in Figure 4. This was possible as there was minimal variation in the data obtained in the individual CBCT scans and further this would decrease any fluctuations in data due to photon flux.

Overall NF decreased for all CBCT systems as FOV increased (see Figure 4a). However, there were some differences in NF between the individual CBCT scanners. The Carestream CS 9300 CBCT had a higher NF than the other CBCT scanners except the Morita Accuitomo 80 with the medium FOV but this minor difference was within statistical error.

The contrast parameter was relatively constant within each CBCT scanner for small, medium and large FOVs a seen in Figure 4b. Contrast appear to decrease with increasing FOV with the Planmeca ProMax Max 3D and the Carestream CS9300 but increased with increasing FOV with the Morita Accuitomo 80. The contrast level was consistently higher on the Carestream CS 9300 CBCT scanner than the other CBCT units for all 3 different FOVs.

Noise decreased for all CBCT systems as FOV increased (see Figure 4c).The Carestream CS9300 consistently had a higher level of noise than the other CBCT scanners.

CNR which is a ratio of contrast to noise increased for all CBCT systems as FOV increased (see Figure 4d).

MTF was evaluated at 10% and 50% of the signal intensity and was relatively constant for the small, medium and large FOV for all the CBCT scanners. While MTF at 10% and 50% decreased for all CBCT systems as FOV increased (see Figures 4e and 4f) this slight deviation is within statistical error. Of note, is the Morita Accuitomo 80 which had a higher MTF value in with the small and medium FOVs but there was no scan for large FOV.

Homogeneity increased as FOV increased for Planmeca Pro Max Max and the Carestream CS 9300, however, it varied for KAVO Kerr i-CAT FLX (lower for medium FOV than small or large), and decreased in the Morita Accuitomo 80 (see Figure 4g).

Overall, the Carestream CS 9300 had the highest contrast ($p<0.0001$) for all FOV of the CBCT systems evaluated, but also had the greatest level of noise for the small and large sizes ($p<0.0001$). For the small and medium FOV (less than 100 mm diameter x 100 mm height), the Morita Accuitomo 80 had the lowest noise ($p<0.0001$) of the CBCT systems in this study. For small FOV, the Morita Accuitomo 80 had the highest homogeneity, for medium FOV the Carestream CS 9300 had the highest homogeneity, and for large FOV Planmeca ProMax Max and Carestream CS 9300 had the highest homogeneity (seeTable 3). NF had an exponential function of voxel size - with a small voxel, high NF and a large voxel, low NF. A similar relationship existed between noise and FOV – low noise related to large FOV, whereas high noise related to small FOV. A similar relationship existed between NF and FOV – as FOV increased, NF decreased. A linear relationship was observed between FOV and CNR. CNR differences in small FOV for all CBCT systems were not statistically significant (see Figure 5).

DISCUSSION

The null hypothesis was rejected as many differences in NF, contrast, noise, CNR, MTF and homogeneity were found among the 4 CBCT systems using the QA phantom. However, the alternative hypothesis was also rejected because although there were multiple differences found among the 4 CBCT devices, there was insufficient information to allow a selection of a CBCT device based only upon the evaluated QA parameters. Selection of a CBCT system should be based on more factors than simply the 6 QA parameters evaluated by this QA phantom.

Each individual CBCT system has differing FOV selections, voxel size, kVP, mA, and exposure time (see Table 1). To best analyze the data from different units with so many variables, it was decided to group the CBCT systems based on FOV. Small FOVs included 50x50 to 80x80 mm, Medium FOVs included 100x55 to 80x80 mm, and Large FOVs had 170x135 to 230x260 mm (see Table 2). Pre-programmed settings were used in obtaining the images with no changes made to voxel, kV, mA or seconds.

Various types of phantoms have been utilized to evaluate CBCT systems. A QA phantom similar to the QUART DVT phantom (CS Kodak 3D CBCT QAT phantom, Kodak, Rochester, NY) was used only on a Carestream CS 9300 to evaluate FOV, voxel size and kV [12]. A SEDENTEXCT CT phantom (Leeds Test Objects Ltd, North Yorkshire, United Kingdom) was used to evaluate three different CBCT systems found that noise levels and low contrast resolution differed among protocols, but high contrast resolution performed well in all [11]. No studies were found that compared the image quality factors obtained between four different CBCT systems. The CBCT systems evaluated in this study were readily accessible and commercially available on the market.

