Influence of anatomical location on CT numbers in cone beam computed tomography

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Objective. To assess the influence of anatomical location on computed tomography (CT) numbers in mid and full field of view (FOV) cone beam computed tomography (CBCT) scans.
Study Design. Polypropylene tubes with varying concentrations of dipotassium hydrogen phosphate (K_2HPO_4) solutions (50 1200 mg/mL) were imaged within the incisor, premolar, and molar dental sockets of a human skull phantom. CBCT scans were acquired using the NewTom 3G and NewTom 5G units. The CT numbers of the K_2HPO_4 phantoms were measured, and the relationship between CT numbers and K_2HPO_4 concentration was examined. The measured CT numbers of the K_2HPO_4 phantoms were compared between anatomical sites.
Results. At all six anatomical locations, there was a strong linear relationship between CT numbers and K_2HPO_4 concentration ($R^2 > 0.93$). However, the absolute CT numbers varied considerably with the anatomical location.
Conclusion. The relationship between CT numbers and object density is not uniform through the dental arch on CBCT scans. (Oral Surg Oral Med Oral Pathol Oral Radiol 2013;115:558 564)

Cone beam computed tomography (CBCT) is an advanced imaging modality with several applications in dentomaxillofacial diagnosis and treatment planning.[1] Compared with conventional two-dimensional radiography, CBCT offers several advantages including visualizing the anatomic region in all three dimensions and producing images without geometric distortion and magnification. In this technique, a cone-shaped x-ray beam and a detector rotate around the object acquiring multiple projections, which are reconstructed into a volumetric image. Currently used image receptors include image intensifier and flat panel detector. Many CBCT units allow collimation of the x-ray beam to limit the amount of tissue imaged. The imaged field of view (FOV) is typically described as small (or limited), medium, or large, depending on the anatomical coverage. Typically, as the FOV increases, the radiation dose increases. Importantly, the radiation dose from CBCT is significantly lower than that from multi-slice computed tomography (MSCT) examinations.[2]

In computed tomography (CT) data, each voxel in the reconstructed CT volume is represented by a numerical value termed the CT number (sometimes referred in the literature to as “gray values”). This number reflects the degree of x-ray attenuation the average linear attenuation coefficient of that voxel. Major factors that influence the CT number include the tissue features (atomic number and density) and homogeneity and energy of the x-ray beam. In MSCT units, the CT numbers are expressed as Hounsfield unit (HU), which expresses x-ray attenuation of a voxel relative to the attenuation of water. Ideally, it would be valuable to have this CT number be also closely representative of the true x-ray attenuation of the tissue. This would be of practical value in examining the degree of mineralization of bone for implant treatment planning and in automatic segmentation of imaged volumes for computer-aided design and computer-aided manufacturing applications. Several studies have examined the relationship between CT numbers and bone quality assessment for implant treatment planning.[3-7] Arisan et al.[6] showed similarities between CT numbers from MSCT and CBCT in

Statement of Clinical Relevance

We show that the relationship between CT numbers and x-ray attenuation is not uniform throughout the dental arch on CBCT scans. Given this nonuniformity, comparison of numerical gray values measured at different anatomical locations is misleading.

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predicting primary implant stability and subjective bone quality classification.

Unlike MSCT units, current dental CBCT units do not use a standard scaling system. Nevertheless, studies have demonstrated that the relationship between CT numbers and x-ray attenuation is linear on CBCT scans.[7,8] These two studies imaged radiographic phantoms by both CBCT and MSCT scanners to demonstrate that there is a strong correlation between CT numbers from the two modalities. Based on these data, methods have been proposed to convert CT numbers, measured on CBCT scans to HU.[8,9] However, such methods make the implicit assumption that the relationship between CT numbers and x-ray attenuation is uniform through the CBCT image volume. There are several factors that contribute to the inhomogeneity of CT numbers on CBCT scans. These include beam hardening, artifacts from metallic restorations, and, importantly, scattered radiation. Of particular relevance to CBCT, the amount of scattered radiation varies with the FOV, with x-ray beam parameters and also with the anatomical location.[5] However, the magnitude of the contribution of these factors to subsequent CT number inhomogeneity is not fully understood. The aim of the present study was to systematically assess the influence of FOV and anatomical location on CT numbers measured on CBCT scans.

