RESEARCH

Characterization and correction of cupping effect artefacts in cone beam CT

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Objective: The purpose of this study was to demonstrate and correct the cupping effect artefact that occurs owing to the presence of beam hardening and scatter radiation during image acquisition in cone beam CT (CBCT).

Methods: A uniform aluminium cylinder (6061) was used to demonstrate the cupping effect artefact on the Planmeca Promax 3D CBCT unit (Planmeca OY, Helsinki, Finland). The cupping effect was studied using a line profile plot of the grey level values using ImageJ software (National Institutes of Health, Bethesda, MD). A hardware-based correction method using copper pre-filtration was used to address this artefact caused by beam hardening and a software-based subtraction algorithm was used to address scatter contamination.

Results: The hardware-based correction used to address the effects of beam hardening suppressed the cupping effect artefact but did not eliminate it. The software-based correction used to address the effects of scatter resulted in elimination of the cupping effect artefact.

Conclusion: Compensating for the presence of beam hardening and scatter radiation improves grey level uniformity in CBCT.

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Introduction

The first cone beam CT (CBCT) machine developed strictly for maxillofacial imaging was the NewTom-9000 (Quantitative Radiology, Verona, Italy).¹ Since its development in 1998, there has been a rapid progression in the production of CBCT units manufactured for imaging the maxillofacial region. Like conventional CT used in medicine, CBCT provides a means for three-dimensional (3D) imaging. However, in dentistry, CBCT is designed for imaging the maxillofacial region and therefore can be applied to diagnostic imaging tasks specific to the field of dental medicine.^{2,3} In addition, the radiation dose is lower in CBCT used in dentistry than in CT used in medicine.⁴

However, there are some drawbacks to using CBCT as an imaging technique. The presence of grey level

non-uniformities in CBCT contributes to artefact formation in reconstructed CBCT images. In CT, the term “artefact” refers to any systematic discrepancy between the CT numbers in the reconstructed image and the true attenuation coefficients of the object.⁵

Beam hardening and scatter radiation, two well-known sources of non-linear error, can contribute to grey level non-uniformity in CT images because they are not included as factors in the mathematics of image formation. This resulting grey level non-uniformity can lead to artefact formation in the final image. Artefact formation by beam hardening and scatter are very similar owing to the fact that both effects reduce the measured attenuation coefficients, which constitute the image, by amounts which depend on the measured intensity.⁶ As a result, beam hardening and scatter produce a common artefact known as the cupping effect artefact.^{6–14} McDavid et al¹⁵ and Brooks and Di Chiro¹⁶ demonstrated that the cupping effect is caused by beam hardening by reconstructing a uniform object with ideal projections and observing the absence of the cupping effect. The cupping effect caused by scatter

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occurs because of the scatter flux, resulting in an underestimation of the linear attenuation coefficient.¹⁷

In image formation, the line integral of the linear attenuation coefficient is used to calculate the density contained within each voxel in the final image. This line integral is calculated from $\ln(N_0/N)$, where N_0 is the unattenuated intensity and N is the transmitted intensity. Under normal conditions (the geometry of the imaging system being constant and N_0 being properly accounted for), the only variable in this equation that can alter the calculated value of the linear attenuation coefficient is the transmitted intensity. When there is an increase in the transmitted intensity, the result is a decrease in the value of the line integral, with a concomitant decrease in the reconstructed value of those voxels represented by each of the affected line integrals. Both beam hardening and scatter radiation provide a source of increased transmitted intensity to the detector, resulting in the underestimation of the true density of the object intercepted by the inaccurate line integrals.

