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REVIEW ARTICLE

Accuracy of cone-beam computed tomography in imaging the components of the periodontal phenotype

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Abstract

The components and dimensions of the periodontal and peri-implant phenotype have a high relevance in contemporary dental research and should be taken into consideration in the decision-making process in the management of a variety of clinical scenarios to optimize the outcomes of therapy. Various assessment methods for quantifying and classifying the phenotypical dimensions have emerged and developed in recent decades. Nevertheless, the use of cone-beam computed tomography (CBCT) scans remains the most commonly used approach worldwide. However, the accuracy to adequately imaging and measuring the dimensions of the hard and soft tissue components around teeth may represent a significant challenge in different clinical scenarios due to factors such as the age of the patient and motion during the scan, presence of metallic artifacts causing streaks and gray-value distortion, overlapping of soft tissue structures, machine performance, file processing, and small voxel size among others. These factors pose a particular challenge when tiny structures are under investigation, for example, the buccal/lingual bony or soft tissue layer of lower/upper incisors. Therefore, this review addresses the underlying technical information of the use of CBCT scans, and suggests some recommendations on the utilization of this method of assessment to optimally use it despite its' system-inherent limitations.

KEYWORDS
3D imaging, cone-beam computed tomography, dental digital radiographs, phenotype

1 | INTRODUCTION

In current clinical practice and research, understanding the effect of the periodontal and peri-implant phenotypical features in different clinical scenarios holds significant importance.[1,2] The periodontal phenotype is determined by the bone morphotype, which is characterized by the thickness of the alveolar bone plate, and the gingival phenotype, constituted by the gingival thickness and the keratinized tissue width.[3] While the supracrestal tissue height, defined as the dimension obtained from the zenith of the gingival margin to the most coronal part of the alveolar bone crest, was not initially included in the definition of periodontal phenotype provided in the 2017 World Workshop, recent studies recommended considering this component as an integral component of the periodontal phenotype due to its correlation with other phenotypic features and relevance in clinical practice.[4,5]

These site-specific phenotypic dimensions are subject to change over time depending on environmental factors (e.g., presence and progression of inflammatory diseases, orthodontic treatment, trauma), and clinical therapeutic interventions (e.g., hard and soft tissue augmentation therapies).[1,3] Nonetheless, the dimensions of

components of the periodontal phenotype have been recognized as a pivotal prognostic factor in periodontics, orthodontics, oral surgery, and in the context of implant therapy. Thus, correct assessment of the dimensions is of key importance.

When teeth are moved orthodontically outside the alveolar bone, labial/lingual bone dehiscence can occur, which can be followed by gingival recession.[6] This tooth movement can happen not only during the active treatment phase[7] but also in the post-treatment period through the activation of fixed round spiral wire retainers.[8] Therefore, determination of the bone morphotype and gingival phenotype is important for the planning of specific orthodontic movements. Nonetheless, the reports in the literature are contradictory as regards possible association between the extent of gingival recession in orthodontic patients and the degree of therapeutic incisor proclination, the width of the attached gingiva, the thickness of the mandibular symphysis, the facial type, oral hygiene, or periodontal conditions.[9]

Thin gingival phenotype, however, has been associated with a higher probability of mucogingival defects.[10] Gingival thickness and keratinized tissue width play also a big role in the long-term mucosal margin stability in gingival phenotype modification therapies, and have been recognized as a predictor for the outcomes of root coverage procedures.[11–13]

In restorative dentistry classic studies reported that the placement of subgingival restorations, inadequate embrasures, poor selection of the restorative material, or overhanging margins among others may induce a local irritation, disruption of the hemostatic biological interface, and the subsequent microbial dysbiosis and initiation of inflammatory disease.[3,14–16] Different studies revealed that sites presenting a thick phenotype respond differently compared to thin tissues under similar conditions (i.e., biofilm accumulation, trauma) or therapies. Thick tissues tend to exhibit a hyperplastic response whereas thin tissues are more prone to develop gingival recession.[11,17,18]

Several studies on the topic of the management of the extraction site have observed that the thicker the alveolar bone after tooth extraction with or without further intervention, the lower the post-extraction dimensional changes at the level of the alveolar ridge.[5,19–25] Similarly, in cases where no further intervention was performed, the thinner the alveolar bone after tooth extraction the higher the alveolar ridge atrophy and the thickening of the mucosal tissues.[5,19,20,26] Other studies have also observed a decrease in the need of bone augmentation procedures and less interproximal soft tissue changes in sites with a thicker bone phenotype.[24,27] Most recently, the dimensions of the supracrestal tissue compartment have been correlated with post-extraction dimensional changes.[5] Therefore, it seems evident that an adequate and reliable assessment of the dimensions of the phenotypical features is crucial in order to make judicious clinical decisions in daily clinical practice and in contemporary dental research to evaluate the effect of these dimensions in different therapies.