MATERIALS AND METHODS

Radiographic phantoms were custom-fabricated using solutions of dipotassium hydrogen phosphate (K_2HPO_4), a highly water-soluble salt whose effective atomic number is very close to that of calcium hydroxyapatite (15.58 and 15.86, respectively). This makes the x-ray attenuation of both substances similar. The effective linear attenuation coefficient of K_2HPO_4 is within 2.2%-2.7% of that for calcium hydroxyapatite over the photon energy range of 20-100 keV.[10] Aqueous solutions of K_2HPO_4 were prepared at concentrations of 50, 200, 400, 600, 800, 1000 and 1200 mg/mL. This concentration range was selected to represent a broad range of x-ray attenuation. When scanned in a uniform field in water and air, solutions with concentrations of 1000 and 1200 mg/mL had approximately the same CT numbers as dentin and cortical bone, respectively. The range from 50 to 800 mg/mL represents attenuation of trabecular bone of varying mineralization.

To assess the relationship between x-ray attenuation and CT numbers and the influence of anatomical location on these CT numbers, we used a human skull phantom. This phantom contained an adult human skull with a permanent dentition and the cervical spine. A uniform layer of wax surrounded the osseous structures to simulate soft tissue absorption and scatter radiation.[11] Six teeth were carefully extracted from the skull: the maxillary and mandibular central incisors, first premolars, and first molars and replaced with polypropylene tubes containing various concentrations of K_2HPO_4 (Figure 1). CBCT scans were performed at three FOVs (6, 9, and 12 in) using the NewTom 3G unit (QR, Verona, Italy) and at two FOVs (8×8 and 18×16 cm) using the NewTom 5G unit (QR). Additionally, a high-resolution mode scan was performed at the 8×8 cm FOV. For each scan, the skull phantom was positioned to simulate the ideal position of a patient's head during a CBCT examination for the specific anatomical region.

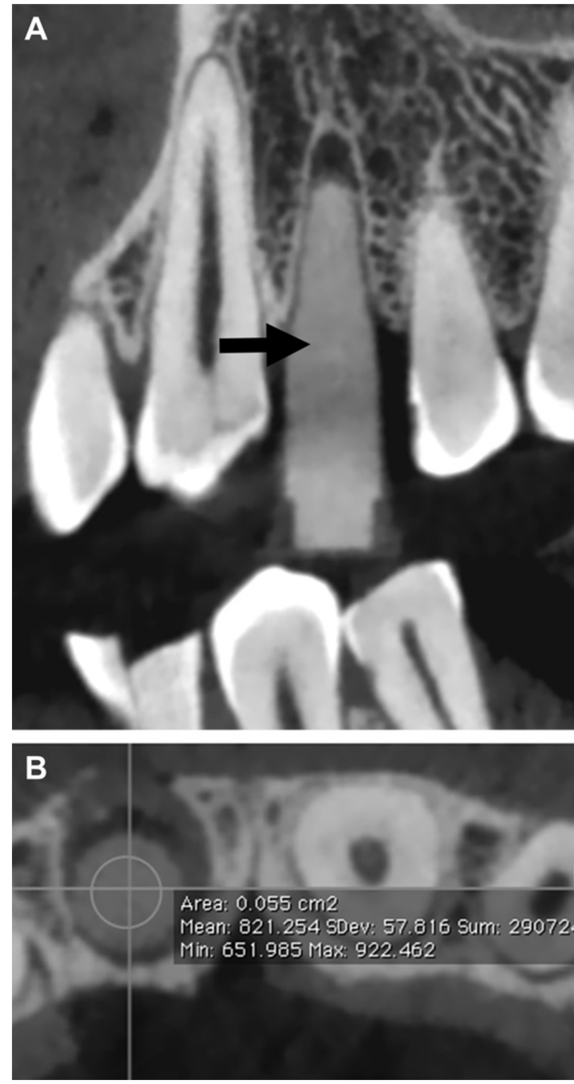

Fig. 1. **A,** Representative section showing placement of the K_2HPO_4 phantom (arrow) in a tooth socket of a human skull phantom. **B,** Representative axial section showing measurement of the CT number within a region of the K_2HPO_4 phantom.