The cupping effect artefact is demonstrated when a uniform cylindrical object is imaged. As the effects of beam hardening and scatter are most prevalent in the centre of a cylindrical object, it is this area that is dominated by the cupping effect artefact. An example of the cupping effect artefact is provided in Figure 1. The upper portion of Figure 1 demonstrates the grey level values representing the density of a uniform cylinder of aluminium under ideal conditions in which the image is reconstructed with accurate projection profiles (line integrals). The lower portion of Figure 1 demonstrates the cupping effect artefact occurring because of contamination of the projection profiles by beam hardening and scatter radiation. The grey levels decrease in value in the centre of the aluminium cylinder owing to the increase in transmitted intensity to the detector from the presence of beam hardening and scatter radiation occurring during image acquisition. The purpose of this study was to demonstrate the cupping effect artefact and to evaluate methods for correction. It would be expected that improvement of the cupping effect artefact can be achieved by compensating for the added intensity recorded by the detector owing to beam hardening and scatter radiation. A null hypothesis would therefore state that there is no difference in grey level uniformity when beam hardening and scatter radiation are accounted for in CBCT.

Materials and methods

The Planmeca Promax 3D cone beam volumetric tomography (CBVT) unit (Planmeca OY, Helsinki, Finland) was used to carry out all research experiments. A uniform cylinder of aluminium (6061) measuring 3.8 cm in diameter and 2.6 cm in height was used to evaluate the cupping effect artefact. The make up of

Figure 1 Cupping effect artefact

aluminium 6061 alloy consists of 98% aluminium, 1% magnesium and 0.6% silicon.¹⁸ The aluminium cylinder was centred within the field of view (FOV) for all image acquisitions. The cupping effect was demonstrated using a line profile plot of the grey level values with ImageJ software (National Institutes of Health, Bethesda, MD). The line profiles were averaged over a number of slices in order to reduce the effects of noise. The cupping effect was defined as the difference between the highest grey level value, which should correspond to the outermost edge of the aluminium

cylinder, and the minimum grey level value, which should be located near the centre of the aluminium cylinder. The degree of the cupping effect was expressed as a percentage.

Cupping effect owing to beam hardening

A hardware-based method of correction was used to suppress the cupping effect artefact caused by beam hardening. The intent was to narrow the X-ray spectrum of the Planmeca Promax 3D CBVT unit (Planmeca OY, Helsinki, Finland) by pre-filtration of the X-ray beam. The spectral distribution of the beam can be regulated by selecting a material with an appropriate atomic number, density and thickness.¹⁹ Copper has an atomic number of 29 with a k-shell binding energy of 9 keV, making it a good material for removing the lower energy portion of the X-ray spectrum, which contributes most to beam hardening.¹⁹ During the period in which this research was conducted, the filtration of the Planmeca Promax 3D CBVT unit was upgraded by the manufacturer. The original filtration system consisted of 2.5 mm of aluminium according to personal communication with Planmeca. During the upgrade, additional filtration consisting of 0.5 mm of copper was added to the original 2.5 mm of aluminium filtration. The 3.8 cm aluminium cylinder was scanned both prior to and after the manufacturer upgrade of the filtration system and the degree of the cupping effect was calculated. The 3.8 cm aluminium cylinder was scanned without any added filtration at the machine settings of 80 kV and 4 mA prior to manufacturer upgrade of the filtration system. The 3.8 cm aluminium cylinder was scanned without any added filtration, with the addition of one layer of copper filtration and with the addition of two layers of copper filtration after manufacturer upgrade of the filtration system. The thickness of the added copper filtration measured 0.56 mm each. The scans performed after the manufacturer upgrade were acquired at the machine settings of 80 kV and 8 mA with no additional filtration, 80 kV and 12 mA with one layer of added copper filtration and 80 kV and 15 mA with two layers of added copper filtration. The increase in milliamperage was done to compensate for the decrease in X-ray output that occurs with added copper filtration.

