RESEARCH ARTICLE

An investigation into dose optimisation for imaging root canal anatomy using cone beam CT

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Objectives: To identify a dose as low as diagnostically acceptable and a threshold level of image quality for cone beam CT (CBCT) imaging root canals, using maxillary first molar (M1M) second mesiobuccal (MB2) canals of varying complexity for two CBCT scanners.

Methods: Dose–area product (DAP) and contrast-to-noise ratio (CNR) were measured for two scanners at a range of exposure parameters. Subjective-image-quality assessment at the same exposures was performed for three M1Ms of varying MB2 complexity, positioned in an anthropomorphic phantom. Nine raters (three endodontists, three dental radiologists and three junior staff) assessed canal visibility, using a 5-point confidence scale rating.

Results: Identification of simple-moderate MB2 canal complexity was achieved at a range of protocols, with DAP values of ≥ 209.3 and ≥ 203.2 mGy cm² and CNRs of 3 and 7.6 for Promax[®]3D and Accuitomo-F170[®] respectively. For complex canal anatomy, target subjective image quality was not achieved, even at the highest DAP values for both scanners. Junior staff classified significantly more images as undiagnostic compared with senior staff ($p = 0.043$).

Conclusions: In this first study to address optimisation of CBCT imaging of root canal anatomy, a similar threshold dose for both scanners was identified for M1Ms with simple-moderate MB2 canal complexity. Increasing dose to enhance visualisation of more complex canal anatomy was ineffective. Selection of standard protocols (while avoiding lower kV/mA protocols) instead of high-resolution scans was a practical means of reducing patient dose. CNR is not a transferable measure of image quality.

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Introduction

The use of cone beam CT (CBCT) in dentistry is not routinely indicated, but can be justified when conventional radiography is insufficient for the specific diagnostic task.^{1–5} Nevertheless, CBCT use is becoming increasingly prevalent in primary care, where there is potentially less supervision and a range of training and

experience among its users.⁶ CBCT can provide acceptable image quality over a wide range of exposures; therefore, a risk exists of over exposing the patients, without any diagnostically useful gain in image quality.⁷

An awareness of the need to “tailor” dose according to the specific diagnostic indication, while also considering patient type, has prompted the evolution from the dose optimisation strategy ALADA (As low as diagnostically acceptable) toward ALADAIP (As Low as Diagnostically Acceptable being Indication-oriented

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and Patient-specific).⁸ Selection criteria guidelines and general dose optimisation guidance serve to aid the practitioner in the appropriateness of CBCT exposure.^{3,9} The pertinence of employing low dose protocols has recently been highlighted,¹⁰ with protocols achieving significant dose reductions suggested in the dental disciplines of paediatric dentistry,¹¹ orthodontics,¹² tooth autotransplantation (TAT),¹³ periodontology¹⁴ and implant dentistry.¹⁵ In the process of optimisation, both the acceptable clinical level of the image quality and the radiation dose may differ according to diagnostic tasks.¹⁶ Although such studies have provided evidence to assist in optimisation efforts for particular scanner models used, there is no evidence that the objective image quality measurements can be transferred to a different manufacturer's CBCT equipment or even to different models from the same manufacturer. Thus, there is a need to identify if a threshold level of objective image quality exists for a specific diagnostic task that might be readily transferable to a different scanner, avoiding the time-consuming assessments used in this kind of research study.

Within endodontics, limited volume, high-resolution CBCT is indicated where the diagnostic yield from conventional radiography is inadequate, such as in cases of complex/atypical anatomy, resorption, perforation and complicated endodontic surgery.^{1,3,5} Complex and atypical anatomy is of particular relevance as evaluation of tooth complexity is subjective and because the success of treatment depends on location, negotiation and chemomechanical debridement of the entire root canal system prior to filling.^{17,18} Recognised differences in maxillary first molar root canal morphology exist due to the anatomic variations of the second mesiobuccal (MB2) canal.^{19,20} within which there is an inherent range of complexity.^{21,22} Of all dental applications of CBCT, endodontics is the one for which a high level of image quality is invariably recommended.³ Imaging the MB2 root canal anatomy of upper first molars represents a good clinical test of image quality needs of an endodontist. High-resolution settings are often selected in such situations, although it is essential to recognise that this is only achieved by changing exposure parameters in ways that increase patient dose, so optimisation of exposures is especially relevant to endodontic practice.

Clinically, image quality is ultimately subjective, being based on whether the diagnostic task can be achieved in the opinion of the reporting clinician. Because of inter- and intraclinician variability in assessment of radiological images, it is important to relate such subjective assessments to objective measurements of image quality, in this case CNR, with the purpose of identifying if minimally acceptable values exist for specific diagnostic tasks that could potentially aid in the process of dose optimisation.²³ Validated methods of assessing objective and subjective image quality using a SedentexCT phantom and anthropomorphic phantoms respectively have been used in the pursuit of optimizing

doses for specific diagnostic tasks^{12,14,15} but not for identification of root canal anatomy/imaging for endodontic purposes. As high-resolution protocols are currently recommended for CBCT imaging to assess root canal anatomy,³ in addition to studying the impact of altering tube voltage and tube current-exposure time product, this study planned to investigate the effect of available scanning protocols including high resolution and 180° scans on achieving this clinical task.

Therefore, the overall aim of this study was to identify a threshold level of dose for CBCT which is ALADA for adequate imaging of MB2 root canal anatomy of maxillary first molars and, additionally, to quantify the objective image quality at this threshold dose. By performing this for two scanner types, some insight into the transferability of the results would be obtained. Additional objectives included investigating the impact of anatomy complexity on establishing this threshold dose and examining the impact of operator experience on diagnostic efficacy.

Methods and materials

Sample selection and preparation

The use of extracted teeth for this study was approved by St James Hospital/Tallaght University Hospital Dublin (2019–02). Maxillary left permanent first molars were selected from a bank of extracted teeth. After extraction, the teeth were washed with water and the adherent tissue removed gently by scraping before being immersed in a 2% sodium hypochlorite solution (Milton solution, Proctor & Gamble Ireland, Dublin, Ireland) for 24 h, prior to storage in a sterile saline solution until ready to use. Included teeth were limited to maxillary permanent first molars (as identified by coronal and root anatomic-morphological appearance and dimension) of normal external anatomy, a mesiodistal crown diameter of 10 mm $\pm$ 0.2,²⁴ three mature distinct roots with closed apices, absence of root fracture, caries or resorption, a complete pulpal floor and no evidence of previous root canal treatment. 12 left maxillary molars which visually adhered to the inclusion criteria, were imaged using the ProMax® 3D Classic CBCT scanner (Planmeca, Helsinki, Finland) to confirm the inclusion characteristics and root canal morphology. From the 12 scanned teeth, 3 representative left maxillary molars of varying MB complexity were provisionally selected for microCT analysis.