The gray scale (bit depth) of the CBCT images was 12 bits for the NewTom 3G unit and 14 bits for the NewTom 5G unit. Volumetric data from both units were reconstructed in the native NNT software program (QR), exported to DICOM file format and imported into

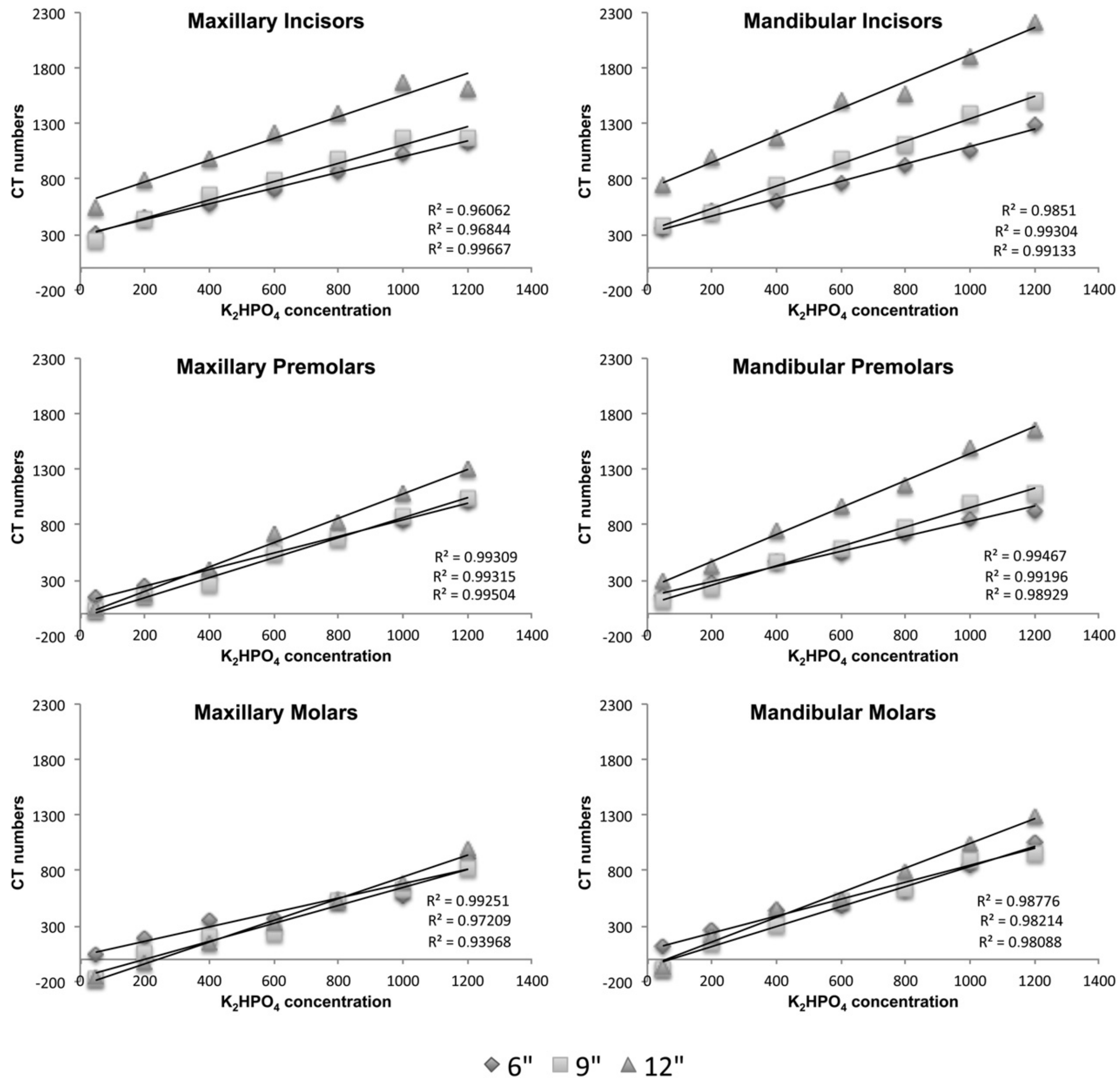

Fig. 2. Relationship between K_2HPO_4 concentration (mg/mL) and CT numbers. The K_2HPO_4 phantoms were imaged at the indicated anatomical locations using a NewTom 3G CBCT unit in 6 , 9 , or 12 in FOV. The linear regression line and the coefficient are indicated.