Cupping effect owing to scatter

Since scatter radiation is also a contributor to the cupping effect artefact, the same 3.8 cm aluminium cylinder was used to evaluate the effects of scatter. Evaluation of the cupping effect caused by scatter was done after manufacturer upgrade of the filtration system. Prior to the correction of the cupping effect due to scatter, the level of scatter was estimated. Three pairs of lead blockers with two thicknesses each were placed directly on the side of the 3.8-cm aluminium cylinder for a total of six lead blockers. The lead blockers measured $5 \times 5.3 \times 2.7$ mm each. The six lead

blockers were centred on the aluminium cylinder in the inferior–superior dimension, and positioned in the centre and on the edges of the aluminium cylinder; each pair was positioned 11.1 mm from one another. The 3.8 cm aluminium cylinder was orientated so that the X-ray beam traversed the lead first and was imaged using a setting of 80 kV. In order to prevent detector saturation from compromising scatter correction, which occurs on the Planmeca Promax 3D CBVT above 4 mA when using a setting of 80 kV, 4 mA was used. The grey level values for scatter estimation were acquired from the corrected raw projections using ImageJ software (National Institutes of Health, Bethesda, MD). Because the lead blocks the primary beam, any grey level value recorded from the area of the projection data corresponding to the position of the lead will represent scatter radiation. To confirm this, an image was acquired with lead placed on the tube head at the position of the exit of the X-ray beam, demonstrating that detector dark current is not a significant contributor to the grey level readings acquired from the corrected raw projection data. The grey level values were also measured from areas surrounding the lead blockers to obtain the value of the total beam intensity. From the grey level values representing the total beam and level of scatter radiation, the scatter-to-primary beam ratios were calculated. The scatter-to-primary beam ratios were calculated to be 24% and 23% for the periphery, left and right edges, respectively, and 49% for the centre.

A software-based method was used to correct the effects of scatter radiation. Scatter can be corrected by the application of a subtraction algorithm to the projection data prior to image reconstruction. Since the total beam intensity should be lowest in the centre of the aluminium cylinder, this allows scatter the opportunity to contribute a greater influence on the grey level values in the centre of the aluminium cylinder vs the periphery. This is reflected in the scatter-to-primary ratios as the centre value is twice that of the periphery. Therefore, the grey level value recorded from the area corresponding to the position of the central lead blocker was used to correct scatter contamination in the image. This grey level value was subtracted from the corrected raw projection data and the projections were then reconstructed using the same reconstruction algorithm (a proprietary Feldkamp-based back projection reconstruction algorithm) as used by Planmeca.

Results

Cupping effect due to beam hardening

The line profiles used to assess the cupping effect due to beam hardening were evaluated using ImageJ software. Prior to manufacturer upgrade of the machine's filtration system, which consisted of only 2.5 mm of aluminium, the cupping effect was determined to be

Figure 2 Pre-upgrade filtration (2.5 mm aluminium). Cupping effect 29%

29%. After the manufacturer upgrade, involving the addition of 0.5 mm of copper to the existing 2.5 mm of aluminium, the cupping effect was reduced to a value of 17%. The additional added copper filtration of one layer of copper applied to the tube head of the Planmeca Promax 3D unit after the manufacturer upgrade of the system filtration resulted in a decrease in the cupping effect from 17% to 13%. By adding one more layer of copper filtration, for a total of two layers of added copper in addition to the manufacturer's addition of 0.5 mm of copper to the filtration system, the cupping effect decreased to a value of 10%. Total elimination of the cupping effect was not achieved. The plots of the cupping effect due to beam hardening for each of the conditions stated above are provided in Figures 2–5. The negative values in these plots represent scaling of the Digital Imaging and Communications in Medicine (DICOM) data by the vendor in order to simulate Hounsfield units. However, without

knowledge of the arithmetic used by the vendor to derive these simulated Hounsfield units and considering the presence of contamination due to beam hardening and scatter, the accuracy of such values is questionable and therefore has been referred to simply as “grey levels”. These results can be validated by plotting the X-ray spectra of the Planmeca Promax 3D CBVT using a computer simulation program developed at the University of Texas Health Science Centre at San Antonio.²⁰ The X-ray spectra were calculated using the target material, the target angle, the distance from the target used for measurement, the kilovoltage setting, the milliamperage setting, the amount of inherent filtration and the amount of added filter material as applicable. The calculated X-ray spectra are provided in Figure 6, which demonstrates that, as copper is added to provide pre-filtration of the X-ray beam, the output spectrum narrows because of the removal of the low-energy portion of the X-ray beam. It should also be