MicroCT analysis

In order to analyse comprehensively the MB root canal system complexity, the three left maxillary molars were subjected to detailed analysis using microCT (μ CT 40 SCANCO Medical AG, Brüttisellen, Switzerland). MicroCT analysis was completed at 70 kVp, 114 mA, 8 W with a spatial resolution of 20 μ m. For each tooth, a microCT three-dimensional (3D) model of the root canal

Figure 1 MicroCT 3D models of the root canal systems of the three maxillary molars: (a) T6 (b) T7 (simple-moderate anatomy) and (c) T8 (complex anatomy) constructed with 3D IPO image processing language (v. 5.15, Scanco Medical, Brüttisellen, IPSwitzerland). 3D, three-dimensional.

system was constructed with 3D IPO image processing language (v. 5.15, Scanco Medical, Brüttisellen, Switzerland). The reconstructed microCT 3D models of the root canal systems and two-dimensional (2D) slices ($n = 502$ per tooth) were viewed independently by two endodontists (defined as an individual who has completed a 3-year full time training programme in endodontics) who by consensus, confirmed the teeth as maxillary first molars. In order to facilitate comparison between the three teeth, the diameter of the main trunk of the MB2 canal was measured. The maximum width of the MB2 canal in the coronal third was; T6 - 760 μm ; T7 - 710 μm ; T8 - 735 μm and the minimum diameter, which was either in the middle or apical third of the root was; T6 - 200 μm ; T7 - 145 μm ; T8 - 163 μm . Subsequently, the canal number, configuration and complexity of the MB2 canals of each of the three maxillary molars were determined and classified accordingly. Specifically, the root canal systems of three representative maxillary first molars were classified into simple, moderate and complex morphology as seen in Figure 1a–c. The “root canal system” was defined as arising from an orifice(s) in the pulp floor, continuing through the canal(s) to the apically positioned foramen (or foramina).²⁵ The maxillary molar positioned in the skull in the first molar position was named T6, (Figure 1a). The MB2 root canal system of T6 originated from one orifice in the pulpal floor, before the MB1 and MB2 canal splits 1–2 mm apical to the pulp floor in the coronal third of the root. The MB2 canal rejoined the MB1 canal in the coronal aspect of the mid-third of the root before terminating in one foramen. This is a common anatomical variation that is relatively easy to manage and was therefore classified to be of simple complexity. The maxillary first molar in the second molar position in the skull was named T7 (Figure 1b). The MB2 root canal system

of T7 originated from two orifices in the floor of the pulp chamber and terminated just short of the MB1 in the apical third of the root. T7 exhibited an added anatomical feature of an anastomosis between the MB1 and MB2 in the mid-root area and, as a result T7, was considered to be of simple to moderate complexity. The maxillary first molar occupying the third molar position in the skull was called T8 (Figure 1c). The MB root canal system of T8 exhibited three separate MB canals (MB2 and MB3 [within the MB2 complex]), with multiple connections between the MB2, MB3 canals and MB1 canal in the middle third of the root. Consequently, T8 was classified as having complex anatomy, being categorised as high difficulty with respect to diagnosis and treatment.²⁶

CBCT scanners and selected exposure parameters

Two scanners were selected to perform CBCT imaging: Accuitomo F170[®] (J. Morita, Kyoto, Japan) and ProMax[®] 3D Classic. The smallest available voxel size and field-of-view (FOV) option applicable to each scanner were selected according to the manufacturers’ guidelines for endodontic imaging. For the Accuitomo F170[®]; the FOV was 4 cm (diameter: D) x 4 cm (height: H) and 80 μm voxel size, the FOV for the ProMax[®] 3D was 5 cm (D) x 5 cm (H) with a 100 μm voxel size. There were 33 different scanning protocols for the Accuitomo F170[®]: X-ray tube operating potentials of 70, 80, 90 kV and X-ray tube current selections of 3, 5, 7 and 9 mA. These combinations were completed using a full rotation 360° at normal (17.5 s) and high resolution (30 s) settings (excluding at 9 mA, for which high resolution settings are not possible) and then again at half rotation: 180° (9 s). For the ProMax[®] 3D scanner the same X-ray tube voltages 70, 80, 90 kV were used, with X-ray tube

currents of 3.2, 5, 7.1 and 9 mA, which were the closest possible corresponding options to the Accuitomo F170® that could be selected. This resulted in 12 exposure combinations for the ProMax® 3D. Rotations of 180° and high resolution options altering time alone were not features of the ProMax® 3D scanner. These combinations represent a wide range of exposures, including those employed in clinical practice and recommended in manufacturer protocols for endodontic imaging.

Dose measurements

Dose measurements were performed on each CBCT scanner for the chosen exposure settings. Dose–area product (DAP) values (mGy cm²) were obtained using a calibrated DAP meter sensor with an active area of 7 cm (VacuDap; VacuTech Messtechnik GmbH, Dresden, Germany) positioned at the centre of the X-ray tube window; this completely intercepted the radiation field (4 × 4 cm: Accuitomo® F170 and 5 × 5 cm: ProMax® 3D) for all combinations of kV and mAs. For the Accuitomo F170®, this resulted in 33 DAP values (as exposures at 9 mA were not possible at high resolution setting) and 12 DAP values for the ProMax® 3D. To assess consistency of the units, the DAP values were repeated and recorded four times for 80 kV, 5 mA at normal and high resolution where applicable and the coefficient of variation calculated.

Image quality: objective measurement

To assess objective image quality, contrast resolution was measured using the SedentexCT IQ phantom (Leeds Test Objects, Boroughbridge, UK): 162 mm (H) x 160 mm (D) along with the corresponding polytetrafluoroethylene (PTFE) insert, consisting of five rods of PTFE of differing diameters (1, 2, 3, 4 and 5 mm) embedded in polymethylmethacrylate (PMMA). The PTFE insert was selected as being representative of dental hard tissue.^{12,14}

The insert was positioned in the upper left molar region in the phantom (as per position of experimental teeth in skull) and the remaining phantom columns in the SedentexCT IQ were filled with PMMA inserts. The dedicated dental CBCT phantom was mounted on a rigid tripod and positioned as per standard patient set-up. In total, all inserts were scanned individually at all exposure protocols for Accuitomo F170® (x33) and ProMax® 3D (x12).