the OsiriX Imaging software for Mac OS X, a public domain software.[12] It is important to note that the native NNT software displays the CT numbers on a scale that is analogous to the HU scale, with the minimum density (air) at −1000 HU and water at approximately zero. This scale is maintained in the DICOM format and is read accordingly by the OsiriX software. On 0.20 mm axial slices, the mean CT numbers were measured at five heights within each tube and averaged (Figure 1). Linear regression was performed to assess the relationship between CT numbers and K_2HPO_4 concentration. Variations in the measured CT numbers for the same K_2HPO_4 concentration placed at different anatomical locations and when scanned in different FOVs were determined.

RESULTS

At all anatomical locations assessed on the human skull phantom, the CT numbers were discriminated between the various K_2HPO_4 concentrations with a strong linear relationship ($R^2 > 0.93$). This was observed at all FOVs with both the NewTom 3G and the NewTom 5G CBCT units and at the high-resolution mode scan of the NewTom 5G unit (Figures 2 and 3).

The absolute CT number varied considerably depending on the anatomical location for both the

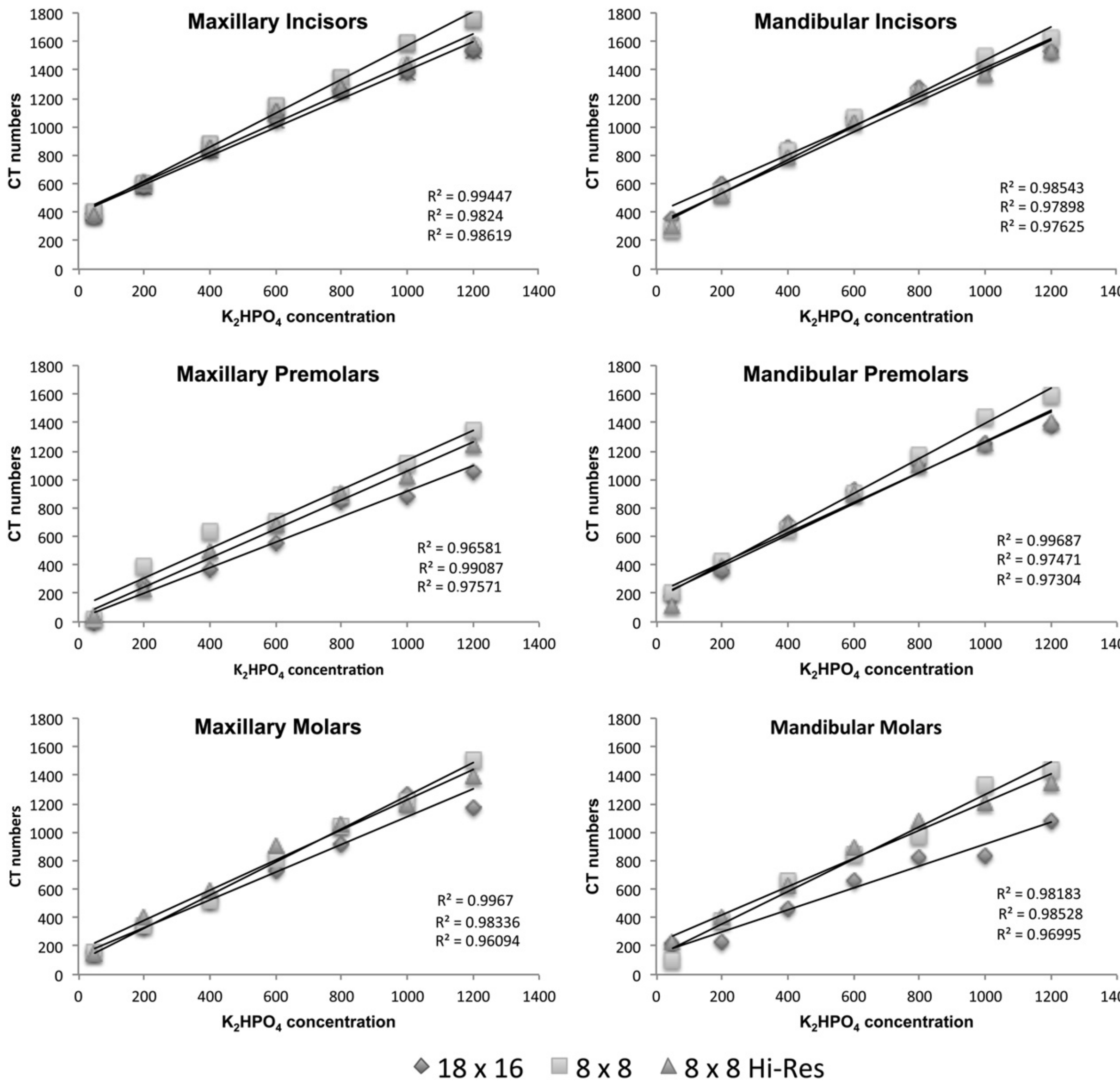