An advantage of the QUART DVT phantom is how simple it is to use. Minimal training is necessary to learn how to position the phantom appropriately in each FOV. No separate parts are required for positioning or equilibration. In April of 2019 the FDA published Performance Standards for Ionizing Radiation Emitting Products [10] stating several regulations regarding QA of CBCT systems. The QUART DVT phantom meets several of the regulations, but not all. Another phantom, the SEDENTEXCT CT phantom meets a few more regulations, but is much less user friendly. There are several movable components that have to be oriented a specific way for accurate measurements. The phantom is also larger than the QUART DVT phantom and concerns arose of whether it would be able to evaluate the small FOV adequately. No phantom was found commercially available that meets all the current regulations of the FDA. The QUART DVT phantom was chosen for this study due to its ease of use amongst different CBCT systems.

The QUART DVT phantom comes with a fixation aid, however it was not used in this study due to using multiple different CBCT units with different axis of rotation in different FOV. Not all CBCT systems had a chin holder adapter available to place a phantom on for scanning. Custom holders for each CBCT were fabricated for the phantom. However, due to limited amount of material that can be used to fabricate the holders. A 0.5 inch acrylic sheet was cut and attached to the custom holders using plastic screws (see Figure 2).

After utilizing a scout image to center the phantom in a horizontal and vertical position, the 5 images for each FOV were captured without interruption or movement of the phantom. All FOV were captured on the same CBCT unit the same day, however, not all units were scanned the same day. Data may vary based on if the CBCT unit was inadverdently moved by a patient or technician or how long of an interval between capturing images and original calibration because of continued use of CBCT units in patient care.

Limitations of the QUART DVT_pro software included only analyzing a single slice from each disc for each scan, selecting which slice to be analyzed, and objectively highlighting on the slice the different sections for the software to analyze. To minimize discrepancies, no changes to initial proposals were made. Further evaluation could be accomplished by selecting different locations than the initial proposal to see if it would produce different results.

Multiple differences were found in NF, contrast, noise, CNR or homogeneity between the different CBCT units within the small, medium or large FOV ranges. NF decreased for all CBCT systems as FOV increased (see Figure 4a). As FOV increased, contrast decreased in the Planmeca Pro Max Max and Carestream CS 9300. However, as FOV increased, contrast increased in the Morita Accuitomo 80, and between the small and medium FOV size of the KAVO Kerr i-CAT FLX system (see Figure 4b). An elevated contrast creates a short scale contrast, and while beneficial to visualize caries and periapical lesions, it makes it more challenging to visualize the alveolar crest and trabecular bone. As FOV increased, noise decreased in all systems (see Figure 4c). As FOV increased, CNR increased in all systems (see Figure 4d). For each respective system, as FOV increased, homogeneity increased in all systems except the Morita Accuitomo 80 (see Figure 4e). An increase in amount of homogeneity is expected as the voxel size also increases. As voxel size increases, less resolution and detail is captured.

Small detail high resolution is often associated with looking at a single tooth or small region such as a fractured tooth or endodontic lesion, whereas a medium FOV is more likely to be associated with bone graft augmentation in a localized region and a large FOV is associated with full scan of the oromaxillofacial complex for orthodontics or facial reconstuction type procedures. Due to the linear relationship between FOV and CNR, selecting an adjustable FOV CBCT device is important to ensure sufficient detail in the region of interest.

Based on the limited data gathered in this study, it is possible to extrapolate that the Morita 40 x 40 mm FOV probably has low noise, low CNR, high contrast and high homogenity comparable to the other small FOVs. In the authors' opinion, although the Morita Accuitomo 80 has multiple small FOVs available, it is too limited of a view for a general dentist practice. A full arch FOV is recommended to plan for implants utilizing digital software programs to create a guide for ideal orientation. A full arch or larger FOV can be used to create 3D models, to plan for complex surgical procedures, orthodontics, or to evaluate suspected pathology. Careful consideration should be taken on benefit vs risk of exposure for each planned procedure.