Calculating CNR

The resulting 45 data sets from the PTFE insert scans were individually exported as DICOM files into Image J software v. 145 s (National Institute of Health, Bethesda, MD). Axial images were analysed at a 16-bit scale. On these images, a circular region of interest (12 mm²) was drawn on the 5 mm diameter rod of the PTFE insert and another in the background PMMA thereby enabling pixel value calculation of each material. Beginning at the centre of the 5 mm rod and moving upwards (to

avoid possible interference in pixel values created by the air gap between the test insert and the blank PMMA) measurements were performed on five consecutive axial images. For each scanning protocol, the mean and standard deviation of the pixel values from the five slices were recorded for the PTFE rod and background material and CNR calculated using the formula:

$$CNR = \frac{(MPV_{insert} - MPV_{background})}{\sqrt{(standard\ deviation_{insert} + standard\ deviation_{background})/2}}$$

Image quality: subjective measurement

The three selected left maxillary molars were mounted in a dried adult skull (obtained from the Anatomy Department of Trinity College Dublin) from which the existing molars had been carefully extracted by sectioning the roots to avoid damage to surrounding bone. Mounting of the three teeth selected for the study involved careful osteoplasty of the alveolar bone using a stainless steel rosehead bur in a slow-speed handpiece to acquire a best possible fit, prioritising an optimal position of the buccal roots. The three study teeth were maintained in place with a radiolucent modelling wax. The skull and implanted teeth were positioned in a head-shaped polystyrene container, specifically designed to house the skull along with upper cervical spine vertebrae (C1–C4) and immersed in water to simulate soft tissue density. This anthropomorphic phantom was the same as that used in previous studies,^{12,27} designed to replicate the clinical scenario as closely as possible, with the skull and cervical vertebrae being soaked in water for 48 h before imaging to ensure water had displaced air from all trabecular spaces.

The container design facilitated fixation to a tripod stand and allowed positioning as for a patient set-up with initial scout images confirming centering of the FOV on the upper left molar region. The phantom was then exposed to all 33 scanning protocols as described for the Accuitomo F170® scanner, this being completed in one session ensuring imaging consistency. This same protocol was repeated for all 12 scanning combinations described for the ProMax® 3D scanner.

Image evaluation

Including both scanners, there were 45 CBCT data sets available for observation. An additional nine datasets (20%) were randomly selected and duplicated within the study sample to assess intraobserver variability, the observer being blinded to the duplicates. The resulting 54 data sets were randomised (via a downloaded internet programme <https://app.studyrandomizer.com/>); volume acquisition parameters anonymised and each allocated a number 1–54.

Images were viewed with the viewing software provided by the manufacturer; Accuitomo datasets using i-Dixel One Volume Viewer software (Morita, Japan) and the ProMax data sets viewed using Planmeca Romexis software (Helsinki, Finland). Evaluation of all

Figure 2 ProMax® 3D dataset (viewed with Romexis software) of the three implanted maxillary molars which were evaluated in all three orthogonal planes to identify the presence and extent of the MB2 canal at the exposure parameters of that image set (80 kV, 5 mA). 3D, three-dimensional. MB2, second mesiobuccal.

the images was facilitated using a new Acer V176LBMD 17" HD Ready Monitor (Acer UK, London), with luminance of 250 cd/m², dynamic contrast ratio of 100,000,000:1 and resolution of 1280 × 1024 pixels. The technical specifications of the monitor are within the range indicated by the Health Protection Agency as required for diagnostic purposes of dental CBCT images (Health Protection Agency, 2010). Evaluation of the monitor using a test pattern [Society of Motion Picture and Television Engineers test pattern (SMPTE)] was carried out to determine that each distinct greyscale levels and all of the bars on each of the resolution test patterns could be individually resolved.

Subjective evaluation of image quality was performed by nine observers, consisting of six senior hospital dentists (three dental and maxillofacial radiologists and three endodontists) and three junior hospital dentists (dentist with ≤2 years post qualification). The observers were informed that the purpose of the study was to evaluate the effect of differing acquisition parameters on identification of MB2 canal anatomy in maxillary first molars. All observers had exposure to CBCT image

interpretation and software. Nonetheless, due to their differing skill sets, range of CBCT interpretation experience and familiarity with the two viewing software systems utilised in the study, a standardised interactive tutorial was given by one of the researchers (MM) prior to the observation and reinforced with a printed document. Viewing conditions for all observers were consistent. Ambient room lighting was recorded using an illuminance meter and ensured that this was less than 50 lux. Observers were able to adjust contrast and brightness as required and to rotate and tilt the volumetric data using the three orthogonal reconstructions, a screenshot from one of the data sets can be seen in Figure 2. No time restriction was placed on the period of observation.

Each observer completed a 7-part questionnaire, which they answered using a 5-point rating scale of agreement for each of the 3 maxillary first molars for all 54 scans, circling the number which corresponded to their answer (Table 1). Questions (Qs) 1–4 related to the presence of the MB2 canal at the pulp floor, in the coronal third, middle third and apical third of the

Table 1 Summary form of questionnaire, with a rating scale to reflect the confidence the observers had in their response

Can you identify a separate second mesiobuccal canal (MB2) in the root anatomy for each maxillary first molar:	0 = No - Complete Confidence
Q1- At level of pulp floor?	1 = No - Partial Confidence
Q2- Within coronal third?	2 = Unsure
Q3- Within mid-third?	3 = Yes - Partial Confidence
Q4- Within apical-third?	4 = Yes - Complete Confidence
Q5- If identified, is the MB2 canal continuously visible from its perceived origins coronally to its termination?	
Q6- Are you confident that this volume is diagnostically acceptable?	
Q7- For each volume 1–54, can you trace over the microCT depiction of the MB2 canal anatomy that you can definitively identify from the image set for the first molar teeth in positions UL6, UL7, UL8 with the provided red pen.	