Fig. 3. Relationship between K_2HPO_4 concentration (mg/mL) and CT numbers. The K_2HPO_4 phantoms were imaged at the indicated anatomical locations using a NewTom 5G CBCT unit, using the following FOVs: 18 × 16 cm, 8 × 8 cm, and 8 × 8 cm, high resolution mode scan. The linear regression line and the coefficient are indicated.

NewTom 3G and the NewTom 5G units (Figures 4 and 5 and Tables I and II). The same concentration of K_2HPO_4 yielded different CT numbers when placed at different anatomical locations within the skull phantom. In general, for any given K_2HPO_4 concentration, the CT numbers were higher in the incisor region compared with the premolar and molar regions. This trend was observed for both the maxilla and the mandible. Furthermore, the variation in the CT numbers between the anatomical locations was observed with all FOVs examined and with both the standard and high-resolution scanning modes of the NewTom 5G unit.

DISCUSSION

CBCT imaging has been increasingly used in dentomaxillofacial diagnosis. In addition to its ability to display images in three dimensions, several studies have explored the utility of CBCT to quantitatively assess the bone quality.[3-7] The practical application of this assessment is limited by the fact that different CBCT units may vary considerably in their exposure parameters and that there is no standard scaling system during image reconstruction.

Using a K_2HPO_4-based phantom, we showed that the CT numbers from CBCT scans are linearly related to x-ray attenuation. This is in concordance with the previous