Data obtained from this study was helpful to see that there are significant differences between the different CBCT units, however, the differences may or may not be clinically relevant. Analyzing single slices of the same FOV groups from different sizes side by side does not really translate to how those images would appear all together in a full CBCT image analysis. To gain a better appreciation of the different quality of images, CBCT images from the different systems would need to be evaluated side by side (preferably using the same image analysis software), which was not accomplished in this study.

The KAVO Kerr i-CAT FLX system is marketed online as being used most often by orthodontists, oral and maxillofacial surgeons and oral radiologists [9]. The Carestream CS 9300 is marketed for implant planning, oral and maxillofacial surgery and orthodontics [2]. The Planmeca Pro Max Max is promoted as having the largest range of sizes available to capture images for all clinical needs [1]. The Morita Accuitomo 80 offers the smallest FOV as well as the One Data Viewer program which allows viewing of 3D images on any computer without special software [11].

Based on the CBCT systems in this study, the highest contrast system also has the greatest noise level. Selection of a CBCT system is task imaging dependent. For example, high contrast may be more desirable for endodontic evaluation, but low noise is preferential for 3D model fabrication and consistency in homogeneity may be more desirable when assessing bone quality. From the information gathered in this study, the Planmeca ProMax Max is suitable for most comprehensive general dentistry practices. Orthodontists, oral and maxillofacial surgeons, orofacial pain specialisits, maxillofacial prosthetics, prosthodontists may consider the Carestream CS 9300 system because of its low CNR in the largest FOV, consistent homogeneity and contrast, however this CBCT is useful in most comprehensive general dentistry practices, as well. Endodontic, periodontal, prosthodontic, and comprehensive general dentistry practices should consider the Morita Accuitomo 80 due to the lowest contrast, lowest noise, and smallest FOV available when a small site is being imaged. However, in this study the smallest FOV 40 x 40 mm was not tested due to the limitation of the QA phantom. The KAVO Kerr i-CAT FLX would be likely suitable for orthodontists and oral surgeons with its low contrast and noise in large FOV.

CONCLUSIONS

No single CBCT system excelled on all QA parameters evaluated. High contrast may be more desirable for endodontic evaluation, but low noise is preferential for 3D model fabrication, and consistency in homogeneity may be more desireable when assessing bone quality. Therefore, selection of a CBCT system is imaging task dependent.

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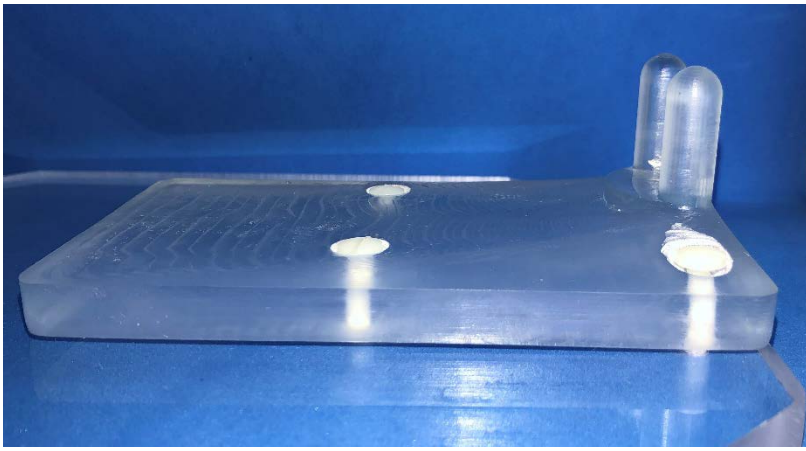
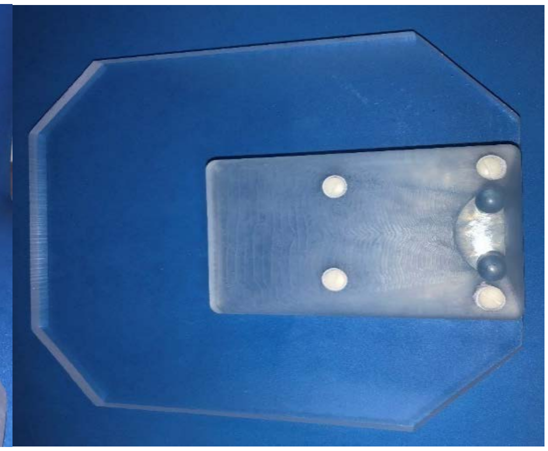
Figure 1 - Quality assurance QUART DVT phantom (QUART GmbH, Zorneding, Germany)