Several methods have been developed for classifying and quantifying bone and soft tissue thickness around dental implants and teeth, such as the use of merely visual inspection of the external features of the alveolar ridge and soft tissues,[28] the insertion of a periodontal probe into the sulcus to evaluate its transparency,[29–32] ultrasound,[30,32] non-invasive ultrasonography,[33,34] transmucosal horizontal probing,[32,35] or the use of cone-beam computed tomography (CBCT) with or without the superimposition of stereolithography (STL) files.[34,36–39] Despite the inherent limitations of each of the assessment modalities, the use of CBCT belongs to the most widely used methods in daily clinical practice and research. Hence, this review is focused on providing the Change “focus” by “emphasis” tion for the use of CBCT scans, with ~~a~~ focus on the technical limits that currently cannot be overcome. Technical and physical factors provide evidence in themselves which can be used to deduct clear and rigorous conclusions for the clinical application. Therefore, this review addresses the underlying technical information ~~of~~ the use of CBCT scans, and suggests some recommendations on how to optimally use it despite its' system-inherent limitations.

replace “of” by "for"

2 | BACKGROUND OF CONE-BEAM COMPUTED TOMOGRAPHY SCAN

2.1 | Background on image CBCT image reconstruction

Unlike two-dimensional (2D) radiographic projection images (e.g., intraoral radiographs), a CBCT (as well as a Computed Tomography (CT) scan) is a reconstructed image generated from the information contained in multiple (several hundred) 2D-projection radiographs. Like a CT a CBCT produces a three-dimensional (3D) representation of patient density from a large series of two-dimensional (2D) radiographic projection images. The latter are generally acquired from a circular (360°-) orbit of the X-ray source and the detector about the patient's head. If the exact imaging/projection-geometry of each of the hundreds of 2D-projection X-rays is exactly known, a process termed “backprojection” allows for accurate estimation of the patients' density at every specific location that has been exposed in the 2D radiographs. Conceptually, this is done by geometrically arranging all projection images relative to the patient in the pose and position in which the image had been acquired. The basic concept will be summarized in the following.

Due to the fact that patient-tissue density needs to be displayed somehow on a computer monitor, the concept of a 3D voxel representation was introduced. Voxels (acronym from “volume element”) are the 3D analogon to ~~the well-known~~ pixel (“picture element”) well known from, for example, digital photography. In other words, the density of patient tissue in a CBCT is represented by small cubic voxels that are arranged in a regular voxel-grid. This way of representation is termed “discrete” since it divides continuous patient anatomy into separate tiny entities, the voxels. Commonly, CBCT-voxels come with a side length between 0.08 and 0.3 mm. What we perceive as a CBCT-image is the array of these tiny cubic voxels, all of which have a distinct gray value (ideally representing the true patient's density

at that particular location) and three coordinates (*x*, *y*, *z*). It should be noted that this representation is not continuous as the actual true patient structure, rather it divides and represents anatomy in tiny cubic entities, the voxels. While at first sight, this seems not important, de facto this representation causes multiple artifacts and also has other shortcomings. Plus, the voxel size eventually determines spatial resolution, the main topic of this review.

The backprojection process can be briefly summarized as follows:

After virtually arranging all source and detector positions around the virtual voxel grid according to the true locations which were effective for every single one of the hundreds of X-ray projection images (Figure 1), from every image detector-pixel a line is constructed aiming at the 3D position of the X-ray source. For each voxel and projection k (i.e., source-to-detector position No. k) a distance $d(x_i,y_i,z_i)$ the "X-ray" (the constructed line) traversing through the voxel at position $v(x_i,y_i,z_i)$ can be computed. The gray value recorded in the detector pixel at this source-receptor position k can then be distributed to the voxels traversed by this "X-ray-line" according to the distances d the line intersects the respective voxels (Figure 1). If this is done for all pixels per source-receptor position over all acquired projections and these entries are subsequently, for example, averaged per voxel, a good estimation of the density of the patient located in each voxel is obtained and represented as gray value.

2.2 | Factors affecting image quality and spatial resolution

2.2.1 | Technical factors

The reader might conclude that if the voxel has a size of, for example, 0.08 mm, it should be possible to visualize a tiny structure of the same size. Indeed, the voxel size determines the physical limit of how small the smallest detail in the image can be to be visualized. The latter is termed "spatial resolution," a technical term defining the smallest detail visible in an image. It is also closely related to sharpness, that is, only high-resolution images also appear sharp. So if the voxel size fundamentally determines spatial resolution, why can it not be directly translated into the maximal spatial resolution? One factor is, for example, the well-known Nyquist-Shannon-Theorem.[40,41] The

