RESEARCH ARTICLE

Evaluation of the dental spectral cone beam CT for metal artefact reduction

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Objectives: Metal artefacts are highly common in dental CT images because of the high X-ray attenuation of metallic dental fillings and implants. This study presents an evaluation of the virtual monochromatic imaging for metal artefact reduction by a recently introduced dental spectral cone beam CT, which is the first commercial dental spectral CBCT with flat-panel detector.

Methods: We carried out phantom experiments and clinical trials in this study. In the phantom study, the head phantom with metallic dental fillings and implants of various materials was scanned. Moreover, standard deviation, metal artefact index, and contrast-to-noise ratio were analyzed for fixed region of interest. Patient study included 23 patients with metallic fillings and metal implants. Traditional CT images and virtual monochromatic images were produced in a single scan, ensuring that the comparison can be made within the same patient and same location. Standard deviation and metal artefact index were analyzed for fixed region of interest.

Results: The phantom study and patient study showed that the metal artefacts caused by metallic dental fillings are well-suppressed by the virtual monochromatic imaging. Moreover, the improvements in virtual monochromatic imaging in terms of image quality are more pronounced for small dental fillings. The noise increase in image slices without metallic objects is a side-effect of the virtual monochromatic images.

Conclusions: Virtual monochromatic imaging by spectral cone beam CT reduces the metal artefact and improves the image contrast-to-noise ratio around dental metallic fillings. This kind of imaging would be recommended for patients with dental metallic fillings.

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Introduction

Metal artefacts are highly common in dental cone beam CT because of the high X-ray attenuation of metallic dental fillings and implants.¹ Metal artefacts obscure structures and reduce the diagnostic values of dental

cone beam CT, occurring as streaks originating from the implant.

Metal artefacts are mainly contributed by beam hardening and photon starvation. The X-ray spectrum is not monochromatic, whereas the low energy photons are easy to be absorbed. This non-linearity absorption causes the reconstructed attenuation value to be misestimated, leading to beam hardening artefacts in CT images. The non-linearity is excessively strong when the

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structure has high a absorption rate. Meanwhile, photon starvation occurs when the absorption is too strong where the detected photon intensity is very low, resulting in excessive noise and loss of information around structures with high absorption. Several approaches have been proposed to reduce metal artefacts.

Among these approaches, one strategy is software-based, which includes adaptive filtration, iterative reconstruction, and projection completion. Projection completion replaces the data affected by metal by interpolation. Various projection completion methods have been proposed.² Among them, the normalized metal artefact reduction (NMAR)^{3,4} and frequency split metal artefact reduction (FSMAR)⁵ use the image reconstructed by other algorithm [e.g. linear metal artefact reduction (LMAR)]^{3,4} as the prior image to improve interpolation accuracy. Projection-completion methods are easily implemented because they do not change the hardware or the acquisition process. However, the metal artefacts cannot be completely removed and unnatural textures may be created.

Another strategy is spectral CT.⁶⁻⁹ In spectral CT, virtual monochromatic imaging synthesizes the monochromatic image from projection data obtained at different spectra. Studies have shown that metal artefact can be reduced with virtual monochromatic imaging.¹⁰⁻¹³ Combining virtual monochromatic imaging and projection completion methods can further reduce metal artefacts with large metallic objects.¹⁴

Spectral CT scanners have been provided by several vendors based on multislice CT and not especially designed for dental imaging, wherein both the teeth and implants are sources of beam hardening artefacts. Recently, a dental spectral cone beam CT (SCBCT) has been produced (UEG Realtime; UEG Imaging Co. Ltd., Shanghai, China). To the best of our knowledge, it is the first commercially available dental SCBCT with flat-panel detector. The main two differences between SCBCT and commercially available DECT are that the projection number of SCBCT is less than that in DECT and the signal-to-noise ratio (SNR) of SCBCT projection is lower. Based on that, more steps are needed in the algorithm design in SCBCT to handle these imperfect conditions. In this study, we investigated the virtual monochromatic imaging in SCBCT by head phantom experiments and clinical trials. Imaging performance with dental implants of various materials was tested in terms of noise, degree of metal artefact, and contrast-to-noise ratio (CNR).