Figure 3 Post-upgrade filtration (0.5 mm copper added). Cupping effect 17%

Figure 4 Additional filtration (1.06 mm copper added). Cupping effect 13%

noted that adding copper results in an increase in the mean energy of the X-ray beam.

Cupping effect due to scatter

Using the line profiles acquired from the files in ImageJ, the degree of the cupping effect was evaluated as before. The cupping effect prior to correcting the image for the effects of scatter was determined to be 17% (Figure 3). The application of the scatter subtraction algorithm to the corrected raw projections resulted in a significant increase in the grey level uniformity throughout the aluminium cylinder as demonstrated by removal of the cupping effect artefact (Figure 7).

Discussion

The reduction in the degree of the cupping effect using copper pre-filtration is indicative of the increase in the homogeneity of attenuation throughout the aluminium

cylinder by removal of the low-energy photons and the subsequent narrowing of the X-ray spectrum. Removal of the low-energy photons from the X-ray spectrum reduces beam hardening and therefore also reduces the increase in transmitted intensity that results from its presence. The use of filtration to decrease beam hardening is supported by the findings of Brooks and Di Chiro,¹⁶ who demonstrated a reduction of beam hardening effects from 9.2% in 20 cm of water using a 4.5 mm aluminium pre-filter to 1.5% using a 3.5 cm aluminium pre-filter and reported that using high atomic number (Z) materials such as copper, tin or Thoraeus filters could produce even better results. In fact, normal aluminium filters are approximately 10% less efficient than filters of other materials such as copper, brass or iron.²¹ Meganck et al⁷ reduced the cupping effect caused by beam hardening on a cortical bone-equivalent phantom to an insignificant level (2%) using a combination of 0.254 mm aluminium and 0.254 mm copper filter. The atomic number of aluminium and the effective atomic number of cortical bone

Figure 5 Additional filtration (1.62 mm copper added). Cupping effect 10%

Figure 6 Planmeca model spectra at 80 kV and 8 mA

are similar; therefore, conclusions may be drawn on the effect of beam hardening correction on aluminium from its effect on cortical bone and *vice versa*.¹⁸ Owing to the fact that our phantom is larger in diameter and thickness than the phantom used by Meganck et al,⁷ the cupping effect should initially be worse in our 3.8 cm cylindrical aluminium phantom and therefore more difficult to eliminate. Meganck et al⁷ used a phantom of 11.811 mm in diameter and demonstrated that the cupping effect due to beam hardening increases as phantom thickness increases.

It seems evident that scatter contamination contributed to the residual cup observed after the application of copper pre-filtration to reduce the cupping effect artefact caused by beam hardening. It is the increase in intensity to the detector that gives rise to the cupping effect artefact; therefore, subtracting this error because of scatter results in improved grey level uniformity. Similar results have been demonstrated by others when a subtraction algorithm was applied to CBCT projection data prior to reconstruction.^{12,13,22–24}

Scatter is considered to be one of the fundamental limitations of CBCT image quality.¹² Also, not only does scatter result in the cupping effect artefact, but scatter radiation can produce grey level non-uniformity throughout the FOV. This non-uniformity throughout the FOV prevents the use of CBCT in quantitative analysis. Siewerdsen and Jaffray²⁵ reported that replanning between treatment fractions during radiation therapy using CBCT is impeded because of scatter pollution in the projection images. As has been demonstrated in this study, scatter radiation reduces the accuracy in reconstructed values, which will degrade accuracy when measuring density.^{25,26} Therefore, the results of this study suggest that scatter radiation may be a potential source of the grey level discrepancies reported within the FOV on CBCT images. It is well known that an artefact referred to as the “truncation artefact” or “truncated-view artefact” is inherent to CBCT imaging. This artefact occurs because the size of the FOV used in CBCT is smaller than the size of the object being imaged. The largest error due to the truncated-view artefact will occur near the edge of the

