3-Dimensional Cone-Beam Computed Tomography Superimposition: A Review

Article *in* Seminars in Orthodontics · July 2015

DOI: 10.1053/j.sodo.2015.07.007

3 authors:

Jae Hyun Park
A.T. Still University

Kiyoshi Tai
Arizona School of Dentistry and Oral Health, A.T. Still University

Payam Owtad
A.T. Still University

3-Dimensional cone-beam computed tomography superimposition: A review

Jae Hyun Park, DMD, MSD, MS, PhD (Professor and chair), Kiyoshi Tai, DDS, PhD (Visiting adjunct professor), and Payam Owtad, DDS, MS, DHEd (Orthodontist)

Traditionally, the superimposition of serial, two-dimensional cephalometric radiographs has been used for the evaluation of growth and treatment effects. Nowadays, the superimposition of cone-beam computed tomography (CBCT) images has become an important tool for three-dimensional (3D) assessment of changes with growth or treatment. However, the assessment of changes with 3D image superimposition poses many challenges such as accuracy and reproducibility. Various methods for the reconstruction of 3D CBCT images have been used in diagnosis, treatment planning, and simulation. In this article, the various 3D CBCT superimposition techniques and relevant evidences are discussed. Furthermore, their clinical applications, benefits, and limitations are addressed. (Semin Orthod 2015; ∎:∎∎∎–∎∎∎.)

Introduction

Cone-beam computed tomography (CBCT) is considered as a supplemental imaging technique when two-dimensional (2D) imaging does not provide sufficient information in orthodontic clinical assessments.[1,2] Common errors with 2D cephalometric radiographs include patient and hardware orientation errors and geometric error which is due to differential magnification and association error, which makes it difficult to identify an identical point seen from different angles on separate projections.[3]

CBCT scanners were introduced in the late 1990s as an evolutionary process, resulting from the demand for three-dimensional (3D) information obtained by conventional computerized tomography (CT) scans.[4,5] 3D CBCT images have been used in orthodontic diagnosis, treatment planning, and simulation to overcome common 2D cephalometric errors.[6–8]

In dentistry and orthodontics, high resolution CBCT is used to acquire a low distortion digital image of the hard and soft tissues of the craniofacial structures. CBCT machines have a cone shape x-ray beam that is the source of the cone-beam name, which is unlike conventional CT. Conventional CT uses a fan-shaped beam to create multiple thin slices. In CBCT systems, the resolution is measured in voxels instead of pixels, which is often sharper than a conventional CT. Panoramic and cephalometric projections that are produced by CBCT are transformed into a 3D format after the data has been reformatted in a volume by computer software.[9]

3D CBCT can be used to gather diagnostic information on temporomandibular joints, anatomic features of the mandible, and the morphology of the palate, and to measure the width of alveolar bones, to determine the position of the dental roots and supernumerary and impacted teeth, and to identify sites for implant placement or osteotomies.[10] CBCT imaging is also used to plan for orthodontic and orthognathic surgery treatment, to assess skeletal displacements after osteotomies, to verify treatment outcomes, and to determine stability.[11]

Arizona School of Dentistry & Oral Health, A.T. Still University, Mesa, AZ; Graduate School of Dentistry, Kyung Hee University, Seoul, South Korea; Private Practice of Orthodontics, Okayama, Japan.

Address correspondence to Jae Hyun Park, DMD, MSD, MS, PhD, Arizona School of Dentistry & Oral Health, A.T. Still University, 5835 East Still Circle, Mesa, AZ 85206. E-mail: JPark@atsu.edu