MB2, second mesiobuccal.

tooth, but did not address continuity of the canal, which was considered in Q5. Q6 related to the confidence the observer had in the acceptability of the image quality of the scan. While Q5 dealt with canal continuity using a confidence scale, a final required task (Q7) involved a quantitative assessment of canal visibility. This involved tracing the extent of the MB2 canal that they could definitively identify for each of the three teeth, using the microCT images of the molar anatomy as a template. These tracings of the anatomy were then measured using a calibrated acetate overlay and the percentage of the MB2 anatomy identified (recorded as a percentage of the total length identified on microCT) and assigned to each of the three maxillary molars per volume. To assess repeatability of this measurement technique, five randomly chosen data sets were selected to repeat the measurements.

The observers had been familiarised with the questionnaire as part of the instruction tutorial. The questionnaire was piloted by 2 endodontists and 2 junior hospital dentists who evaluated 10 randomly chosen data sets and their feedback on the instructions and questionnaire was used to refine the final documents.

Data analysis

Diagnostic acceptability (Q6) responses for each of the 45 data sets (excluding repeats) were examined and if the percentage of observers recording a scan as diagnostically acceptable (*i.e.* agreed or strongly agreed options) fell below 67% (*i.e.* 6 out of 9 observers), it was considered a negative result and was excluded from further analysis.

Assessment of pilot study results identified target levels for specific subjective imaging tasks: identification of the percentage of MB2 root canal identifiable and secondly for both confidence in the presence of the canal at the different levels of the root (Qs 1–4, Table 1) and identification of canal continuity (Q5, Table 1).

On analysis of percentage of MB2 root canal anatomy identified by each observer for each of the three maxillary first molars at every diagnostic exposure protocol in the pilot study, a target subjective image task was provisionally set as identifying 95% of the MB2 canal anatomy. This task included identification of the canal at the level of the pulp chamber floor and the coronal third of the MB root, which by consensus was deemed most relevant from an endodontist’s perspective.

Employing the confidence scale ratings from questionnaires for diagnostic exposure protocols from the pilot study, the median of the observers’ confidence scale rating (CSR) responses for the identification of the MB2 canal for Q’s 1–4 at the level of the pulpal floor and in the coronal, middle and apical thirds of the root were identified for each of T6, T7 and T8. Similarly, the median CSR responses related to Q5: identification of a continuous MB2 canal from perceived origin to termination, were established. Using these data, a second target subjective image task of achieving median CSRs

of 3.5 was set from the pilot study. This corresponded to 95% MB2 canal anatomy identification, achieving close to complete confidence in identifying the MB2 canal in all thirds of the root canal and identifying the MB2 canal continuously from origin to its termination.

These combined subjective image tasks were used to indicate the CNR values necessary to achieve the diagnostic task of root canal identification and from which the corresponding threshold exposure factors and DAP values could be identified.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics (v. 24.0; IBM Corporation, NY). Intra and interobserver agreement for subjective image quality assessment was calculated using Cohen’s κ test (K) using the scale for strength of agreement described by Altman; $K < 0.20$: poor, $K = 0.21–0.40$: fair, $K = 0.41–0.60$: moderate, $K = 0.61–0.80$: good, $K = 0.81–1.00$: very good.²⁸ Intraobserver agreement was calculated for each of the observers by considering their responses for Q’s 1–5 (identification of root canal anatomy) in the questionnaire and also separately for Q6 (diagnostic acceptability of the data sets). To facilitate the analysis, the responses to the six questions were dichotomised, with values 4 and 5 considered as a positive result while 1, 2 and 3 were considered as negative result.^{12,29} Interobserver agreement was evaluated for Q’s 1–6 separately. The proportion of acceptable/unacceptable images identified by the junior hospital dentists and senior hospital dentists (endodontists and radiologists) was calculated. Contingency tables and a χ^2 test was used to determine statistical significance of the difference in proportions of these two groups with statistical significance set at $p < 0.05$.

Results

Dose measurements

DAP values for the ProMax® 3D Classic (Table 2a) and Accuitomo F170® (Table 2b), demonstrate expected variations according to exposure settings. DAP value reproducibility for the ProMax® 3D scanner, based on four measurements at 80 kV and 5 mA resulted in a standard deviation (SD) of ± 0.96 mGy cm². For the Accuitomo F170®, reproducibility at 80kV and 5 mA

Table 2a For ProMax® 3D:

DAP values				
Tube current		Tube voltage (kV)		
mA	mAs	70	80	90
3.2	38.4	49.5	90.3	135.3
5	60	77.1	139.4	209.3
7.1	85.2	107.6	195	294
9	108	134.4	244.6	373.3

DAP, Dose–area product.

Table 2b Accutomo F170®: DAP values and associated exposure protocols of datasets that observer assessment identified as being:

DAP values												
Tube current				Tube voltage (kV)								
mA	mAs			70			80			90		
	180°	S	HR	180°	S	HR	180°	S	HR	180°	S	HR
3	27	52.5	92.4	54.3	106.4	187.5	72.3	143.8	251.2	90.5	181.7	316.8
5	45	87.5	154	88.5	174.9	306.7	118.0	233.9	409.5	147.1	294	517.5
7	63	122.5	215.6	120.9	240.7	426.3	163.2	324.4	568.9	203.2	405.1	714.4
9	81	157.5	277.2	154.6	304.6	N/A	207.9	410.5	N/A	257.6	520.2	N/A

Undiagnostic: ■

Diagnostic: ■

Diagnostic and achieving 'combined target subjective image tasks':

DAP, dose–area product.

for both standard and high resolution settings had a resulting SD ± 1.07 and ± 1.39 mGy cm² respectively.

Image quality: Objective measurement

Figure 3a and b relate CNR values to DAP values for the ProMax® 3D and Accutomo F170® respectively. This approximates to a second-order polynomial relationship. Figure 3b demonstrates that high resolution settings achieve comparatively lower CNR values than the standard and 180° scans for the Accutomo F170®

at equivalent DAP. CNR values are notably lower for the ProMax® 3D compared with the Accutomo F170® at equivalent kV and mA protocols (Figure 3a and b).

Image quality: subjective measurement

κ values for intraobserver agreement are detailed in Table 3. Junior hospital dentists demonstrated fair–moderate strength of agreement ($\kappa = 0.31$ – 0.56), while senior hospital dentists (radiologists and endodontists) exhibited good–very good strength of agreement ($\kappa = 0.65$ – 1) for questions relating to identification of root canal anatomy and continuity of the canal (Q1–5) as well as the diagnostic acceptability of the data sets (Q6). Interobserver agreement for questions relating to root canal anatomy identification (Q2–5) and diagnostic acceptability (Q6) ranged from moderate to good ($\kappa = 0.45$ – 0.58). Levels of agreement were only fair for Q1: identification of the MB2 canal at the level of the pulp chamber floor ($\kappa = 0.27$).