Methods and materials

Dental spectral cone beam CT

All scans were performed on a dental SCBCT scanner (UEG Realtime; UEG Imaging Co. Ltd., Shanghai, China). A feature of this scanner is that it provides a spectral scan mode while the X-ray beams with two different spectrums are emitted alternatively by dynamic

filtration technique, which uses a rotating copper plate that placed in front of the X-ray source to generate the high energy and low energy X-ray spectrum. Then the virtual monochromatic CT image can be produced by a frequency split virtual monochromatic imaging (FSVMI) algorithm, which was an enhanced algorithm based on the raw data based virtual monochromatic imaging algorithm¹⁵⁻¹⁷ with dual energy calibration.¹⁸⁻²⁰ The spectral scan data can also be reconstructed by a traditional method, which mixes the dual spectrum data and reconstructs the image by using a traditional Feldkamp, Davis, and Kress (FDK) algorithm.^{21,22} Subsequently, a traditional-like image is produced. Moreover, the scanner provides the traditional scan mode where only one X-ray spectrum is produced and a traditional FDK algorithm is applied to produce the traditional image.

In summary, two scan modes and three image types were provided by SCBCT, namely, spectral scan and FSVMI reconstruction (virtual monochromatic image, also referred as spectral image), spectral scan and FDK reconstruction (traditional-like image), and traditional scan and FDK reconstruction (traditional image).

CT image acquisition

Spectral scan and traditional scan were performed at equivalent dose levels for comparison. The dose of each scan was 8.4 mGy, which is measured at the centre of detector during a scan without objects. The flat-panel detector (HAMAMATSU C12821DK-40 flat panel sensor) has a size of 265 × 215mm, with each pixel size of 0.12 × 0.12mm. The “Binning mode”, wherein 2 × 2 adjacent pixels are combined into one value, is used in the spectral and traditional scan to improve the reading speed and reduce read-out noise. Thus, there are 1096 rows and 888 columns in each frame. The rotation times were 30 s for spectral scan and 17 s for traditional scan.

CT image reconstruction

After spectral acquisition of projection data, an FSVMI algorithm was applied to reconstruct the CT image. FSVMI is a enhanced raw-data-based virtual monochromatic imaging algorithm¹⁵⁻¹⁷ with dual energy calibration.¹⁸⁻²⁰ FSVMI works as follows: First, several preprocessing steps are applied before reconstruction, including detector sensitivity correction, denoising, scatter correction, and empirical based beam hardening correction. The projection data of two different spectra are then synthesized to generate the virtual monochromatic projection data. Finally, the virtual monochromatic image can be produced from the projection data. Workflow of FSVMI is illustrated in [Figure 1](#).

In addition to the spectral image, a traditional-like CT image can be generated from the same spectral projection data by the traditional FDK-based algorithm.²¹

The dental SCBCT also provides a traditional imaging protocol, wherein the spectrum of X-ray beam remains unchanged during the scan. In the traditional

Figure 1 Flowchart of FSVMI algorithm. FSVMI, frequency split virtual monochromatic imaging.

imaging protocol, a FDK-based algorithm is applied to generate the traditional CT image.

Settings of phantom study: To evaluate the spectral imaging for metal artefact reduction, a head phantom (Model 711-HN, ATOM®Max, CIRS) with metallic dental fillings and implants of various materials (including a zirconia all-ceramic crown, a Co–Cr metal–ceramic crown, two titanium implants of 3.3 and 4.1 mm, and a healing cap) was scanned (Figure 2a,b). During each scan, the position of the head phantom remained unchanged. Dental fillings and implants were placed near the maxillary canine and first premolar. A head phantom without metal implants was also scanned as reference. Both the spectral scan and traditional scan were performed, and the images of the three types (virtual monochromatic image from spectral scan, traditional-like image from spectral scan, and traditional-like image from traditional scan) were produced for comparison.