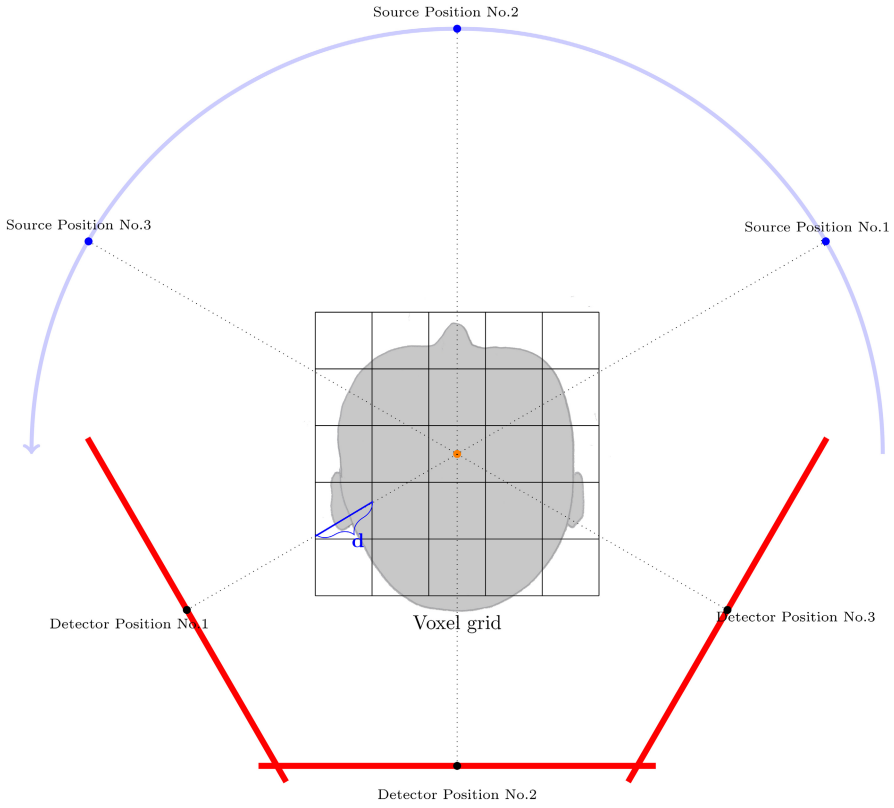

FIGURE 1 Sketch of the backprojection procedure used for 3D reconstruction. For simplicity, three exemplary out of several hundreds of exposure geometries are shown. The source-detector-unit rotates (here 180°) around the patient (center of rotation: red dot in the center of the voxel grid) who needs to be placed where the machines assume the virtual voxel array. For every geometry, that is, source-detector position in 3D-space each detector pixel (here illustrated as a black dot in the red detector line) a virtual line (corresponding to the "X-ray") to the source position (blue dot) is constructed. This intersects with some voxels of the virtual voxel grid which corresponds to the (steady) position where the patient needs to be positioned during exposure. The distance d within each respective voxel is used as a measure for which share of the gray value measured in the detector pixel at that particular geometry has to be distributed to that particular voxel. Averaging all entries for all pixels and all geometries within the voxels provides gray values that rather accurately represent the patient-tissue-density within the location of the voxel. last word should be plural: "voxels".

theorem states that for a signal to be correctly reproduced, any signal needs to be sampled at least twice the highest frequency contained in the signal. For a CBCT image, this means that the voxel size needs to be 1/2 or less than the size of the smallest detail under study.[40,41]

Apart from this fundamental signal processing theorem, there are a multitude of other issues involved with CBCT-data degrading its spatial resolution. Patient motion is one of the most important factors. As explained before, for the 3D-reconstruction process knowledge of the exact imaging geometry of every 2D radiograph is essential, otherwise the backprojection process is not feasible. As the reconstruction assumes a completely steady patient during the scan of several seconds, every single deviation (i.e., patient motion) from this assumption directly propagates as an error into the 3D-reconstruction process.[42] In other words, the patient during the scan moves outside the voxels in which the tissue was located at the beginning of the scan (see also Figure 1). The main effect apart from other artifacts is a degraded spatial resolution, also known as motion blur (unsharpness in the image).[42–44] Spin-Neto and colleagues showed that up to 83% of the patients move to an extent of >0.5 mm.[45] When considering typical voxel sizes of around 0.1 mm, this motion amplitude of 0.5 mm is fivefold the voxel size. It is easy to understand why the back projection process in this case fails to produce a sharp, that is, highly resolving image. Hardware solutions to immobilize the patient's head such as a chin-rest, or head strap should be used to limit head motion during the scan. However, it is known that such devices have their limits and likely will not eliminate small motion.[45]

Spatial resolution is not constant throughout the CBCT volume, rather it can vary up to 30% between the center of the volume and its periphery.[46] This can be mainly attributed to the Feldkamp-Kress reconstruction algorithm, which is commonly applied.[47] Due to mathematical reasons, this algorithm produces a more accurate reconstruction in the center of the CBCT volume.

Given all these parameters influencing spatial resolution, luckily, a multitude of exact measurements of the available (true) spatial resolution of CBCT machines for non-moving objects (phantoms) are available. More specifically, these come from quality assurance measurements which have to be repeated on a regular (commonly monthly) basis in some countries.[48,49] Repeated quality tests on spatial resolution are also advocated by medical physicists.[50] These tests are very advisable since very small changes in the geometric set-up and calibration of the machines have a direct effect on spatial resolution. For instance, if the machine is not perfectly leveled with respect to its horizontal rotation or if some wobbling of the source-detector-unit occurs, this will immediately introduce geometrical errors that manifest themselves as blurring/reduced spatial resolution in the images. De facto, both patient movement, as well as machine-related inaccuracies, induce identical errors in the reconstruction process. These errors can be summarized as "geometrical errors."