The proportion of data sets judged as being of acceptable/unacceptable image quality (Q6) by the radiologist and endodontists were similar, being 84%/16% and 81%/19% respectively, but differed from the judgments of junior hospital dentists; 67%/33%. Using the χ^2 test, a significant difference was identified ($p = 0.043$) with junior staff classifying significantly more images as undiagnostic compared with senior staff.

Tables 2a and 2b shows the results of the subjective image quality assessments for ProMax® 3D and Accutomo F170® respectively at each exposure protocol and corresponding DAP value. Four scans taken using the ProMax® 3D and four using Accutomo F170® were categorised as undiagnostic and excluded from further analysis.

On analysing the percentage of MB2 root canal anatomy identified by each observer for the 37 diagnostic data sets, for simple–moderately complex anatomy, senior staff consistently identified a marginally increased percentage (0–7.2%) of MB2 root canal anatomy than junior staff; the difference was not evident at the highest DAP values for both scanners (Supplementary Table 1). This trend between junior and senior staff was repeated for complex anatomy, but with

Figure 3 CNR values plotted against DAP values for (a) ProMax® 3D and (b) Accutomo F170®. Additionally, the DAP values corresponding to the CNR value necessary to achieve the combined subjective image tasks for root canal identification are highlighted. CNR, contrast-to-noise ratio; DAP, dose–area product.

Table 3 Intraobserver agreement of the nine observers (END = Endodontist, RAD = Radiologist, JHD = Junior hospital dentist) for Q's 1–5 (root canal anatomy identification and continuity) and Q6 (diagnostic acceptability), measured using κ.

Table with 10 columns: Observer code, END1, END2, END3, RAD1, RAD2, RAD3, JHD1, JHD2, JHD3. It contains kappa values for Q's 1-5 and Q6 for three observer groups: END, RAD, and JHD.

END, Endodontist; JHD, Junior hospital dentist; RAD, Radiologist.

margin of difference increasing (1.9–18.1%); however, for complex anatomy, increasing the DAP values did not reduce the differences between junior and senior staff in the percentage of canal identified. Agreement within both groups was greatly reduced for complex anatomy, as reflected by their greatly increased standard deviation values.

Repeatability assessment of the recording of the percentage of canal identified using the 5 repeat volumes (15 teeth) demonstrated that while 10 teeth showed no

difference from the original recording, 5 teeth exhibited a small variation ranging from 1 to 1.7%.

CNR values necessary to achieve diagnostic task of root canal identification

Figure 4a and b highlights that the percentage of MB2 canal anatomy identified increased along with CNR values. The target subjective image task of identifying ≥95% of the MB2 canal anatomy corresponded to a CNR of 3 for simple to moderate anatomy (T6, T7) for the ProMax® 3D and a markedly different CNR of 7.6 for the Accutomo F170® scanner. The target subjective image task was not achieved at any DAP value for complex anatomy (T8).

The second subjective task of achieving median CSR's ≥ 3.5 for Q's 1–4 and Q5 were related to CNR for both scanners and are depicted in Figure 5a–d. With the ProMax® 3D scanner; for simple-moderate anatomy, achieving median CSR responses of ≥3.5 occurred at a CNR of 3 for both identifying the MB2 canal in all thirds of root canal anatomy (Q's 1–4) and for identifying it as continuous from perceived origin to termination (Q5) and at 3.6 and 3.7 respectively for complex anatomy (Figure 5a and b). For the Accutomo F170® scanner, median CSR responses of ≥3.5 for both tasks Q1-4 and Q5 for simple-moderate anatomy corresponded to a CNR value of 7.5 and 7.3 respectively and at 8.5 and 11.3 values for complex anatomy (Figure 5c and d).

Identifying DAP and exposure protocols that correspond to threshold CNR values

As shown in Figure 3a and b, the DAP values necessary to achieve the combined subjective image tasks for simple-moderate MB root canal complexity (T6, T7), were 209.3 and 203.2 mGy cm² for Promax® 3D and Accutomo F170® scanners respectively. For complex anatomy (T8), this subjective image task was not achieved, even at the highest DAP values for both scanners.

For maxillary first molars exhibiting simple-moderate root canal complexity, Table 2a, b summarise the exposure protocols and resultant DAP values that were considered undiagnostic, diagnostic and those which were at or above the “threshold dose” to achieve the combined “target subjective image quality tasks.” For the ProMax® 3D the threshold dose (≥209.3 mGy cm²), included 90 kV protocols of 5 mA and above and one 80 kV/9 mA protocol (Table 2a). For the Accutomo F170®, the threshold dose (≥203.2 mGy cm²) was achieved for

Figure 4 Mean percentage of MB2 canal anatomy identified by all observers related to CNR values, calculated for each exposure protocol judged as diagnostically acceptable for (a) ProMax® 3D and (b) Accutomo F170®. Regarding simple-moderate anatomy, a CNR of ≥3 and ≥7.6 were necessary to achieve the subjective task (i.e. identifying ≥95% MB2 canal anatomy) for the ProMax® 3D and Accutomo F170® respectively. CNR, contrast-to-noise ratio; MB2, second mesiobuccal.

Figure 5 Median of the observer CSRs related to CNR for Qs 1–4 (a) and Q5 (b) for ProMax® 3D and Q1-4 (c) and Q5 (d) for Accuitomo F170®. Regarding simple-moderate anatomy, achievement of the second subjective task (median CSRs of ≥ 3.5) was possible at a CNR of 3 for the ProMax® 3D for both Qs 1–4 and Q5 and 7.5 and 7.3 respectively for the Accuitomo F170®. Shaded areas outlined in (c, d) highlight the trend of markedly lower median CSRs scored with complex anatomy compared to simple-moderate anatomy. CNR, contrast-to-noise ratio; CSR, confidence scale rating.

a range of protocols (Table 2b). Only three 180° scan protocol at the higher range of the kV and mA protocols were identified as achieving these combined “target subjective image quality tasks.” Conversely, all high resolution Accuitomo F170® scans reached this level of subjective image quality, except at the lowest kV and mA experimental selection. These tables do not include complex anatomy (T8) as the combined subjective task was not achieved at any experimental DAP value.