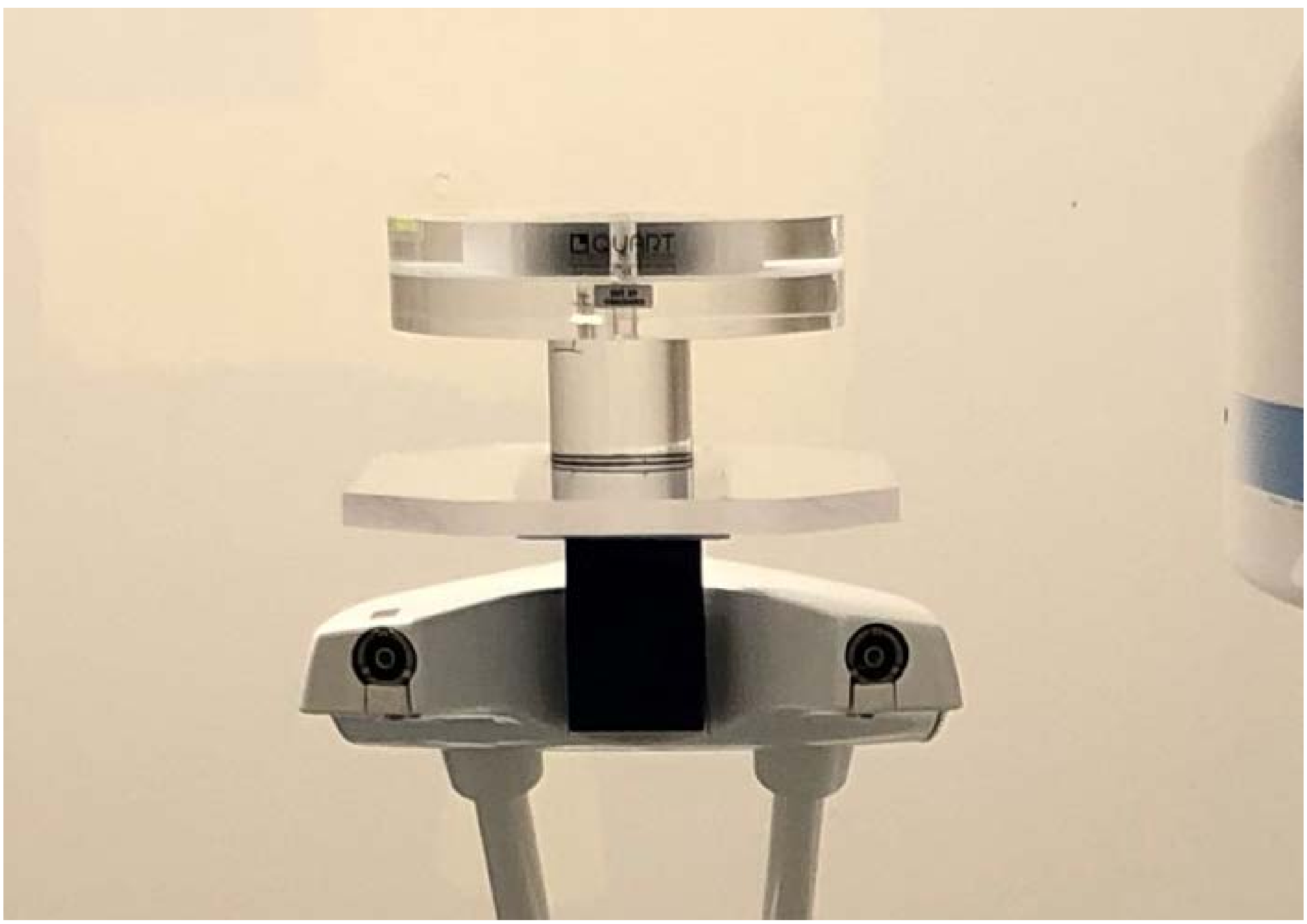
Figure 2 – Custom 3D platform attached to acrylic sheet using plastic screws, demonstrated in use in the Planmeca ProMax Max system in lower picture. An acryclic cylinder was used to center the phantom.