Spatial resolution can be measured by a subjective (line pairs per millimeter) and objective (Modulation Transfer Function (MTF)) method. While the first method visually assesses the number of perceptible lines per millimeter in a phantom image (Figure 2), the latter is a metric that can be automatically and objectively assessed from specific phantoms. Roughly translated, the MTF measures spatial resolution in relation to (normalized) contrast. While it produces an output in "cycles per millimeter," this can be safely translated into "line pairs per millimeter" as well. The limiting spatial resolution is normally associated with the value where the MTF falls to 10% of maximum contrast since this is the limit of visibility.[51]

Due to the above-mentioned quality assurance tests, values for MTF 10% are widely available. They typically range between 0.5 and 2.5 lp/mm (mean: 1.6 lp/mm, median: 1.8 lp/mm).[52] In this context, it should be noted that to qualify as dental CBCT, a publication by the European Commission requests a minimum spatial resolution of 1 lp/mm.[53] Some measured values are clearly below this minimum value. So how does a value of 1 lp/mm translate into visible detail size? Since a line pair contains two lines (a black one plus a white one in the phantom image Figure 3), the smallest detail is 1 mm/2 lines = 0.5 mm/line in size. In other words, a CBCT fulfilling the minimum requirements to qualify as dental CBCT[53] resolves only details of a minimum size of 0.5 mm. Table 1 lists the respective detail sizes computed from this equation for some typical spatial resolution values. We observe that for the highest measured MTF 10%-values (2.5 lp/mm) the smallest visible detail size amounts to 0.2 mm. Clearly, from these objective measurement values obtained from non-moving phantoms we understand that the true (available) spatial resolution of CBCT machines is always lower than the voxel size would imply. Noise is another factor posing limitations on spatial resolution. It represents inconsistent attenuation (gray) values in the projection images, that is, large standard deviations in areas where a constant gray should be present. In the reconstruction process, noisy projection images also yield a noisy 3D-reconstruction. Generally, CBCTs due to different reasons are relatively noisy images.[26,54] There are two major reasons for this characteristic: first of all, the wide-area detector captures a lot of scattered radiation that will appear as noise. Secondly, dental CBCT images need to be produced at lower radiation doses as compared to medical CT images. A lower dose increases the noise level in the image. Noisy images show large fluctuations in pixel values in the image that can mask lesions or structures of interest.[50] Thus noise also lowers the available (true) spatial resolution of the images.

In addition to these factors, artifacts in the area/vicinity of the structure under study will negatively affect its visibility. Artifacts can be defined as a visualized structure in the reconstructed data that is not present in the object under investigation.[42] For instance, beam hardening artifacts from high-density objects (e.g., metal, Figure 3) in the vicinity may severely interfere when assessing the object under study. As there is a multitude of artifacts contained in CBCT-images it is obvious that these may be another limiting factor for spatial resolution of the images.[42]

As a consequence, there are a multitude of different factors that interfere with CBCT image quality, particularly with its spatial resolution. From these technical limitations, it is evident that ~~the error~~

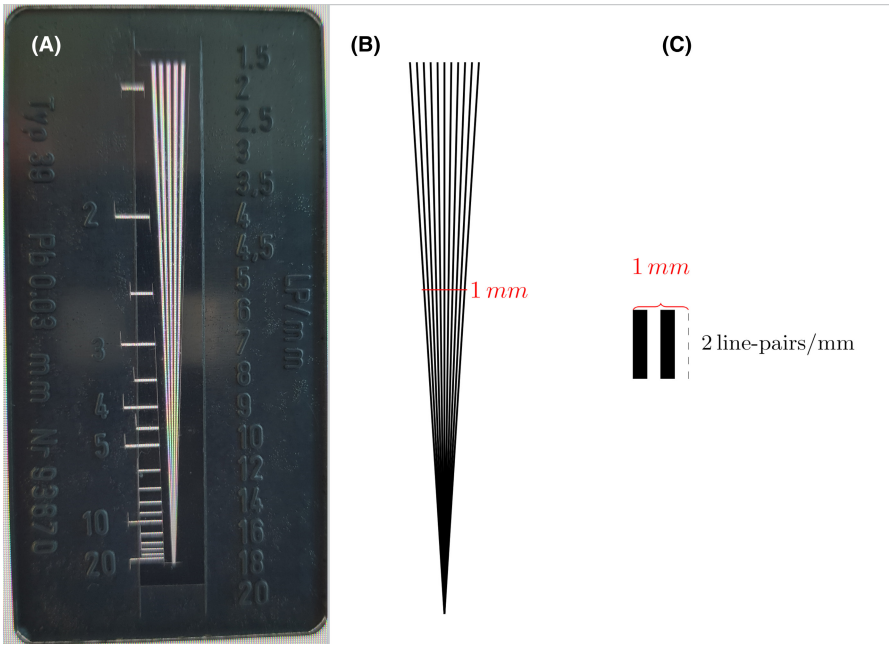

FIGURE 2 Photo (A) and Sketch (B) of a PMMA (polymethyl-methacrylate) line-pair phantom containing thin divergent lead-lines of defined small width. (C) Example for a measure of two line-pairs (LP) per millimeter which corresponds to visible detail of a minimum of 1 mm/4 lines = 0.25 mm/line.