Image analysis for phantom study: A region of interest (ROI) (ROI_{tissue} of Figure 2c) was selected to evaluate the

Figure 2 (a) Photograph of the head phantom used in phantom study. (b) Three dimensional rendering of the virtual monochromatic image. (Right) Illustration of ROIs. ROI_{tissue} is the Region of interests for measurements of the metal artefact index in the head phantom study. ROI_{tissue} is also the ROI for measurements of HU_{tissue} and SD_{tissue}. ROI_{teeth} is the ROI for measurements of HU_{teeth}. HU, Hounsfield unit; ROI, region of interest; SD, standard deviation.

metal artefact. The ROI was a trapezium region placed in the soft tissue near the maxillary first premolar, and was close to the metallic object. The ROI was filled with homogenous tissue-equivalent material. Thus, the standard deviation (SD) in the ROI should be 0 ideally if no noise or image distortion existed. Therefore, SD can be used as an indicator of metal artefact-induced image distortion. To reduce the effect of noise, the SD in the same location of the image without metallic objects was calculated. Then, the metal artefact index (MAI) was calculated from the formula:

$$MAI_{(phantom)} = \sqrt{SD_{metal}^2 - SD_{ref}^2} \quad (1)$$

where SD_{metal} is measured from the ROI_{tissue} of scans with metallic objects, and SD_{ref} is measured from the ROI_{tissue} of the reference scan without metallic objects. Similar artefact indexes were also used in previous studies to evaluate the metal artefacts.^{23,24}

To evaluate the contrast, CNR was also calculated for each image. The formula is as follows:

$$CNR = \frac{|HU_{teeth} - HU_{tissue}|}{SD_{tissue}} \quad (2)$$

where HU_{teeth} is the mean Hounsfield unit (HU) value of the teeth region, and HU_{tissue} is the mean HU value of the tissue region. Figure 2 shows the ROIs for measurements of HU_{teeth} , HU_{tissue} , and SD_{tissue} .

In each scan with and without metallic objects, the position of head phantom was fixed. The position and size of ROIs were the same in all study samples. Thus, calculating the SD, $MAI_{phantom}$, and CNR in the fixed ROIs of each study sample was easy by running a Matlab code.

Subjects of patient study: The patient study was performed on 23 patients with metallic fillings and metal

Figure 3 Two ROIs selected for each patient. (a) ROI_{metal} in oral cavity with metal artefacts and (b) ROI_{ref} in mylohyoid muscle without metallic objects. ROI, region of interest.

implants in the Shanghai Ninth Hospital. The patients were between age 18 and 57, and the median age was 28 years old, with 16 males and 7 females. The locations of dental fillings and implants were as follows: both sides (5), right side (11), and left side (7). Spectral scan was performed for each patient, and the traditional-like image and virtual monochromatic image were generated in a single scan.

Image analysis for patient study: Quantitative image analysis was performed by a radiologist with ImageJ software, whereas the SD of a selected ROI was calculated by the software. Two ROIs were selected for each patient, one in the image slice with metallic objects (ROI_{metal}) and another in mylohyoid muscle without metallic objects (ROI_{ref}) (Figure 3). Each ROI was a circular region with a fixed radius of 1 cm. By using the “ROI manager” in ImageJ, the position and size of ROIs were positioned the same between different reconstruction images within a patient. The SD in ROI_{metal} was contributed by metal artefact and noise, and SD in ROI_{ref} was caused by noise. The MAI of the patient study was calculated as follows:

$$MAI_{patient} = \sqrt{SD_{metal}^2 - SD_{ref}^2} \quad (3)$$

where SD_{metal} is calculated from the ROI_{metal} with metallic object artefacts, and SD_{ref} is calculated from the ROI_{ref} in the mylohyoid muscle without metallic objects. This definition of MAI was similar to that of MAI_{phantom}, except that the selected ROIs were different. Moreover, similar artefact indexes were used in previous studies to evaluate the metal artefacts.^{23,24}