A



B



C

Figure 3 – Images captured during analysis using QUART DVT_pro software. Left image is a single slice of the CBCT image of disc 1, center is demonstrating where MTF, CNR and Nyquist Frequency are measured, right is measuring average homogeneity of a slice of PMMA from disc 2.

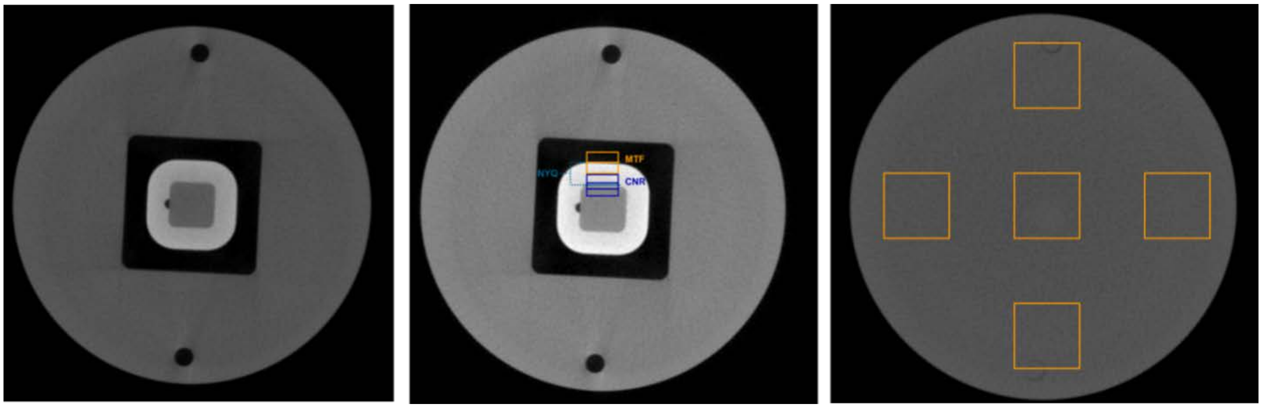


Figure 4 – Averages of each parameter in small, medium and large FOV groups

Figure 5 – Compilation of data from all CBCT units demonstrating comparisons between NF, Noise, FOV, Voxel, and CNR