Figure 7 Post-upgrade filtration with scatter subtraction

FOV.²⁷ Lehr²⁷ imaged a 52 cm water disc phantom centred in a 48 cm FOV, which resulted in an increase in CT numbers at the edge of the FOV. Bryant et al²⁸ described a similar observed effect, termed the “exomass effect”, on the i-CAT (Imaging Sciences International, LLC, Hatfield, PA) CBCT unit. Bryant et al²⁸ observed an increase in the grey level values in the anterior to the posterior direction of the scan field, the posterior representing the position within the scan field, adjacent to the portion of the object located outside of the FOV. Katsumata et al²⁹ evaluated the effect of the truncation artefact on the Alphard Vega CBCT unit (Asahi Roentgen, Kyoto, Japan), reporting improved uniformity of the density values with the larger FOVs used. However, to our knowledge, the effects of scatter radiation have not been evaluated as a potential source of grey level non-uniformity in CBCT imaging in dentistry. It is expected

that scatter radiation will contribute most to the total beam intensity in the centre of the FOV, resulting in grey levels of lower value in the centre vs the periphery of the FOV.

In conclusion, it has been demonstrated that both beam hardening and scatter radiation contribute to the cupping effect artefact on the Planmeca Promax 3D CBVT as it is presently configured. Also, our results suggest that scatter radiation may serve as a potential source contributing to the grey level non-uniformity encountered throughout the FOV in CBCT. Therefore, we can reject the null hypothesis stating that there is no difference in grey level uniformity when beam hardening and scatter radiation are accounted for in CBCT. However, as the effects of scatter and beam hardening were only evaluated on the Planmeca Promax 3D CBVT unit, these conclusions may only apply to this particular CBCT unit.