1073-8746/12/1801-$30.00/0
http://dx.doi.org/10.1053/j.sodo.2015.07.007

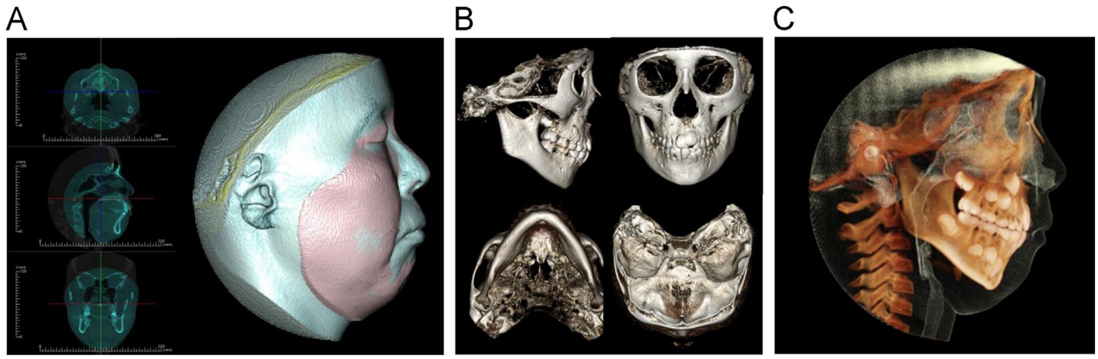

Figure 1. Multi-planar reconstruction (MPR) and volume rendered images. (A) Pre- and post-treatment superimposed MPR images and soft tissue volume rendered image. (B) Volume rendered hard tissue. (C) Volume rendered hard tissue overlaid by translucent soft tissue.

Multi-planar reconstruction (MPR) and volume rendered are the most commonly used 3D planes for measuring CBCT-derived cephalograms (Fig. 1).[12–15] When comparing physical skull measurements with 3D image measurements, point-to-point MPR measurements have been found to be highly accurate, while minor error is seen with volume rendered mode measurements, most likely due to surface contour estimations.[16,17] Therefore, identification and targeting of anatomical landmarks should be done in the MPR display mode.[15]

Superimposition of orthodontic 3D CBCT images is usually used for evaluating a patient's craniofacial growth or for comparing craniofacial structures before and after treatment.[11,18] The superimposition can be performed by registering stable anatomic landmarks or by software-assisted best-fit registration of stable anatomic structures such as the anterior cranial base.[18] A variety of software tools have been designed for 3D CBCT superimposition, which align the registered landmarks or cranial base structures.[19] For example, one of the anatomical structures that is commonly used for CBCT registration is the anterior cranial base.[11,18] It should be remembered that the accuracy and reproducibility of these superimposition methods are directly dependent on the accuracy of the landmarks and anatomic structures.

Superimposition of CBCT images has become an important tool for 3D assessment of changes with growth or treatment. 3D CBCT superimposition methods and clinical applications, benefits and limitations are discussed in this review.

3D CBCT superimposition in orthodontics

Two common 2D superimposition methods are the best-fit method and the structural method. The usual approaches for 3D superimposition are registration points or mathematical algorithms.[3] In the registration point approach, certain landmarks are registered on two volumetric images, which will coincide when the superimposition is made. After initial superimposition of the two images, the operator can manually move the superimposed images for further 3D fine-tuning. In mathematical algorithms, the initial 3D CBCT scan is considered to be the volume of interest (VOI) or the reference volume. Software, based on probability and information theory, then superimposes the second scan over the VOI in its best-fit position. The fusion process of the two images occurs automatically. It is not dependent on an operator's skill and is faster than manual methods.[3]

Various 3D superimposition methods are used for clinical diagnosis and treatment evaluation purposes in orthodontic treatment and craniofacial surgeries. There are valuable benefits and some limitations with each method. They are discussed in this article. A summary of 3D CBCT superimposition methods, applications, advantages, and limitations is presented in Table 1.

3D CBCT superimposition methods

With most software programs, a clinician does the initial alignment of the landmarks or anatomic structures of the two images to be superimposed, then computer software measures the changes in other anatomic