The CT number accuracy can also be used as an indicator of artefacts. The mean (HU) value was measured on ROI_{metal} in the image with metallic object (HU_{metal}) and on ROI_{ref} in the image without metallic object (HU_{ref}). The HU error ($\Delta HU_{patient}$) was then calculated by

$$\Delta HU_{patient} = |HU_{metal} - HU_{ref}| \quad (4)$$

CNR was also calculated by

Figure 4 Reconstruction images of the head phantom. (a, d, g) Virtual monochromatic image from spectral scan, (b, e, h) traditional-like image from spectral scan, and (c, f, i) traditional-like image from traditional scan. The corresponding metal fillings are (a, b, c) Co-Cr crown, (d, e, f) Ti implant 4.1 mm, and (g, h, i) two Ti implants with 3.3 and 4.1 mm.

$$CNR = \frac{|HU_{teeth} - HU_{tissue}|}{SD_{tissue}} \quad (5)$$

where HU_{teeth} is the mean HU value of the teeth region, and HU_{tissue} is the mean HU value of the tissue region (ROI_{metal}).

In statistical analysis, paired sample *t*-test was performed on the MAI_{patient}, SD, CNR and HU error of the spectral image and traditional-like image. $p < 0.05$ was regarded to be statistically significant.

Results

Phantom study

The three image types (virtual monochromatic image from spectral scan, traditional-like image from spectral scan, and traditional-like image from traditional scan) were generated. Images of three of the study samples are shown in Figure 4. Streaks originating from the metallic objects can be observed in the traditional images, whereas the virtual monochromatic images showed fewer streaks. For small metallic objects (titanium implants and healing cap), the metal artefact was reduced to a low level, and the edge of the soft tissue was preserved in the virtual monochromatic image. For large metallic objects (metallic crowns), reduction of metal artefact was observed in the virtual monochromatic image. However, the edge of the soft tissue remained distorted.

Table 1 Quantitative image analysis for phantom study (SD, MAI and CNR)

Metallatic object	SD			MAI			CNR		
	S	TL	T	S	TL	T	S	TL	T
No	40.6	39.9	39.1	/	/	/	32.37	36.86	35.54
Zirconia crown	347.6	359.5	439.5	345.2	357.3	437.7	4.59	4.64	3.86
Co–Cr crown	284.9	313.2	366.1	282.0	310.6	364.0	5.49	5.32	4.54
Ti Implant 3.3 mm	159.4	248.9	261.1	154.1	245.7	258.1	9.08	6.62	6.01
Ti Implant 4.1 mm	126.1	226.3	245.7	119.4	222.7	242.6	11.16	7.39	6.36
Two Ti Implants ^a	68.8	158.2	150.3	55.5	153.1	145.1	19.66	9.22	9.10
Healing cap	53.1	118.2	112.6	34.2	111.3	105.6	26.22	12.78	12.55

CNR, contrast-to-noise ratio; MAI, artefact index; S, spectral image; SD, standard deviation; T, traditional image; TL, traditional-like image;

^aTwo Ti implants: two ti implants of 3.3mm and 4.1 mm.

The detailed results of the quantitative analysis are listed in Table 1. For the head phantom without metallic objects, the virtual monochromatic and traditional images showed low SD. For samples with metallic objects, SD was extraordinarily high due to metal artefacts. The SD of the ROI near metallic objects in the virtual monochromatic image was lower than that in the traditional-like and traditional images because of the reduction of metal artefacts. In the head phantom without metallic objects, the SD of the virtual monochromatic image was larger than that of the traditional-like and traditional images. The MAI of all samples with metallic objects in the virtual monochromatic image were lower than those in the traditional-like and traditional images. For small metallic objects (titanium implants and healing cap), the reduction of MAI was pronounced. For large metallic objects (metallic crowns), the reduction of MAI was less pronounced.