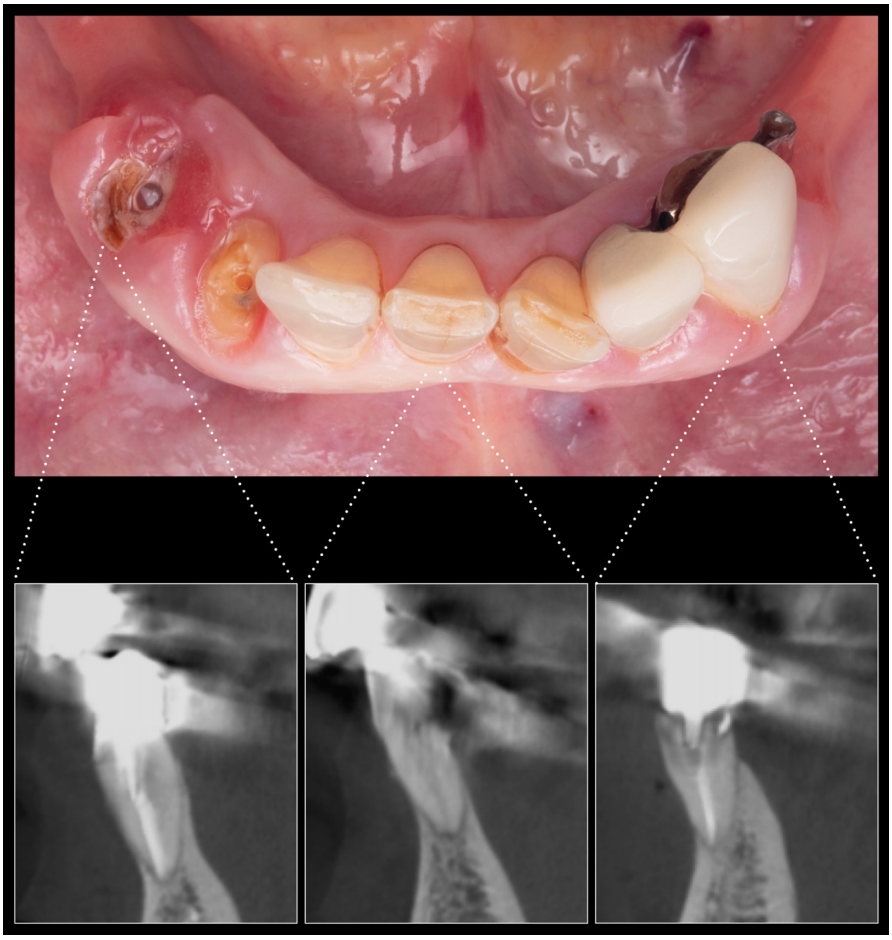

FIGURE 3 Example of beam hardening artifacts in the CBCT scan due to the presence of crowns and root canal material for endodontic purposes.

"the error in" needs to be discarded in this sentence!

~~in~~ CBCT-based assessment of tiny structures in the submillimeter range will be beset with a significant margin of error. This is supported by the observations of Domic and colleagues who found a detection accuracy of only 54% for a bone layer of <1 mm at dental implants.[55] Here, it should be noted that the metallic implant poses another difficulty in the assessment of adjacent structures as it also induces beam-hardening (plus other) artifacts in its vicinity.

As these pure accuracy deficiencies are independent of the size of a measured distance, obviously the absolute error will become more prominent with decreasing object size. In other words:

TABLE 1 Smallest visible detail size for the typical spatial resolution range of CBCTs as computed from values provided in the literature.[52]

MTF 10%	Resulting smallest visible detail size
1.0 lp/mm	0.50 mm
1.5 lp/mm	0.33 mm
2.0 lp/mm	0.25 mm
2.5 lp/mm	0.20 mm

Abbreviation: MTF 10%, Modulation Transfer Function at 10% modulation (explanation see Section 2.2.1).

measurements of small distances will be far more affected than those of large distances. If the distance under investigation is in the range of the size of a few voxels only, the error will largely contribute to the measured size.

Another error related to the observer is to pick the correct voxels as measurement endpoints. It is well known that even the image of a clearly visible machined sharp edge is being spread out over several voxels.[56] This makes a correct assignment of the endpoint voxels difficult. It should be noted that this error adds to the general inaccuracy contained in CBCT images.

2.2.2 | Anatomical factors

Considering the fact that a CBCT currently is constructed for visualization of hard-tissue contrast, soft tissues such as the gingiva/mucosa can only be clearly visualized if there is a high contrast to the adjacent tissue or structures. Since air appears very dark in the images, the best contrast will be between soft-tissue and air. If for instance air is not filling the oral vestibulum since the lip is directly adjacent to the gingiva/mucosa (Figure 4), the gingiva/mucosa cannot at all be discriminated in the image.