Table 1. 3D CBCT superimposition

Methods	*Clinical applications*	*Advantages*	*Limitations*
Registration points: software-assisted best-fit registration of arbitrary selected points, also called point-based *Information theory and mathematical algorithm*: software-assisted superimposition of the registered structures: *Surface-based*: iterative closest point (ICP) method *Voxel-based*: voxel by voxel best-fit registration method	Evaluating patients' craniofacial growth and/or craniofacial structures before and after orthodontics and orthognathic surgery treatment Quantifying and visually assessing hard and soft tissue changes between the two scans relative to the registered landmarks or structures; i.e., evaluating mid-facial soft tissue changes in the condyles, rami, chin, maxilla, and dentition, quantifying transverse dimensions and axial inclinations of dentition, and ramus displacement and airway assessments in 3D	3D assessments by the fusing of two 3D images in growing patients and/or during treatment process Observation of bilateral structures such as condylion, in real size 3D images is more precise and more reproducible than conventional 2D cephalometric images Provides a more realistic way to evaluate the changes A comprehensive visual and quantitative analysis Software-assisted 3D CBCT analysis Human error is eliminated during the automated superimposition processes Final manual fine-tuning in some of the techniques Creates accurate 3D surface models and accurate measurements with multi-planar reconstruction and color-coded images[a] Great repeatability and reproducibility[a] Minimal errors[a] Creates an unbiased scientific set up for the superimposition process[a]	Time consuming and computing intensive Measurement outcomes of a CBCT images can differ depending on window settings, plane definition, number and thickness of sections Slightly inferior to reality when threshold-based measurements are used Clinical measurements may be impacted by segmentation process Landmark identification and registration errors

[a]Subjects of controversy in the literature.

structures relative to the registered points or structures. The final superimposed image shows changes that have resulted from growth or treatment.[15,19–22]

Choi and Mah[23] reported a 3D superimposition method that is performed without prior landmark designation. This method is based on a matching criterion that uses the information theory and mutual information or relative entropy that was originally used for conventional CT images and magnetic resonance imaging.[24] By applying this theory, an operator is able to acquire geometrical information from a software program and use it in another one for a pre-segmented surface model comparison. In this way, it is possible to achieve a clear and precise registration plus subvoxel accuracy.[25] Moreover, with this system, it is possible to superimpose images and scans from different CBCT devices and software programs.[23]

With the iterative closest point (ICP) method, a more accurate measurement can be made by using the same points on the same surface with fusion at different time points.[26,27] The accuracy of linear measurements in 2D cephalograms and 3D scans are not the same because of a difference in the size and location of the objects in the two imaging systems.[28] Unlike conventional cephalometric radiographic analysis, the ICP method allows for the precise fusing of two 3D images from growing patients.[26,27] In the ICP technique, an operator manually defines a certain domain on the surface of the CBCT scans such as the outline of the anterior cranial base from the superior view (Fig. 2). Then the software automatically matches and registers the identical landmarks of the selected domains on the two scans and completes the superimposition process. The operator can evaluate and measure the changes relative to the registered surfaces. Learning to take image measurements is not difficult, but as with other software programs, it takes time to become proficient. After mastering the use of the software, image measurements can be made with great repeatability.[26] With the ICP 3D superimposition technique, registration of the scans over the cranial base is reported to be an accurate method for superimposition.[29–31] This method can be used for a valid and reproducible assessment of treatment outcomes for growing subjects. ICP is also considered to be clinically valuable because of the manageability and 3D accuracy of data comparison with MPR images (Fig. 3).[30]

The other method is voxel-based image registration, which is an accurate and reproducible semi-automated technique for 3D CBCT superimposition.[32,33] For example, when a patient is fully grown and developed, registration of the superimposed CBCT images of the zygomatic arches can be considered as an alternative to the anterior cranial base.[34] After superimposition, the differences between the two surfaces are mapped with about 600,000 color-coded surface distances in millimeters, which helps a practitioner quantify and visually assess the hard and soft tissue changes between the two scans relative to the cranial base.[19,35]

Gianquinto et al.[36] introduced a reproducible CBCT superimposition method based on the posterior cranial base in a single software package using a step-by-step manual technique. With this method, the craniofacial volume for each of their patients is imported to their 3D