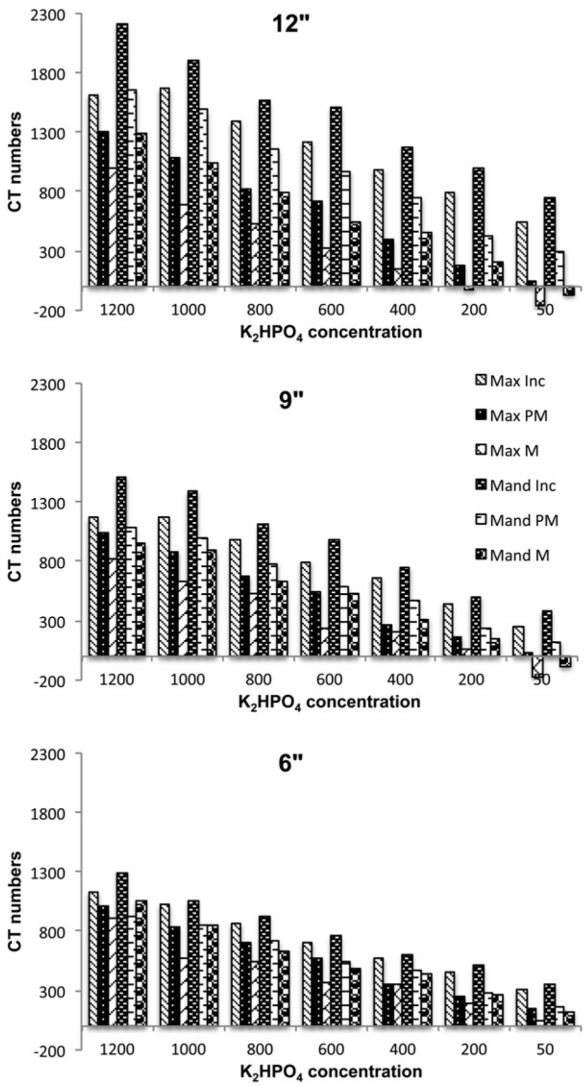

Fig. 4. Effect of anatomical location on CT numbers in the NewTom 3G CBCT unit.

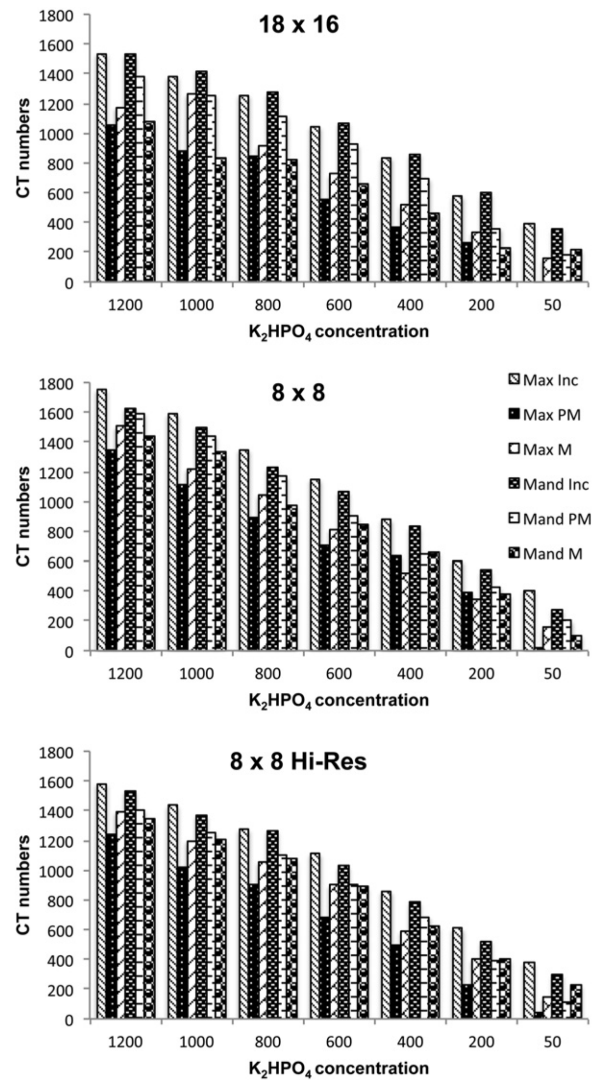

Fig. 5. Effect of anatomical location on CT numbers in the NewTom 5G CBCT unit.

reports.[7,8,13,14] Additionally, in a pilot study performed prior to this, we observed similar linear relationship when the K_2HPO_4-based phantom was scanned in a uniform fields, either in water or in air. Solutions with concentrations of 1000 and 1200 mg/mL had approximately the same CT numbers as well-mineralized trabecular bone and dentin and cortical bone, respectively, of a dentate mandible scanned under the same conditions.

Using radiographic phantoms imaged in CBCT and MSCT units, it has been shown that CT numbers also correlate well with HU. Some investigators have proposed that HU can be derived from CT numbers measured on CBCT scans, using factors that are specific for a given CBCT unit.[8,15] Such conversions are based on the assumption that the relationship between CT numbers and object density is uniform through the imaged CBCT volume. However, our study provides evidence that this is not the case. Our data systematically demonstrates that the CT numbers are strongly influenced by the anatomical site. We show that the CT number of the same object differed depending on the anatomical location in which it was imaged. Specifically, the CT numbers of phantom objects were higher when placed within the anterior region of the jaw and lower in the posterior regions. This finding underscores an important limitation of using CT numbers on CBCT scans bone with similar mineralization would yield different CT numbers depending on its anatomical location. Furthermore, our results also show that the magnitude of variation also differed considerably depending on the x-ray attenuation of the object. Objects with low x-ray attenuation suffered greater variability than objects with high attenuation. Overall, our results conclusively demonstrate that CT numbers are not consistent through the image volume, and thus, mathematical equations cannot be easily applied to accurately derive HU through the imaged volume. Perhaps, future development