So if there is sufficient contrast, can the gingival tissue around teeth be accurately assessed in a CBCT? The answer again is mainly determined by the dimension (thickness) of this layer. In a human cadaver study based on histomorphometric measurements, it was found that soft tissue thickness in the anterior maxilla on average was entirely below 1 mm, with minimum values of 0.13 mm.[57] This minimum value is roughly in the range of CBCT-voxel size and thus cannot be correctly reproduced (and assessed) by a CBCT. Due to the factors discussed before any values below 1 mm will be beset with considerable error when assessed in a CBCT-image. No wonder, the authors found significant differences between the histomorphometric values (ground truth) and the CBCT assessed values. On average, CBCT values were 0.2 mm smaller than their histologically assessed counterparts.[57]

The hard tissue underneath this thin soft-tissue layer, that is, the buccal/lingual bony layer on frontal teeth commonly is also a very thin structure. Todorovic and colleagues in a micro-CT-study using human skulls observed that the buccal/lingual bone layer on

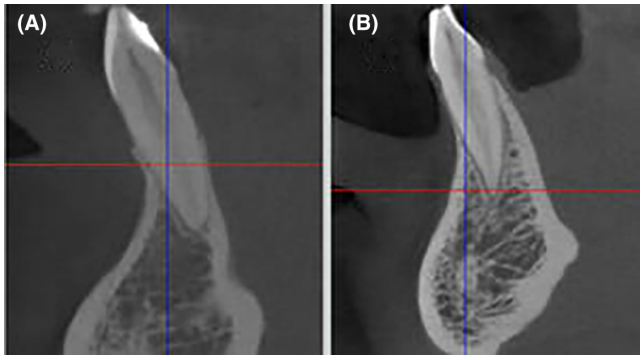

FIGURE 4 Illustration of the effect of overlapping soft tissue anatomical structures on the assessment of soft tissue dimensions. (A) Overlapping of the lip/cheek and tongue does not allow an adequate assessment of the buccal and lingual soft tissue. (B) Adequate visualization of the buccal and lingual gingival tissues; the CBCT was taken after placement of two paramedian cotton rolls buccally to hold the lower lip away from the teeth and instructing the patient to keep his tongue at the floor of the mouth (from the material analyzed in the study by Kloukos et al.[61]).

maxillary teeth commonly is <0.5 mm,[58] (Figures 5 and 6). In another human cadaver study, Patcas and colleagues found, 15 mm caudally to the incisal edge at mandibular anterior teeth, a median bone thickness of 0.82 mm with a minimum value of 0.14 mm.[59] Note that the authors used a measurement point rather deep into the alveoli where the bony layer is already relatively thick. These values prove the assumption that the thickness of the bony layer in frontal teeth commonly is in a range of the magnitude of the available CBCT spatial resolution. Therefore, even a 0.125 mm voxel could not depict the thin buccal/lingual alveolar bone covering reliably, having as a risk the overestimation of fenestrations and dehiscences.[59]

3 | CLINICAL AND TECHNICAL RECOMMENDATIONS

The limitations of a CBCT in the dimensional assessment of tiny structures are due to inevitable technical factors, which have to be accepted to avoid overinterpretation of the images. Thus, the most important general recommendation is not to expect a higher accuracy than 0.3–0.5 mm in a non-visibly motion-deteriorated CBCT image.[52] In light of these facts and despite the multitude of existing measurements (summary, e.g., in Ref. [52]) of the true accuracy of a CBCT, it is surprising that this very general recommendation in a clinical context often is neglected.

This is of particular importance for the assessment of the soft tissue compartment, as here the local contrast is generally poor making correct assessment of the tiny distance under investigation even more challenging. To enhance this local contrast to a maximum, measures to avoid the overlapping of soft tissue structures should be taken. This can be done by, for example, using lip-holders or inflating the mouth with air to keep the lips away from the gingiva.[36,60]

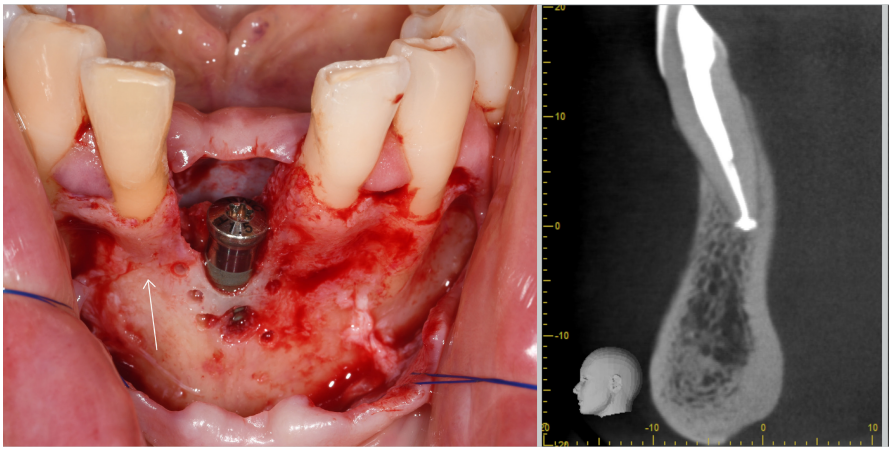

FIGURE 5 Clearly visible labial bony layer at tooth #41 in the photograph (left image) whereas no bony layer is visible in the central part of the root in the respective CBCT (right image).