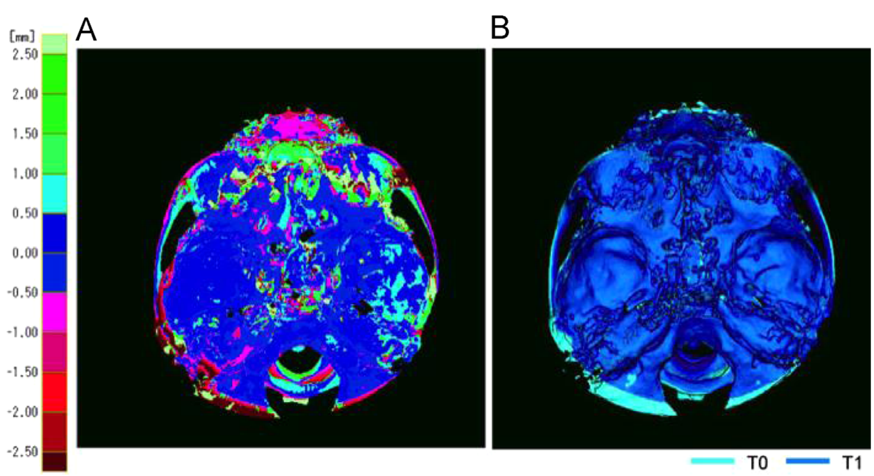

Figure 2. The iterative closest point (ICP) method. (A) Cranial base superimposition performed on all areas of the cranial base except the peripheral growing zone. (B) Merged image of pre-(T0) and post-treatment (T1) CBCT scans, superimposed at the cranial base.

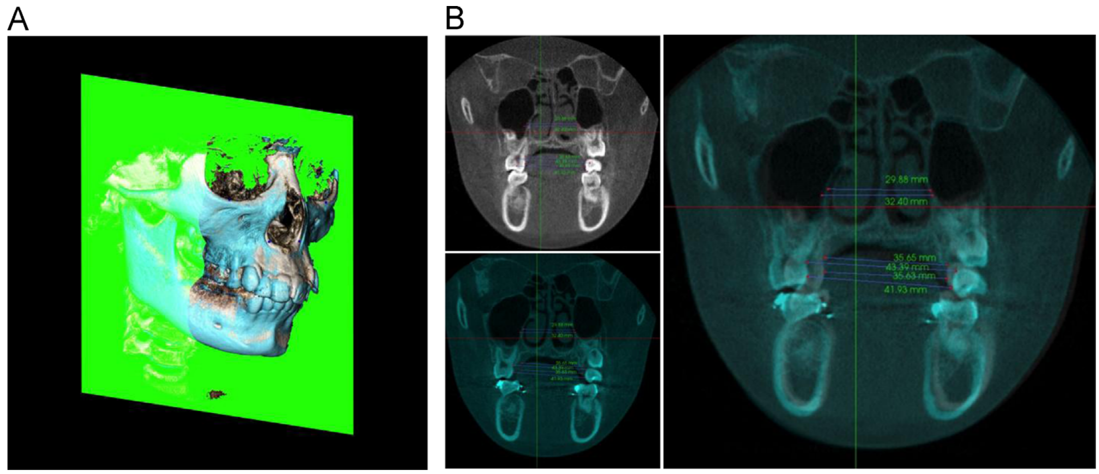

Figure 3. Superimposition using the iterative closest point (ICP) method. (A) The combined images, pre- (gray) and post-treatment (light blue) images, with illustration of an arbitrary coronal plane (green). (B) To facilitate measurement, the 3D sections were converted to 2D data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CBCT superimposition software. The software resamples the scans to a 0.5 mm voxel size, and then superimposes the images with a mutual information algorithm. At this stage, the operator uses a semi-automatic technique to extract posterior cranial base surface data, which results in a colored map based on the distance between the two volumes relative to the cranial base.[37]

Triple voxel-based CBCT superimposition is another method, which is used to build an augmented 3D skull model using rigid registration points from three separate CBCT scans made at a certain time point; the first scan with wax bite wafer in place and the second low-dose scan with a triple tray bite registration in place. Then the third CBCT scan is taken from the triple tray bite registration. With this method, the three scans are fused to create detailed occlusal and intercuspation data without the use of dental models.[33]

Clinical applications of 3D CBCT superimpositions

3D CBCT superimposition can be used to evaluate facial growth, craniofacial anomalies, and skeletal changes after orthodontics and orthognathic surgery (i.e., nasal morphologic and maxillary or mandibular skeletal changes after bimaxillary surgery), and to create 3D virtual craniofacial models (Fig. 4).[37–39] In addition, CBCT images can be used to evaluate mid-facial soft tissue changes,[21,40] to assess changes in the condyles, rami, chin, maxilla, and dentition,[11,18] and to measure the transverse dimensions and axial inclinations of dentition.[26]