Discussion

This purpose of this study was to ascertain whether a threshold level of image quality, and hence an optimised dose level, could be established for the accurate identification of root canal anatomy using CBCT imaging, a diagnostic task which is believed to necessitate high image detail and an associated increase in patient dose compared with less demanding diagnostic tasks.^{30,31} By measuring DAP values at a range of exposure protocols and carrying out parallel subjective and objective image quality assessments, it was anticipated that the impact of varying exposure settings could lead to the identification of a threshold dose and CNR value as well as identification of a practical strategy for the reduction and optimisation of radiographic exposures within endodontics. Furthermore, by carrying out the investigations using two commercial CBCT scanners, an analysis

of whether the threshold level of objective image quality for this specific diagnostic task could be transferred to a different scanner was carried out. Protocols achieving significant dose reductions for specific dental diagnostic tasks have been established,^{11–15} involving dose measurement, objective and subjective assessment, but not in an endodontic context and none of these has investigated the transferability of objective image quality measurements between scanners. Additionally, this study also examined the impact of anatomy complexity on establishing a threshold dose for this diagnostic task and the effect of operator experience on diagnostic efficacy. One previous study has investigated the relationship between objective and subjective image quality and the potential for transferability of findings between different CBCT scanners, recording observer findings of various anatomical features in a human skull phantom. These included “pulp canal” assessments, but were in the form of a general overview of all teeth in a skull phantom rather than a detailed endodontic assessment. They did not find evidence that minimally acceptable image quality values were applicable to multiple CBCT models, but did not specifically consider the root canal visualisation, focusing on implant planning, root pathology and sinus pathology.

CBCT imaging of root canal systems prior to endodontic management is indicated in cases in which anatomically challenging morphology is predicted and

for which a combination of conventional radiography and potential clinical investigation with a dental operating microscope cannot indicate the orifice, portals of exit or extent/continuity of the canal.⁵ Identification and negotiation of more complex anatomy is important, as failure to locate anatomy reduces chemomechanical debridement and results in excessive dentine removal, which can lead to potential clinical complications including root fracture and perforation,³² as well as an increased risk of root canal treatment failure and possible tooth loss.³³ The mesiobuccal root of a maxillary first molar is recognised as having the most predictably complex root canal anatomy in adult teeth^{17,18} and therefore was used within the current study as a “model” to investigate the effect of reducing dose on the diagnostic task of root canal identification in teeth with a range of root complexities.

The need for dose reduction strategies within the discipline of endodontics and specifically canal anatomy identification is particularly pertinent. While it is difficult to currently ascertain the incidence of CBCT use for this indication, it appears that routine endodontic preoperative CBCT scans of teeth are being suggested for a more accurate assessment of root canal anatomy³⁴ which is not in keeping with current guidelines on dental CBCT imaging.³

This diagnostic task-based study ultimately relied on subjective analysis of the CBCT images. In order to reproduce the clinical situation as accurately as possible, the skull and cervical spine set up was used to replicate the normal attenuation and scatter by a human head.²⁷ However, like other optimisation studies in the literature,^{11–15} it does not replicate the impact of patient movement on image quality, which can be particularly pertinent for high resolution settings with extended scan times.³⁵ Similarly, in this study the first molar and adjacent teeth had not been restored with metal restorations and were not previously root canal treated, which can both produce artefacts throughout the FOV that can negatively impact on image quality and thus on canal visualisation.^{36,37}

Assessing the impact of differing exposure protocols on root canal anatomy identification necessitated selection of maxillary first molars with differing root canal anatomies, reflecting a spectrum of both complexity and difficulty with respect to diagnosis and treatment. To exclude the impact of MB2 canal width, it was ensured that all MB2 canals exceeded 100 μm at their narrowest point, this figure was extrapolated from the literature on CBCT detection of vertical fractures,^{38,39} which has shown that defects above a minimum width of $\geq 100 \mu\text{m}$ could be predictably appreciated and diagnosed with CBCT imaging.

Anatomical variations in the MB root canal system vary in both incidence and complexity,^{20,22} with recognised variations considered in this study encompassing additional, accessory and connecting canals, anastomoses and canal divisions. The three selected

molars in this study all displayed a MB2 canal, but with variations in origin, length, anastomoses, divisions and as a result, complexity of the MB2 canal. T6 was classed as having simple anatomy as this canal variation (Type II Vertucci) is the most common in the MB root.⁴⁰ T7 was classed as representing a simple-moderate complexity, being Type II Vertucci, with an incidence of 25–45%,^{22,41} but with an added anastomosis between MB1 and MB2, which is reported to occur in 2.9% of cases.²² Although these anastomoses cannot be instrumented, their visualisation is relevant to alert the clinician regarding potential reservoirs of bacteria and need for enhanced irrigation. T8, possessing several variations and classified as complex (a variation of Type VIII Vertucci), has a reported incidence of 1.3% and 0.2–12%.^{42,43} Obviously the selected sample of MB2 root anatomical configurations is not exhaustive; however, in combination with two CBCT scanners and range of exposure protocols it was not considered feasible to include a greater selection of teeth, not least because of observer time commitment requirements.

No validated tool for subjective assessment of root canal identification at a range of exposure protocols exists; the development of the 7-part questionnaire and subsequent assessment of the results took into account methodology from other previously published studies reporting on the measurement of image quality in diagnostic radiology.^{12,14,44} This design approach was used in conjunction with a discussion amongst the researchers and the pilot study results. Use of a 5-point rating scale for observer assessments is a validated tool for assessing image quality in diagnostic radiology. This scale permits the observers to have a wider scope in which to record their answer, rather than being limited only to a positive/negative response, an approach utilised/validated in other subjective image quality studies.^{12,29} This facilitates assessment of the degree of certainty and uncertainty and the option of being unsure to be reflected in elements of the analysis (median CSR responses). Additionally, dichotomisation of the data was necessary for other aspects (identification of diagnostic/undiagnostic data) with 0, 1, 2 responses being classified as a negative response and 3, 4 as a positive response. Unsure (=2) was noted as a negative response leaving just two positive options (=3, 4) ensuring that a positive response was documented only when the observer recorded as such.