For the head phantom without metallic objects, virtual monochromatic images showed increased noise and reduced CNR. In five of the six samples with metallic objects, CNR was improved in the virtual monochromatic image. One exception was the head phantom with zirconia crown, where CNR was slightly smaller in the virtual monochromatic image than in the traditional-like image.

The phantom study indicated that metal artefacts are reduced in virtual monochromatic images in the spectral dental CT. For small metallic objects, the reduction of metal artefact is pronounced. Moreover, these results showed that virtual monochromatic image leads to increased noise for regions without metal artefacts.

Patient study

The virtual monochromatic image reconstructed by the FSVMI method and the traditional-like image reconstructed by the FDK method were generated in a single scan of each person. Images of three of the study samples are shown in Figure 5. Streaks originating from metallic fillings can be observed in the traditional-like images, whereas the virtual monochromatic images showed fewer streaks.

Quantitative measurements for each patient are listed in Table 2. For image slices with metallic objects, the SD value of the virtual monochromatic images (73.8) was lower than that of the traditional-like image (89.7). For image slices without metallic objects, the SD of the virtual monochromatic image (48.1) was slightly larger than that of the traditional-like image (40.6). The MAI of the oral cavity in the virtual monochromatic image (56.0) was significantly lower than that in the traditional image (79.9) ($p = 6.9e^{-10}$). The SD value of the oral cavity

Figure 5 Virtual monochromatic image (a, c, e) and traditional-like image (b, d, f) of 3 of the 23 patients. Images of each row are from the same location within the same patient.

Table 2 Quantitative image analysis for patient study.

Patient number	SD				MAI				CNR				HU error			
	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$	$S (ROI_{metal})$	$TL (ROI_{metal})$
1	52.0	53.4	48.3	43.3	19.2	31.2	28.8	29.3	10.3	19.4	10.3	19.4	10.3	19.4	10.3	19.4
2	53.5	69.3	45.6	40.9	28.0	55.9	27.2	21.8	8.2	65.0	8.2	65.0	8.2	65.0	8.2	65.0
3	45.4	50.6	44.7	39.0	8.1	32.3	32.4	30.6	9.2	23.1	9.2	23.1	9.2	23.1	9.2	23.1
4	76.5	90.0	45.3	40.6	61.6	80.3	19.2	17.1	5.5	31.0	5.5	31.0	5.5	31.0	5.5	31.0
5	64.1	91.1	45.0	40.6	45.7	81.5	23.2	17.4	28.8	9.3	28.8	9.3	28.8	9.3	28.8	9.3
6	85.1	89.7	46.2	40.7	71.4	79.9	16.7	16.6	36.6	79.5	36.6	79.5	36.6	79.5	36.6	79.5
7	76.2	90.6	45.3	39.2	61.3	81.7	19.6	17.4	30.9	8.0	30.9	8.0	30.9	8.0	30.9	8.0
8	56.4	65.6	45.7	39.8	33.1	52.1	26.3	23.6	23.4	24.2	23.4	24.2	23.4	24.2	23.4	24.2
9	73.1	85.6	56.1	54.0	47.0	66.4	20.4	18.6	2.1	0.7	2.1	0.7	2.1	0.7	2.1	0.7
10	107.3	118.2	49.0	44.5	95.4	109.5	14.0	13.7	44.3	38.9	44.3	38.9	44.3	38.9	44.3	38.9
11	81.0	104.5	48.3	43.8	65.0	94.9	17.9	15.0	11.7	11.3	11.7	11.3	11.7	11.3	11.7	11.3
12	89.3	116.5	49.1	44.8	74.6	107.5	16.1	13.3	26.4	29.9	26.4	29.9	26.4	29.9	26.4	29.9
13	101.9	144.7	54.8	47.9	85.9	136.6	14.6	11.0	12.3	1.3	12.3	1.3	12.3	1.3	12.3	1.3
14	140.8	176.1	54.9	48.0	129.6	169.5	11.0	9.6	46.3	94.5	46.3	94.5	46.3	94.5	46.3	94.5
15	82.6	97.9	54.3	47.8	62.2	85.4	18.4	16.8	24.8	51.5	24.8	51.5	24.8	51.5	24.8	51.5
16	65.5	67.4	38.7	31.2	52.8	59.7	24.0	25.0	64.1	41.6	64.1	41.6	64.1	41.6	64.1	41.6
17	71.6	84.9	44.8	29.3	55.9	79.7	21.6	18.8	10.2	60.8	10.2	60.8	10.2	60.8	10.2	60.8
18	78.6	76.0	46.2	28.8	63.6	70.3	19.6	20.6	4.0	92.3	4.0	92.3	4.0	92.3	4.0	92.3
19	92.9	121.7	49.3	40.6	78.8	114.7	15.4	12.5	86.0	141.5	86.0	141.5	86.0	141.5	86.0	141.5
20	73.8	82.4	48.1	30.5	56.0	76.6	18.2	17.3	173.2	218.3	173.2	218.3	173.2	218.3	173.2	218.3
21	62.6	65.3	42.3	32.7	46.2	56.5	21.8	22.0	109.5	166.4	109.5	166.4	109.5	166.4	109.5	166.4
22	64.6	79.1	48.3	32.0	42.9	72.3	21.9	19.0	86.4	152.3	86.4	152.3	86.4	152.3	86.4	152.3
23	71.6	93.0	49.1	32.3	52.1	87.2	18.5	14.7	173.8	289.7	173.8	289.7	173.8	289.7	173.8	289.7
Median	73.8	89.7	48.1	40.6	56.0	79.9	18.2	15.6	26.4	41.6	26.4	41.6	26.4	41.6	26.4	41.6