References

1. Mozzo P, Procacci C, Tacconi A, Tinazzi Martini P, Bergamo Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *Eur Radiol* 1998; **8**: 1558–1564.
2. Mol A, Balasundaram A. In vitro cone beam CT imaging of periodontal bone. *Dentomaxillofac Radiol* 2008; **37**: 319–324.
3. Swennen GRJ, Mommaerts MY, Abeloos J, De Clercq C, Lamoral P, Neyt N, et al. A cone-beam CT based technique to augment the 3D virtual skull model with a detailed dental surface. *Int J Oral Maxillofac Surg* 2009; **38**: 48–57.
4. Ludlow JB, Ivanovic M. Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; **106**: 106–114.
5. Barrett JF, Keat N. Artifacts in CT: recognition and avoidance. *Radiographics* 2004; **24**: 1679–1691.
6. Glover GH. Compton scatter effects in CT reconstructions. *Med Phys* 1982; **9**: 860–867.
7. Meganck JA, Kozloff KM, Thornton MM, Broski SM, Goldstein SA. Beam hardening artifacts in micro-CT scanning can be reduced by X-ray beam filtration and the resulting images can be used to accurately measure BMD. *Bone* 2009; **45**: 1104–1116.
8. Van de Castele E, Van Dyck D, Sijbers J, Raman E. An energy-based beam hardening model in tomography. *Phys Med Biol* 2002; **47**: 4181–4190.
9. Maltz JS, Gangadharan B, Bose S, Hristov DH, Faddegon BA, Paidi A, et al. Algorithm for X-ray scatter, beam-hardening, and beam profile correction in diagnostic (kilovoltage) and treatment (megavoltage) cone beam CT. *IEEE Trans Med Imaging* 2008; **27**: 1791–1810.
10. Joseph PM, Spital RD. A method for correcting bone induced artifacts in CT scanners. *J Comput Assist Tomogr* 1978; **2**: 100–108.
11. Joseph PM, Spital RD. The effects of scatter in x-ray CT. *Med Phys* 1982; **9**: 464–472.
12. Zhu L, Xie Y, Wang J, Xing L. Scatter correction for cone-beam CT in radiation therapy. *Med Phys* 2009; **36**: 2258–2268.
13. Jarry G, Graham SA, Moseley DJ, Jaffray DJ, Siewerdsen JH, Verhaegen F. Characterization of scattered radiation in kV CBCT images using Monte Carlo simulations. *Med Phys* 2006; **33**: 4320–4329.
14. Siewerdsen JH, Moseley DJ, Bakhtiar B, Richard S, Jaffray DA. The influence of antiscatter grids on soft-tissue detectability in cone-beam CT with flat-panel detectors. *Med Phys* 2004; **31**: 3506–3520.
15. McDavid WD, Waggner RG, Payne WH, Dennis MJ. Spectral effects on three-dimensional reconstruction from x-rays. *Med Phys* 1975; **2**: 321–324.
16. Brooks RA, Di Chiro G. Beam hardening in X-ray reconstructive tomography. *Phys Med Biol* 1976; **21**: 390–398.
17. Rinkel J, Gerfault L, Estève F, Dinten JM. A new method for x-ray scatter correction: first assessment on a cone-beam CT experimental setup. *Phys Med Biol* 2007; **52**: 4633–4652.
18. Chen CY, Chuang KS, Wu J, Lin HR, Li MJ. Beam hardening correction for CT images using a post reconstruction method and equivalent tissue concept. *J Digit Imaging* 2001; **14**: 54–61.
19. Curry TE, Dowdey JE, Murry RC, Jr. *Christensen's physics of diagnostic radiology*, 4th edn. Philadelphia, PA: Lea and Febiger, 1990.
20. Lankipalli BR. Computer model for studying the detection of intraoral pathology using digital radiography. A dissertation presented to the faculty of the University of Texas Graduate School of Biomedical Sciences at San Antonio, 2003. San Antonio, TX: University of Texas at Austin; 2003.
21. Jennings RJ. A method for comparing beam-hardening filter materials for diagnostic radiology. *Med Phys* 1988; **15**: 588–599.
22. Poludniowski G, Evans PM, Hansen VN, Webb S. An efficient Monte Carlo-based algorithm for scatter correction in keV cone-beam CT. *Phys Med Biol* 2009; **54**: 3847–3864.
23. Ning R, Tang X, Conover D. X-ray scatter correction algorithm for cone beam CT imaging. *Med Phys* 2004; **31**: 1195–1202.
24. Siewerdsen JH, Daly MJ, Bakhtiar B, Moseley DJ, Richard S, Keller H, et al. A simple, direct method for x-ray scatter estimation and correction in digital radiography and cone-beam CT. *Med Phys* 2005; **33**: 187–197.
25. Siewerdsen JH, Jaffray DA. Cone-beam CT with a flat-panel imager: magnitude and effects of x-ray scatter. *Med Phys* 2001; **28**: 220–231.
26. Honda M, Kikuchi K, Komatsu K. Method for estimating the intensity of scattered radiation using a scatter generation model. *Med Phys* 1991; **18**: 219–226.
27. Lehr JL. Truncated-view artifacts: clinical importance on CT. *Am J Roentgenol* 1983; **141**: 183–191.
28. Bryant JA, Drage NA, Richmond S. Study of the scan uniformity from an i-CAT cone beam CT dental imaging system. *Dentomaxillofac Radiol* 2008; **37**: 365–374.
29. Katsumata A, Hirukawa A, Okumura S, Naitoh M, Fujishita M, Aiji E, et al. Relationship between density variability and imaging volume size in cone-beam computerized tomographic scanning of the maxillofacial region: an in vitro study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **107**: 420–425.