Nine observers (three radiologists, three endodontists and three junior hospital dentists) were enlisted to perform subjective image quality assessments under standardised conditions in order to reflect the varying experience and skill set of a range of operators, who would realistically be carrying out this diagnostic task in primary/tertiary clinical/referral practice. Although, the number of observers was in keeping with other image quality assessment studies, there is no clear guidance on how many observers are needed in imaging studies.⁴⁵ Larger numbers of observers would reduce the impact

of subjectivity; however, recruiting greater number of observers was not possible.

Identifying a “target subjective image task” involved analysing the endodontists opinion of the volume of root canal identification necessary to fulfil the diagnostic task, balanced with clinical relevance. A consensus of opinion between the three endodontists established that the position of the MB2 orifice relative to the floor of the pulp chamber was particularly important, as this would dictate the volume of dentine required to be removed prior to potential canal location. Additionally, whether the canal was readily visible in the coronal third of the root was also clinically relevant, as it would be unlikely that the operator would search for a canal beyond the coronal third of the root, due to the potential complication of perforation and weakening of the root structure.³² Percentage of root canal identified was assessed from tracing over the microCT “truth” and not from being asked to simply draw that part of the MB2 canal that they could definitively identify. It is of course possible that the availability of the “diagnostic truth” might have led to higher proportions of root canal length by observers than were genuinely seen by them, but the strategy was considered to be the only practicable way forward.

After analysis of the pilot study results and discussion with three “study” endodontists, a provisional figure of 95% of the MB2 canal identified was chosen as a “target subjective image task.” It was observed from the pilot study data that when the observers identified $\geq 95\%$ canal anatomy, that the MB2 canal was also always successfully identified at the level of the pulp floor and in the coronal third of the MB root, these two objectives being deemed by endodontists to be particularly clinically relevant to this diagnostic task. The target subjective image task of 95% was reassessed after analysis of the completed study results and it was identified that this same pattern was evident. Similarly, analysis of the pilot study results also elicited a further subjective image target of achieving median CSRs ≥ 3.5 (questionnaire scale 0–4), which reflected the observer’s confidence in continuously identifying the canal in all thirds of the tooth and was established with 95% canal identification as the combined “target subjective image tasks.”

Randomly selecting and randomly repeating 20% of data sets within the study sample was used as the method to assess intraobserver reliability, resulting in 54 of data sets (including duplicates). It could be argued that a means of reducing recall bias further would be to include a greater number of teeth but this would have increased the number of datasets and time required from observers to an impractical level. For the three junior hospital dentists, although statistically significantly lower than those of the specialists, intraobserver reliability was still classifiable as “moderate” for all questions except for one observer for the question (relating to overall image quality, not specific to root canal visualisation), which was only “fair.” It might be

argued that the lower intra observer reliability of the junior clinicians was not sufficient for a research study. Their inclusion was, however, considered worthwhile in being representative of the real world, in which use of CBCT is not limited to specialists.

Although pairwise comparison of observer results for questions relating to root canal identification and diagnostic acceptability (Q’s 2–5 and 6) revealed moderate to good interobserver agreement, agreement was only ‘fair’ for identification of the MB2 canal at the level of the pulp chamber floor (Q1). Differing perceptions as to whether this referred to a common orifice for MB and MB2 or a separate orifice for MB2 could potentially explain this as would observer perception of the pulpal floor.

Undiagnostic scans were removed prior to analysis, being identified as those scans which at least six out of the nine observers did not record as diagnostic (67%). This was keeping with majority based image quality acceptance that been utilised in optimisation studies.¹² The percentage of scans identified as undiagnostic by junior hospital dentists was significantly greater than that by the senior hospital staff ($p = 0.043$). This is likely to be due to the influence of experience and training that radiologists and endodontists possess with regard to diagnostic skills compared with recently qualified graduates. Notably, it has been suggested that the inexperienced operator is also more likely to request a CBCT scan,⁴⁶ highlighting less confidence with diagnostic skills in general and perhaps a familiarity and reliance on new technologies.

DAP was used to establish dose of each of the scanning protocols for both scanners; it is practically easy to achieve, relates relatively well to effective dose and has been recommended for establishing diagnostic reference levels (DRL’s).³ It is understood that DAP has the potential limitation of being over or underestimated⁴⁷; nonetheless, DAP is still advocated and utilised for comparing dose between machines and assessing dose reduction strategies.^{14,15,47}

A range of physical phantoms has been employed to facilitate dental CBCT objective image quality assessment.^{48–50} The SedentexCT phantom was used in the current study, as it was designed specifically for dental CBCT and is successful in assessing basic image quality parameters.^{51,52} The SedentexCT phantom is the size of an adult human head and is constructed from PMMA on the basis that this material simulates the average attenuation of the soft tissues of the human head, taking into account that there are also high attenuation structures (*e.g.* mandibular cortical bone and tooth enamel) in addition to the low attenuating contribution of air cavities (sinuses and oral cavity); this is reported to result in detector photon fluences similar to the human head.^{51,53} Therefore, the objective image parameters measured using the selected inserts can be related to the scanners’ clinical performance.

CNR is an objective measure of technical image quality and an effective means of assessing performance and constancy of a CBCT device.⁵¹ CNR can be easily interpreted and has been widely used to assess the impact of tube voltage and tube current-exposure time product on image quality and therefore is considered an appropriate tool in optimisation strategies.^{12,54–56} CNR was assessed using a PTFE insert (this particular insert approximating bone density), with previous related clinical diagnostic studies confirming that the PTFE insert generated CNR values which had a significant relationship with bone tissue.^{12,14} While other software exists for evaluation of physical parameters on IQ phantoms for dental CBCT, Image J was employed in this study as it is readily accessible and its effectiveness has been validated in several similar studies.^{12,14,51,53}

The results demonstrated that CNR increased with increasing DAP and hence with tube voltage and tube current (Figure 3b). Differences in CNR have been identified as largely influenced by the noise element of the equation.^{23, 58} Increasing mAs decreases the image noise by increasing signal at the detector but, since the beam penetration remains the same, contrast is unaffected. Higher kV values increase the detector signal due to the increased photon count and energy, resulting in a proportional fall in photoelectric effects and an increase in Compton scatter. In 2D radiography, reducing tube voltage within diagnostic range leads to an increased difference in attenuation between tissues of varying density and therefore increased image contrast, the opposite being the case when tube voltage is increased. In contrast, with CBCT imaging, the pure signal that reaches the detector does not solely determine contrast due to the additional information from the projectional data at many angles. Therefore, for CBCT imaging in this otherwise fixed scanning set up, contrast over the range of exposures exhibited relatively little variation (as could be identified from the pixel/grey value data) whereas noise varied with exposure protocol (as identified from the SD of grey values consistently decreasing with increased tube voltage and tube current) causing noise to be the major contributor to CNR.