Table I. CT numbers of K_2HPO_4 phantoms measured at the various anatomical locations of a NewTom 3G CBCT scan

	Maxilla			*Mandible*		
K_2HPO_4 (mg/mL)	*Incisor*	*Premolar*	*Molar*	*Incisor*	*Premolar*	*Molar*
6 in FOV						
50	311 ± 53	148 ± 81	47 ± 64	347 ± 30	165 ± 49	120 ± 27
200	458 ± 46	253 ± 73	189 ± 74	511 ± 27	275 ± 62	265 ± 31
400	580 ± 44	356 ± 73	353 ± 68	599 ± 25	470 ± 58	434 ± 30
600	706 ± 47	573 ± 80	375 ± 55	761 ± 32	549 ± 58	486 ± 27
800	863 ± 50	699 ± 110	550 ± 52	931 ± 31	717 ± 67	637 ± 38
1000	1024 ± 59	829 ± 76	570 ± 60	1062 ± 24	858 ± 59	845 ± 27
1200	1127 ± 78	1005 ± 102	908 ± 47	1292 ± 21	931 ± 56	1053 ± 28
9 in FOV						
50	256 ± 58	24 ± 80	−170 ± 53	379 ± 35	118 ± 59	−82 ± 52
200	445 ± 55	156 ± 90	60 ± 66	505 ± 22	231 ± 63	144 ± 45
400	662 ± 48	262 ± 89	213 ± 62	752 ± 32	475 ± 55	314 ± 46
600	799 ± 56	541 ± 116	231 ± 68	985 ± 31	590 ± 57	528 ± 35
800	978 ± 55	673 ± 70	532 ± 52	1110 ± 37	782 ± 45	627 ± 42
1000	1173 ± 77	879 ± 96	625 ± 65	1388 ± 25	1001 ± 64	895 ± 53
1200	1170 ± 86	1040 ± 90	821 ± 50	1508 ± 35	1090 ± 57	956 ± 30
12 in FOV						
50	546 ± 70	44 ± 89	−166 ± 79	748 ± 70	299 ± 82	−64 ± 53
200	794 ± 68	183 ± 87	−27 ± 82	993 ± 62	425 ± 80	205 ± 57
400	987 ± 86	396 ± 120	149 ± 78	1175 ± 68	749 ± 55	458 ± 46
600	1216 ± 79	717 ± 115	326 ± 80	1512 ± 57	974 ± 54	545 ± 46
800	1391 ± 66	815 ± 97	533 ± 64	1566 ± 47	1156 ± 63	794 ± 53
1000	1665 ± 68	1082 ± 95	695 ± 79	1909 ± 41	1489 ± 67	1035 ± 46
1200	1614 ± 73	1298 ± 90	1001 ± 68	2214 ± 46	1661 ± 57	1292 ± 34

Table II. CT numbers of K_2HPO_4 measured at the various anatomical locations of a NewTom 5G CBCT scan