CNR, contrast-to-noise ratio; MAI, metal artefact index; ROI, region of interest; S, spectral image; SD, standard deviation; T, traditional image; TL, traditional-like image;

in the virtual monochromatic image (73.8) was significantly lower than that in the traditional image (89.7) ($p = 1e^{-6}$). The CNR of the oral cavity in the virtual monochromatic image (19.6) was significantly better than that in the traditional image (17.4) ($p = 1.8e^{-5}$). The HU error of the oral cavity in the virtual monochromatic image (26.4) was significantly lower than that in the traditional image (41.6) ($p = 1e^{-3}$).

Discussion

Metal artefacts in dental CT are highly common because dental fillings and implants are made of high-density materials. The phantom and patient studies indicated that virtual monochromatic imaging by using dental SCBCT reduces metal artefacts. For small metallic objects, the reduction of metal artefacts is pronounced. The reduction of metal artefact by virtual monochromatic imaging has been reported by previous studies.^{10–12,23} However, the data in these reports are from multislice CT. In this study, reduction of metal artefact has been proved for dental SCBCT.

This study indicated that virtual monochromatic imaging leads to increased noise in image slices without metal artefacts. This result is due to the energy extrapolation in the FSVMI method.²⁵ To overcome the increased noise, the traditional-like and virtual monochromatic images were produced in a single scan. In combining the low-noise traditional-like and low-artefact virtual

monochromatic images, precise information can be provided in a single scan.

Several limitations exist in this study. Metal fillings in the phantom study were placed outside of the head phantom. Thus, implants cannot be placed at the right location of the head phantom because the head phantom was a solid phantom. The second limitation is that this study included a small number of patients and did not analyze the diagnostic performance. Future studies can be applied on several realistic phantoms and a large group of patients to consider the diagnostic performance. Third, this study only compares the performance between traditional and virtual monochromatic images provided from the same vender.

Conclusion

Dental SCBCT reduces metal artefacts and improves the image CNR around dental metallic fillings by virtual monochromatic imaging. This method would be recommended for patients with dental metallic fillings.

Ethics Statement

The human study was approved by the Review Committee of Shanghai Ninth Hospital affiliated to Shanghai Jiaotong University School of Medicine, and written informed consents were obtained from all the subjects.

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