CBCT imaging has been proven to be an essential tool for assessing growth and development, which provides the most comprehensive visual and quantitative analysis.[11,18] While some researchers consider 3D superimposition systems to be accurate,[15,41,42] there are some scientific reports that question the accuracy of these techniques.[34,43]

The anterior cranial base has been used as a reference structure for CBCT superimposition after orthognathic surgery in cases of skeletal Class III malocclusion to evaluate the postoperative mid-facial soft-tissue changes (Fig. 4B and C).[26,44] Anterior cranial bases are superimposed using the best fit of certain anatomic landmarks of the anterior cranial base followed by an automated voxel-based superimposition by the software. The anatomic landmarks of the anterior cranial base might be the inner cortical layer of the frontal bones, superior surfaces of the orbital roofs, superior aspect of the ethmoid and cribriform plate and cortical ridges on the medial, lesser wings of the sphenoid, planum sphenoidale, anterior clinoid processes, or the anterior wall of sella.[19] Cevidanes et al.[19] stated that

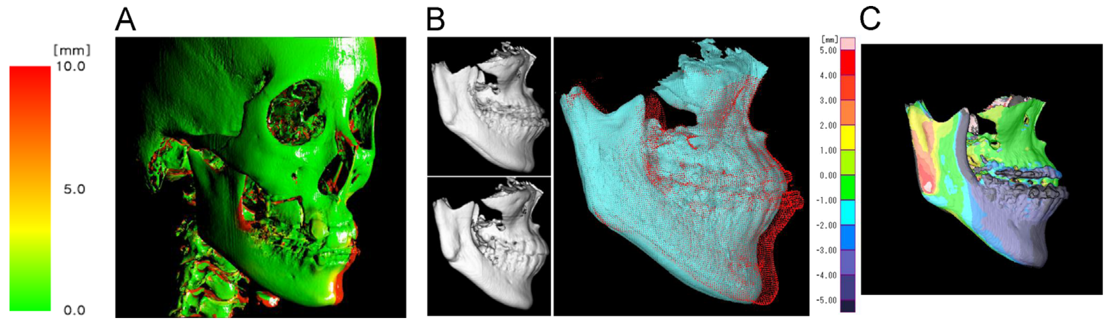

Figure 4. Different ways of visualization of the treatment outcome using overlay of registered 3D models. (A) The displacement magnitude of interface distances of pre- and post-treatment, registered by voxel-based method, is expressed by the different colors using quantitative color mapping by Morpheus3D CT Viewer (Morpheus). (B) Pre-treatment scan shown as a dotted red mesh and post-treatment scan shown in light blue, registered by ICP method, by Micro AVS (Cybernet). (C) The displacement magnitude of interface distances of pre- and post-treatment, registered by ICP method; quantitative color mapping by 3D-Rugle (Medic Engineering). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a precise registration on the anterior cranial base provides a reliable 3D assessment of craniofacial changes during growth and development by evaluating displacement of facial structures relative to the cranial base. In addition, clinicians can evaluate and describe treatment outcomes and changes due to future remodeling after treatment in a more comprehensive manner.

The anterior cranial base is reported to be one of the most accurate registration structures for 3D superimposition. However, with the anterior cranial base superimposition method, clinicians cannot definitively describe mandibular movement relative to the maxilla.[45,46] In order to evaluate mandibular changes relative to the maxilla, practitioners can register the two scans on a maxillary structure and perform the superimposition. This process is conventionally used in 2D structural superimposition methods. For this purpose, the registration points or structures can arbitrarily be selected by the operator, i.e., registering CBCTs over zygomatic structures in order to evaluate the changes in craniofacial structures relative to the zygomatic bones as a mid-face structure.[34]

Advantages of 3D CBCT superimposition

The accuracy of CBCT-derived cephalograms has been noted in numerous peer-reviewed articles, and it is reported that there is no statistical difference when comparing linear and angular measurements of traditional cephalograms and CBCT-derived cephalograms.[15,18,41,42] However, the accuracy is still a subject of some controversy in the literature because of the errors that could be introduced in CBCT scans.[26,32–34,43]