When compared to standard protocols, 180° scans resulted in CNR values at the lower end of the range (Figure 3b), this being related to decreased basis images and a concomitant increase in noise. For each kV and mA protocol, high resolution setting selection delivered CNR values only marginally greater than 180° scans and markedly lower than standard protocols. Moreover, when considering equivalent DAP, CNR values of high resolution settings were distinctly lower than both standard and 180° protocols. This can be attributed to the fact at high resolution setting the pixel array changes from a 2×2 array (*i.e.* four for standard setting) to an individual pixel (*i.e.* one for high resolution setting), thereby reducing the signal by one quarter, increasing noise and resulting in a decreased CNR values. Additionally, the small FOV (4×4 cm) reduces photon

fluence further, allowing noise to dominate. Accuitomo F170® CNR values for standard protocols were considerably higher than for the equivalent protocols using the ProMax® 3D scanner. This may be related to the differing voxel size and/or differing technologies, *e.g.* detector efficiency

The evaluation of clinical image quality by observers is unavoidably subjective, as can be seen from interobserver agreement levels, whereas physical parameters can largely be measured in a reliable and repeatable manner; however, there is no direct way of translating these physical parameters to clinical image quality. This study defined a combination of subjective image tasks for the diagnostic task of root canal identification and identified the objective image quality, in this case CNR, that achieved these tasks for two different scanners. Regarding the ProMax® 3D, achieving all components of the combined “target subjective image task” elicited identical CNR values (3) and similar CNR values for the Accuitomo F170® (7.3, 7.5, 7.6), this being for maxillary first molars exhibiting simple-moderate root canal complexity. This indicates that for the same scanner, these clinically relevant and necessary tasks to achieve root canal identification all demanded the same or similar CNR level, indicating that CNR is a relevant measure of objective image quality in the task of canal identification. For both CBCT models, on relating CNR to the subjective measurements of image quality, similar patterns of improved subjective image quality with increased CNR were evidenced in the scatter plots (Figures 4a, b and 5a–d), albeit the relationship between CSRs and CNR for the Accuitomo F170 was less clear cut/evident (Figure 5c–d). However, it has to be concluded that in this study the CNR values identified to achieve the diagnostic task were not the same, or even similar, for the two CBCT models and therefore indicates that a reference CNR value for this diagnostic task cannot be applied between CBCT models. This can likely be attributed to differing technologies such as tube filtration, detector efficiency, FOV, filtering or voxel size of both scanners. Relating CNR alone to subjective image quality has some limitations in that it does not account for spatial resolution and, as can be seen from Figure 4b, focusing on the complex anatomy, there is a pattern of lower CNR high resolution scans achieving similar levels of canal identification to CNR standard protocols, which perhaps may be attributable to enhanced spatial resolution of these high resolution protocols. Therefore, in agreement with other studies, the relationship between objective measurements of image quality (in this case CNR) and subjective image quality is complex, with it being difficult to definitively relate one to the other in order to devise optimisation strategies.^{11,12,14,57,58}

For maxillary first molars exhibiting simple-moderate root canal complexity, the threshold DAP values necessary to achieve the combined subjective image tasks were similar for both scanners (209.3 and 203.2 mGy

cm² for Promax® 3D and Accuitomo F170® scanners respectively) and lower than the recently published National Diagnostic Reference Level (NDRL) for adult CBCT (based on maxillary molar preoperative implant assessment) in the UK of 265mGy cm²⁵⁹ and much lower than the Finnish NDRL (specifically for CBCT examination aimed at assessment of tooth's periapical region and root canal morphology) of 550 mGy.cm².⁶⁰ This study suggests that there is scope for optimisation of patient dose in CBCT used in endodontic practice. Nonetheless, it is recognised that these study data are not clinical data and exclude the impact of movement and restoration artefact and that clinical studies would still be required. Furthermore, Table 2b highlights that standard protocols, except at the lower mA settings, achieved the diagnostic task while avoiding large DAP values that can be associated with high resolution scans.

The tables do not include complex anatomy (T8), as the target of 95% canal identification was not achieved at any experimental DAP value. This study suggests that factors other than diameter of a structure can impact on its visibility on CBCT scans. Rotating the 3D reconstructions of the MB2 canals of the selected molars, identified T8 as exhibiting the most curved MB2 canal structure, resulting in the canal “weaving in and out” of a coronal and sagittal slices and altering position in axial slices. These features were complicated further by the presence of isthmuses and reduced observer ability to confidently identify its path. It could be concluded that in perceived complex cases, as judged from clinical perception or preoperative 2D radiography, increasing kV and mAs and resultant patient dose [maximum experimental DAP values achieving canal identification of 65% (ProMax® 3D) and 77% (Accuitomo F170®)] could not be justified on the basis that it seemed probable that there was no likelihood of potentially improving diagnostic or clinical outcome.

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Conclusions

This study found that for the diagnostic task of root canal anatomy identification as “modelled” by the maxillary first molar MB2 canal, a representative threshold dose of just over 200mGy cm² was identified for the ProMax® 3D and Accuitomo F170®, lower than published NDRLs. While achieving the individual subjective image tasks for root canal identification required a consistent CNR value within each scanner, the markedly different CNR values identified for the two CBCT models suggest that it not possible to determine a single threshold level of objective image quality that could be universally applicable to other CBCT models. Experience and expertise was shown to have a significant impact on the diagnostic efficacy of observers in the diagnostic task of root canal identification. Ultimately all dose reduction strategies are scanner specific and in practice needs to be achieved with the advice of a medical physics expert. The results suggested that selection of standard protocols instead of high resolution scans is a practical means of reducing patient dose and that increasing dose to enhance visualisation of the most complex anatomy was ineffective. As with all *ex-vivo* optimisation studies, these findings must be interpreted with caution. The *ex vivo* design, with a limited number of teeth, without patient movement or the presence of restorations, along with the subjective criteria for image quality and the complex inter relationship between subjective and objective image quality, all mean that there are significant limitations. Clinical studies are still required, presenting considerable challenges to researchers in terms of testing different exposure protocols.

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