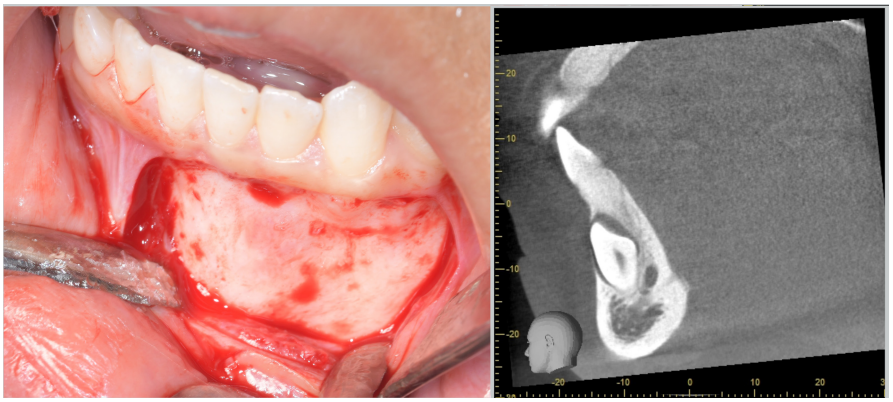

FIGURE 6 Another example for a partly non-visible bony layer covering a retained #43 in the CBCT (right image). The photograph (left image) clearly shows the covering bone.

Cotton rolls as retractor of the lip have also been proposed[61] (Figure 4). However, it should be noted that these will only have an effect on local contrast, not on the general measurement accuracy of the displayed tissue.

If we really want to achieve more accurate measurements, one solution is to use an optical scanner in addition, either on the anatomy itself or on a plaster model. Optical scanners have been shown to highly accurately detect and quantify gingival recessions using plaster models as a basis.[62] However, an intraoral optical scan may also be superimposed to a CBCT so that a combined image from the two modalities is generated. Here, the gingival/mucosal surface will be indicated as a clear line.[34,37] Since the spatial resolution of optical scanners is much higher than that of a CBCT, from a technical perspective these measurements should be far more accurate than those of a CBCT alone.[34,37] This theoretical assumption is supported by the findings of several experimental and clinical studies,[35,37,57] This non-tissue invasive optical scan method has also demonstrated adequate reliability and reproducibility.[5,37,63] Nevertheless, studies should be conducted using, for example, histomorphometric assessment of the gingival thickness to compare direct scans versus scans on the plaster model for this purpose. Unfortunately, this method does not help to enhance accuracy in the assessment of the thin buccal/lingual bony layer since this is hidden in the patient's anatomy. Here we can neither enhance local contrast by external measures nor can we easily obtain an auxiliary visualization of its surface. Only general measures will help to increase the image to an optimum. First of all, we should carefully select the appropriate, relatively small voxel size for the scan. In this context, however, it should be noted that small voxel sizes commonly increase scan time giving the patient more time to move. As motion counteracts spatial resolution, it is essential to find the "best possible" balance between voxel size and potential patient motion. If possible, hardware head immobilization should be applied, albeit this is also known to have its limits and probably cannot eliminate small movements.[45] It should be generally avoided to assume missing bone or a bony defect if there is no bony coverage visible in the CBCT image. Rather a careful conclusion should be drawn that it is simply impossible to accurately detect the presence or absence of a thin bony layer on a CBCT-image. For soft tissue, for the reasoning above, it is even more challenging to detect tiny structures in a CBCT. To maximize the chance for visualization of these structures, the following relatively simple measures should be considered:

- The patient should be immobilized by using the chin- and headrest (if existing).
- An appropriate voxel size should be selected (ca. 100 µm).
- The patient should be positioned such that artifacts from neighboring structures (e.g., metal) do not overlap the structure under study (see Ref. [42]).
- During the scan, facial soft tissue (lip) should be separated from the alveolar crest, for example, by a cotton roll placed in the vestibulum to increase local contrast.
- And, contrast and gray values should be appropriately adapted in the viewer before the measurement.

4 | DISCUSSION

This narrative review summarizes the technical background information providing insight into the options and limitations of CBCTs in the visualization of small/thin structures. While the technique is great to get a 3D impression of a patient's anatomy, it often fails when it comes to detecting tiny bony or, even worse, soft tissue. There are a variety of technical reasons for this limitation which can be summarized in one simple statement: the CBCT like any other imagery, technically spoken is a "good guess" of true anatomy, yet it is not "truth" itself. Simplified physical assumptions, coarse reconstruction methods and discrete representation of continuous patient anatomy are the most important reasons why a CBCT image does not show the full truth, but rather a decent "guess" on it.

Nevertheless, the images are extremely helpful in a clinical context, and it is no wonder that the technique has a triumphant success in many areas of dental medicine. If applied correctly, its use is manifold and patients will likely benefit in a multitude of different clinical scenarios. However, in the context of analyzing the gingival phenotype and bone morphotype, the technique has severe limitations when it comes to imaging small structures of submillimeter width. This may come as a surprise to clinical users, as often the industry promotes a resolution in the size of the tiny voxels, that is, even below 0.1 mm. This is even more surprising since established standards for quality testing provide excellent insight into the available spatial resolution of a variety of machines.[49] In addition, there are reviews published on the matter.[52] All this information very clearly shows that a CBCT resolves between 1 Lp/mm and maybe at a maximum 3 Lp/mm. We learned that this translates to 0.5 and 0.16 mm. However, as these values are all generated from non-moving phantoms, they do not contain motion blur which will almost inevitably occur to some extent in living patients.[42–44,64]

Interestingly, it has been shown that even in young and healthy subjects with normal blood pressure the amplitude measured at the front teeth for each heartbeat is >0.08 mm.[65] Here, the subjects were fixated on a chin rest and asked to relax. That means, that over a typical exposition time of, for example, 12 s assuming a normal heart-rate of 60/min at least 12 beats will be effective, each of which dislocates the patient's anatomy out of his/her initial position. Clearly, the smaller the voxels the more this effect will be of interest.