Observing full-scale 3D superimposed images of bilateral structures offers a more realistic way to evaluate the changes.[18,19,44] Comparison of 3D surfaces is also more reliable and precise than traditional 2D cephalometric evaluations.[18] By visualizing 3D model superimpositions, the location, magnitude, and direction of the hard tissue changes can easily be determined. This allows quantifying the ramal displacement in three dimensions.[47]

The availability of automated software for analyzing 3D CBCT scans is a big advantage of 3D digital systems over conventional 2D analyzing methods. In addition, using software for cranial base superimposition is better than conventional superimposition methods, since errors relative to landmark identification are eliminated and it is possible to determine anatomic structures and their contours. The software creates an unbiased scientific method for using the superimposition process.[18,42]

3D CBCT superimposition software offers operators the ability to superimpose 3D CBCT scanned surfaces, but it also provides a platform for performing quantitative analysis, which can provide valuable information.[48] Some software allows the operator to open two CBCT scans at the same time to register common landmarks more precisely. This software creates a cross-sectional visualization of the superimposed data set with different colors, which makes it possible to evaluate the differences between the two CBCT scans relative to the registered landmarks (Fig. 4).[42]

Limitations of 3D CBCT superimposition

Even though CBCT is now widely used in orthodontics,[47–49] orthognathic surgery treatments[18,25,47] and airway assessments,[1,9,10,50] only limited evidence is currently available in the literature regarding the accuracy of 3D CBCT superimposition techniques and the options for registration points or structures.[34] Certain errors have been associated with 3D superimpositions such as errors during visualization and improper identification or location of landmarks. It is also challenging to use the anterior cranial base as a registration structure.[3] In addition, reliable directional tendencies relative to growth are hard to determine since different structures grow and move in different directions. In the future, the development of vectorial analysis tools may help to clarify the displacement directions.[10,18,19]

Moreover, while the use of CBCT superimposition has significantly increased for assessing changes between serial CBCT scans, the accuracy of CBCT scan superimposition techniques and a standardized method of selecting anatomical structures for 3D superimposition has not yet been established.[34] The measurement outcomes from CBCT images can differ depending on window settings, plane definition, and the number and thickness of sections. Therefore, universal software should be used for CBCT image measurement as well as software with an ability to control variables.[43]

One of the other limitations of 3D CBCT superimposition is the fact that even though CBCT images can be used to create very accurate 3D surface models, they are somewhat inferior to reality when threshold-based methods are used. Differences in the segmentation process of CBCT analysis can result in clinically significant variances between measurements that can affect treatment. Therefore, when making a decision based on CBCT measurement on a 3D surface model, special attention must be given in the areas of the condyle and the lingual side of the mandible, as it is reported that the risk of measurement errors is higher in these areas.[51]

Even though 3D CBCT superimposition software can provide a significant amount of quantitative data, this high amount of information sometimes makes it difficult for the practitioner to formulate a straight and concise conclusion.[18] This problem can be overcome by limiting the quantitative analysis to particular landmarks and very particular surfaces or points at each intervention and quantitative analysis.

In order to apply 3D CBCT superimposition techniques in routine orthodontic treatment planning, a faster, simpler, and more user-friendly method must be implemented. It is imperative that scientific studies on the current 3D superimposition techniques be conducted in orthodontic clinical practices and graduate programs, to further the developmental process of these techniques.[11]

Photographs/digital models and CBCT superimposition

More recently, CBCT has been used with the registration of skin surface images,[29] so clinicians can quantitatively assess 3D maxillofacial morphology, and evaluate linear and angular changes in facial soft and hard tissues in clinical procedures. Standard normative 3D values for the craniofacial hard and soft tissues of normal women were calculated by Terajima et al.,[52] and were then compared with 3D CT measurements before and after patients had orthognathic surgery. It is reported that with this method, they were able to quantitatively assess craniofacial structure deviation from the norm before surgery and the changes in the hard and soft tissues after surgery. While this method is reliable and clinically sound, they reported that more investigation is needed with before this method is used in other diagnostic and treatment planning applications.[52] Cevidanes et al.[19] also reported that because 3D surface models superimposition is currently time consuming and computing intensive, its use in routine clinical practice is not very practical. Therefore, more simplified analysis techniques are required for 3D superimposition techniques to be viable in routine daily practice.