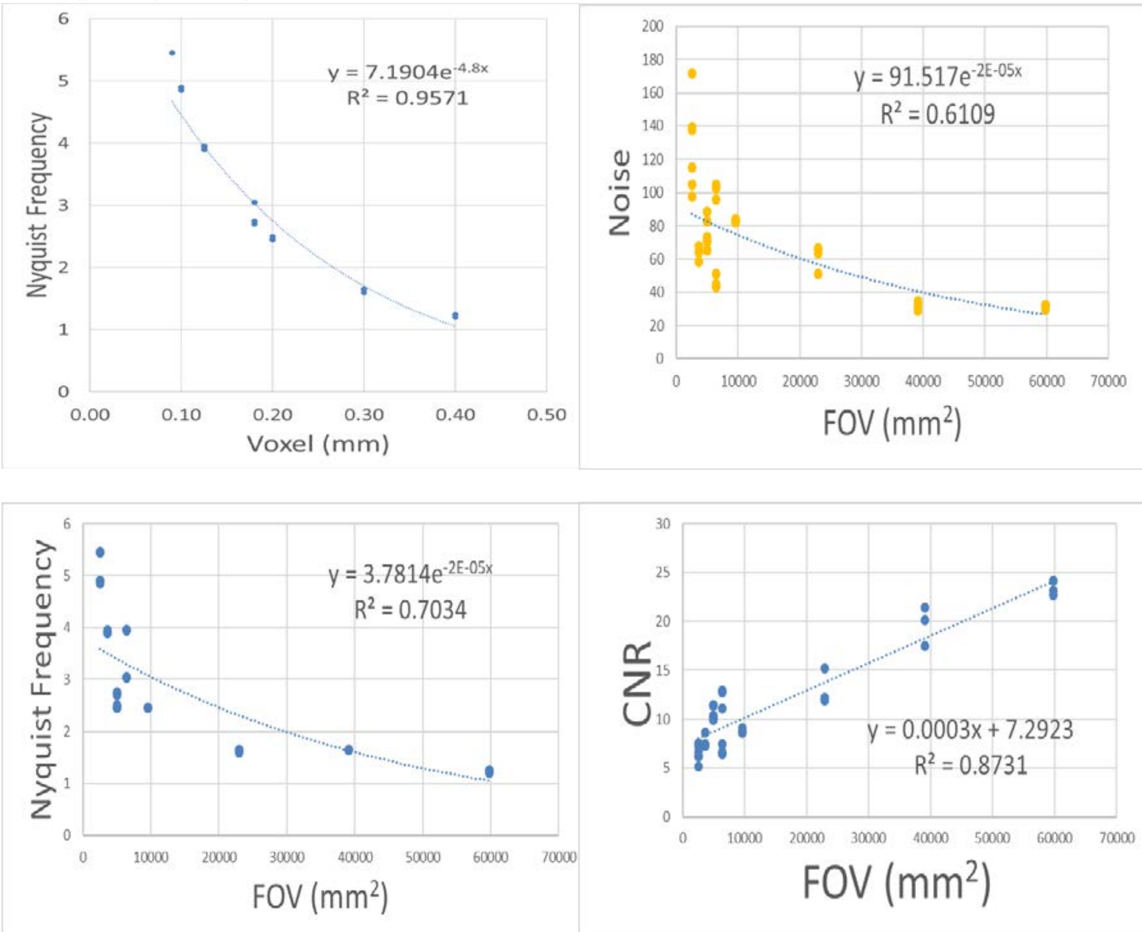


Table I – CBCT device specifications

CBCT Manufacturer	Model	Detector	FOV (mm)	Voxel (mm)	kVp	mA	s	Focal Spot (mm)	Dose Display	Scan Mode	Arc of Rotation
Carestream	CS9300	CMOS FPD	50 x 50	0.09 - 0.20	84 - 90	5 - 6.3	12.0 - 20.0	0.7	DAP	Pulsed	360
			80 x 80	0.18 - 0.20	85 - 90	4 - 5.0	8 - 12.1				
			100 x 50	0.18	90	4.0	8.0				
			100 x 100	0.18	90	4.0	8.0				
			170 x 60	0.20	90	4.0	6.3				
			170 x 110	0.25 - 0.30	90	4 - 5.0	6.4 - 11.3				
			170 x 135	0.30	85 - 90	4 - 5.0	11.30				
KavoKerr	iCAT FLX	aSi	80 x 80	0.12 - 0.40	90 - 120	3.0 - 5.0	4.8 - 26.9	0.5	DAP	Pulsed	360
			160 x 40	0.12 - 0.40	91 - 120	3.0 - 5.0	4.8 - 26.9				
			160 x 60	0.12 - 0.40	92 - 120	3.0 - 5.0	4.8 - 26.9				
			160 x 80	0.2 - 0.40	93 - 120	3.0 - 5.0	4.8 - 26.9				
			160 x 100	0.25 - 0.40	94 - 120	3.0 - 5.0	4.8 - 26.9				
			160 x 110	0.25 - 0.40	95 - 120	3.0 - 5.0	4.8 - 26.9				
			160 x 130	0.25 - 0.40	96 - 120	3.0 - 5.0	4.8 - 26.9				
			230 x 170	0.30 - 0.40	120	5.0	8.9 - 17.8				
Planmeca	ProMax 3D Max	a-Si	50 x 55	0.1 - 0.40	96	5 - 12.0	3.6 - 15.0	0.6	DAP	Pulsed	360
			100 x 55	0.15 - 0.40	96	5 - 12.0	4.3 - 15.0				
			100 x 90	0.15 - 0.40	96	5 - 12.0	4.3 - 15.0				
			130 x 55	0.20 - 0.40	96	5 - 12.0	4.3 - 12.0				
			130 x 90	0.20 - 0.40	96	5 - 12.0	4.3 - 12.0				
			130 x 130	0.20 - 0.40	96	5 - 12.0	4.3 - 12.0				
			130 x 160	0.20 - 0.40	96	5 - 12.0	4.3 - 12.0				
			230 x 160	0.20 - 0.40	96	5 - 12.0	9 - 12.0				
			230 x 260 *	0.40	96	5 - 12.0	18 - 24.0				
Morita	3D Accuitomo 80	CMOS FPD	40 x 40	0.08	90	3.0 - 6.0	9.0 - 17.5	0.5	CTDI	Continuous	180/360
			60 x 60	0.125	90	3.0 - 6.0	9.0 - 17.5				
			80 x 80	0.16	80 - 90	3.0 - 5.0	9.0 - 17.5				