Thus, true spatial resolution in a living patient is somewhat lower than the one assessed in phantoms. To what extent it is lower is not well investigated yet, mainly since such measures in datasets only showing human anatomy are more complicated. De facto no established such method exists.

Typical tiny periodontal structures of interest are the gingiva and the bone-support of the anterior maxillary and mandibular teeth. In this context, we should also bear in mind that the threshold value discriminating between thick and thin phenotype is 1 mm.[3,5,19,22] While the image of a thick morphotype bone-layer is mostly visible in the CBCT (Figure 7), the issue with the accuracy of measuring that bone

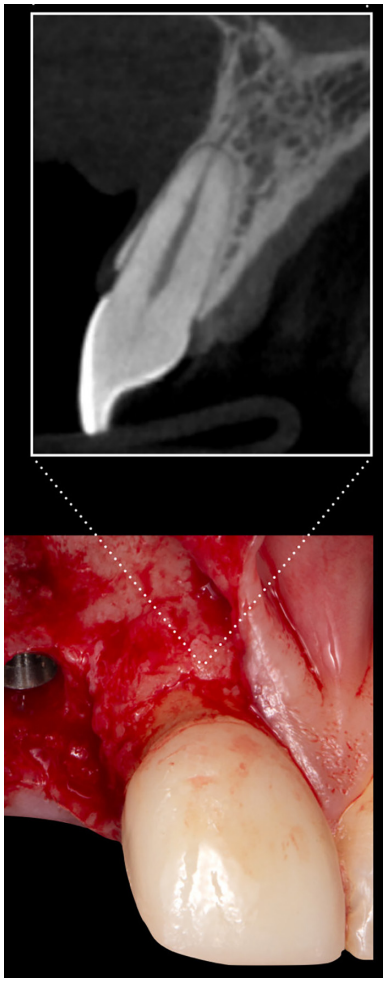

FIGURE 7 Contrastive example of a thick bone morphotype which, as opposed to thin bone, is clearly visible in the CBCT image.

in the image remains identical. Obviously, particularly for the thin phenotype due to the reasons above it will be challenging to visualize such thin structures. And even if it is visualized, what does a thickness value of 0.32 mm as displayed by the measuring software mean in reality? Certainly, we can safely suggest skipping the second digit, thus we arrive at 0.3 mm. A measurement error of ±1 voxel should be considered as potential uncertainty in the imaging plus the measurement process. So if the measured dimension is, for example, 0.32 mm and we have a voxel size of 100 µm (i.e., 0.1 mm), we will have a margin of error of 0.3 ± 0.1 mm. Yet if the data exhibit signs of increased patient motion or/and additional beam hardening or other artifacts in the measurement region, this value should be even more interpreted cautiously. For all the reasons mentioned, it is safe to conclude that CBCT is not the most accurate method in dimensional assessment of small/tiny structures of a size around or below 0.5 mm.

Here, albeit the authors claim a lack of sufficient studies, ultrasonography may be a viable and radiation-free alternative.[66] However, this method has the limitations of having a narrow field of view, the need to use a medium for sound conduction, and not being widely available due to its costs, and technical difficulties.[29,67] For soft-tissue components such as the labial gingiva

or the supracrestal tissue dimensions, the combination of a CBCT with an optical surface scan can provide more accurate results.[57] However, it has to be borne in mind that a CBCT induces a significant radiation dose, which greatly exceeds that of the 2D dental radiographic techniques.[68] Following the internationally established justification principle, each and every radiograph has to be individually justified balancing the patient's risk with the potential benefit.[69] As a consequence, alternative methods need to be taken into account.

In light of the limitations, CBCT studies only aiming to assess gingiva thickness or thin bony support dimensions seem hard to justify. Yet if acquired for other reasons, such measurements on an existing CBCT of course may be conducted. If applied cautiously and conservatively, these may still be valuable for clinical diagnosis and therapy. What should be avoided, however, are overinterpretation and overestimation of the accuracy since both may yield negative effects on the patient's side. For example, interpreting missing bone in a CBCT image as truly missing bone may jeopardize a front tooth without true reason. One can certainly think of many other similar examples along that line. Hence, the fundamental take-home message of this review is to interpret a CBCT cautiously and to realize it is a good (technically acquired) guess of reality yet not reality itself.

5 | CONCLUSION

CBCT scan is a viable method to measure the hard and soft tissue components of the periodontal phenotype. However, a thorough evaluation of factors influencing image quality and spatial resolution is necessary to prevent potential misinterpretations. Additionally, in the presence of thin periodontal phenotypes, the absence of visible bone/soft tissue layers in a CBCT scan might not necessarily imply their true absence. These technical limitations are inherent to CBCT-imaging and should be borne in mind when interpreting such images.

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CONFLICT OF INTEREST STATEMENT

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