	Maxilla			*Mandible*		
K_2HPO_4 (mg/mL)	*Incisor*	*Premolar*	*Molar*	*Incisor*	*Premolar*	*Molar*
8 × 8 cm FOV						
50	406 ± 47	24 ± 145	154 ± 95	278 ± 24	202 ± 36	105 ± 87
200	604 ± 35	388 ± 72	340 ± 59	538 ± 27	423 ± 37	378 ± 70
400	879 ± 41	639 ± 82	515 ± 92	829 ± 38	648 ± 28	659 ± 49
600	1148 ± 58	704 ± 122	816 ± 88	1067 ± 35	900 ± 34	849 ± 71
800	1350 ± 53	894 ± 110	1046 ± 97	1227 ± 37	1169 ± 28	974 ± 62
1000	1589 ± 52	1114 ± 133	1220 ± 105	1503 ± 40	1438 ± 42	1330 ± 52
1200	1754 ± 45	1349 ± 107	1504 ± 78	1628 ± 27	1596 ± 40	1438 ± 36
8 × 8 cm FOV, high resolution mode scan						
50	378 ± 68	47 ± 100	145 ± 74	296 ± 51	118 ± 53	229 ± 50
200	608 ± 56	228 ± 100	405 ± 82	524 ± 57	397 ± 46	399 ± 96
400	858 ± 51	497 ± 99	592 ± 58	787 ± 59	688 ± 50	622 ± 72
600	1110 ± 66	679 ± 119	900 ± 70	1027 ± 41	900 ± 49	888 ± 58
800	1275 ± 55	908 ± 89	1054 ± 61	1268 ± 65	1104 ± 47	1073 ± 51
1000	1437 ± 69	1023 ± 90	1198 ± 95	1370 ± 63	1255 ± 45	1208 ± 64
1200	1583 ± 48	1236 ± 75	1393 ± 87	1529 ± 71	1404 ± 52	1342 ± 48
18 × 16 cm FOV						
50	389 ± 49	−18 ± 103	154 ± 77	357 ± 37	187 ± 34	213 ± 30
200	577 ± 35	259 ± 70	335 ± 55	596 ± 45	361 ± 106	225 ± 132
400	835 ± 31	366 ± 123	518 ± 87	589 ± 29	694 ± 39	457 ± 80
600	1044 ± 41	560 ± 133	724 ± 74	1072 ± 31	925 ± 49	665 ± 59
800	1258 ± 38	841 ± 106	916 ± 62	1271 ± 58	1118 ± 37	821 ± 58
1000	1382 ± 43	882 ± 95	1263 ± 57	1418 ± 41	1258 ± 37	837 ± 41
1200	1537 ± 30	1059 ± 110	1176 ± 52	1530 ± 49	1380 ± 36	1081 ± 23

of such algorithms should take into account the discrepancy in CT numbers based on anatomical location.

There are several factors that could contribute to the anatomical location based variation of CT numbers on CBCT scans.[5] Most importantly is the concept of "exomass" in CBCT images, the entire craniofacial skeleton is not included in the image volume.[16] Thus, there is a significant amount of the patient's tissue that attenuates x-radiation but is not included in the imaged volume. However, typical CBCT reconstruction algorithms assume that the x-ray attenuation takes place only within the imaged volume. A second cause of variation is the amount of scattered radiation.[17] Given the differences in the tissue thickness at the anatomical sites, it is conceivable that the noise from the scattered radiation might contribute, in part, to this inconsistency in the CT numbers. Both the above causes of inconsistency in CT number calculation vary between patients and perhaps also between the scans for each patient. Therefore, it is not practical to apply a mathematical correction to account for these factors. These concepts also highlight a limitation of studies that have used radiographic phantoms such phantoms typically consist of materials with different densities, encased within a cylinder of homogenous material, usually poly-methyl-methacrylate or water. Frequently, such phantoms are smaller than the FOV and would not suffer the exomass effect encountered in patient imaging.[16]

Our studies were done using the NewTom 3G unit, which uses an image intensifier as the x-ray detector, and the NewTom 5G unit, which uses a flat panel detector. Thus, our results are applicable to all currently available CBCT units. Another factor to consider in interpreting our result is that the kilovolt peak (kVp) used was of 110 for both units. Some CBCT units permit the use of a higher or lower kVp. Notably, lower kVp beams would be more susceptible to artifacts from beam hardening, and plausibly, these imaging protocols may exhibit greater anatomical location based variation in CT numbers. Similarly, the effect of milliamperage, which differs between different units and between FOVs within the same unit, may also contribute to the inhomogeneity of CT numbers.[18]

In conclusion, the relationship between CT numbers and object density is not uniform throughout the dental arch. Given this nonuniformity, simple comparison of absolute CT numbers measured at different anatomical locations may be misleading.

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