a-Si = amorphous silicon, CMOS FPD = Complementary Metal-Oxide-Semiconductor Flat Panel Detector, FOV = field of view, kVp = kilovoltage peak, mA = milliampere, s = second, * Stitched volumes, DAP = Dose Area Product, CTDI = Computed Tomography Dose Index

Table 2 – CBCT exposure parameters

Size FOV*	Brand	FOV (mm)	Voxel (mm)	kVp	mA	s
Small	Carestream	50 x 50	0.090	84	5	20.00
	KAVO Kerr	80 x 80	0.120	120	5	26.90
	Planmeca	50 x 55	0.100	96	11	12.00
	Morita	60 x 60	0.125	90	5	17.50
Medium	Carestream	100 x 50	0.180	90	4	8.00
	KAVO Kerr	160 x 60	0.200	120	5	26.90
	Planmeca	100 x 55	0.200	96	11	12.00
	Morita	80 x 80	0.160	90	5	17.50
Large	Carestream	170 x 135	0.300	90	4	11.30
	KAVO Kerr	230 x 170	0.300	120	5	17.80
	Planmeca	230 x 260 *	0.400	96	11	18.00
	Morita	-----	-----	-----	-----	-----

FOV = field of view, kVp = kilovoltage peak, mA = milliampere, s = second, * Stitched volumes

Table 3 – Data summary based on FOV

FOV Size*	Model	Homogeneity	SD		Contrast	SD		Noise	SD		CNR	SD		NF	SD	
Small	CS9300	16.28	0.40	B	893.36	27.70	A	149.40	19.10	A	6.05	0.80	A	5.45	0.000	A
	iCAT FLX	25.22	0.50	B	688.89	21.50	B	101.20	4.60	B	6.82	0.50	A	3.95	0.000	C
	ProMax 3D Max	23.12	4.50	B	734.91	26.20	B	105.86	8.60	B	6.98	0.70	A	4.88	0.029	B
	3D Accuitomo 80	59.86	8.40	A	489.60	13.10	C	63.37	4.70	C	7.76	0.70	A	3.92	0.000	C
Medium	CS9300	31.26	0.80	A	849.87	25.80	A	81.45	7.70	A	10.48	0.80	AB	2.73	0.029	B
	iCAT FLX	17.31	0.30	C	730.10	13.50	B	83.11	1.10	A	8.79	0.30	B	2.45	0.000	C
	ProMax 3D Max	27.00	1.60	B	734.75	12.80	B	68.95	3.20	B	10.68	0.70	AB	2.47	0.029	C
	3D Accuitomo 80	18.17	0.30	C	567.33	6.90	C	46.53	4.10	C	12.25	1.00	A	3.05	0.000	A
Large	CS9300	73.37	1.20	A	782.98	10.20	A	60.50	8.30	A	13.11	1.80	B	1.63	0.029	A
	iCAT FLX	36.86	0.90	B	627.70	22.90	C	32.08	2.80	B	19.68	2.00	A	1.65	0.000	A
	ProMax 3D Max	62.36	12.30	A	724.70	20.70	B	31.07	1.20	B	23.34	0.70	A	1.23	0.029	B
	3D Accuitomo 80	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----

*Small FOV includes 2500-6400 mm2, Medium includes 5000-9600 mm2, Large includes 22950-59800 mm2
For each FOV size, when comparing variables the same letters are not significantly different ($p > 0.05$)

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