Clinicians, scientists, and engineers have developed techniques for superimposing facial

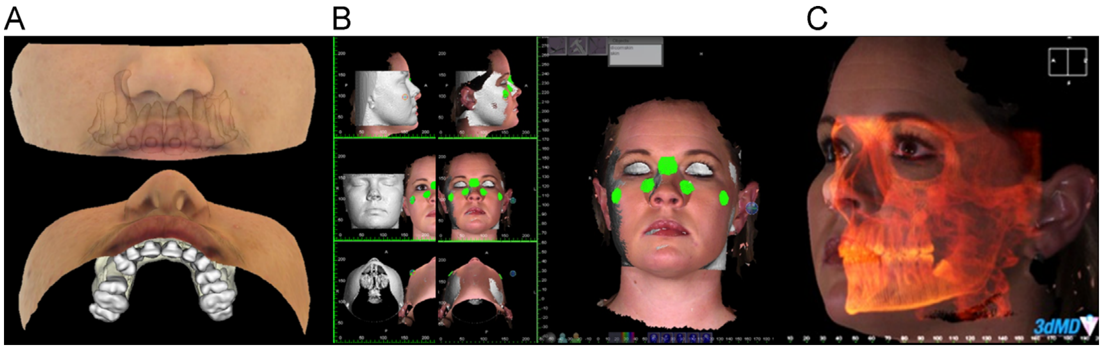

Figure 5. 2D photograph and 3D stereophotograph superimposition over CBCT scan. (A) Limited view of a 2D photographs superimposed over volume rendered maxillary dentition from a CBCT scan with InVivoDental software by Anatomage. (B) The matching process of CBCT soft tissue, and 3D stereophotograph, captured by 3D MDface^{TM} stereophotograhic system; initial registration surfaces are shown in green. (C) Merged image of the 3D soft tissue stereophotograph and the 3D CBCT hard tissue image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2D photographs[48] and 3D photographs,[29,37,39,53] and digital models[40,42,54,55] over CBCT scans. It is reported that the integration of 3D photographs and CBCT images has shown minimal errors in the assessment of bone and soft tissue.[56] Therefore, this process can be used as an objective tool for diagnosis and treatment planning in orthodontics and orthognathic surgery (Figs. 5 and 6).[56]

Multi-sensor image fusion techniques have allowed for more advanced diagnosis and treatment strategies in the field of 3D imaging.[57] In addition, image fusion is considered to be a dependable and precise method which is not affected by surgical and longitudinal changes.[19,58] There has also been an increase in use of image fusion techniques in orthodontics and maxillofacial surgery, which has provided more accurate and reliable information for surgical outcomes and treatment progress.[10,25,59] However, 3D CBCT image superimposition via semi-automatic registration methods is a relatively new concept on which little research has been conducted yet relative to its accuracy.[58] The superimposition of certain landmarks is a more precise and reproducible method than conventional 2D cephalometric images, especially with the bilateral landmarks such as condylion, gonion, and orbitale in 3D images. On the other hand, it is more difficult to accurately define certain landmarks in the third dimension of the mediolateral direction.[60] A summary of photographs/digital models and CBCT superimposition methods, applications, advantages, and limitations is presented in Table 2.

Conclusion

Superimposition of 3D CBCT scans in orthodontics and orthognathic surgery is usually used for craniofacial growth evaluations or for post-treatment assessment of changes in the craniofacial structures such as a 3D evaluation of changes in the mid-facial soft tissue, the condyles, rami, chin, maxilla, and dentition. Performing quantitative analysis on superimposed images and visualization of the craniofacial changes at different time points by color-coded fused images are two of the main advantages of 3D superimpositions.

Various 3D superimposition methods have been developed including the use of registration points, information theory such as the ICP method and voxel-based image registration, a single software package using a step-by-step manual technique, and triple voxel-based superimposition. These methods are mainly based on registration of anatomic structures and automated fusion of the images using computerized mathematical algorithms. More recently, superimposition of CBCT scans with 2D and 3D skin surface photographs have been used to assess 3D maxillofacial hard and soft tissue morphology, in addition to the evaluation of the linear and angular changes in clinical procedures.

Even though the 3D superimposition methods are clinically more accurate and reproducible than conventional 2D methods, the precision of these methods is still a subject of

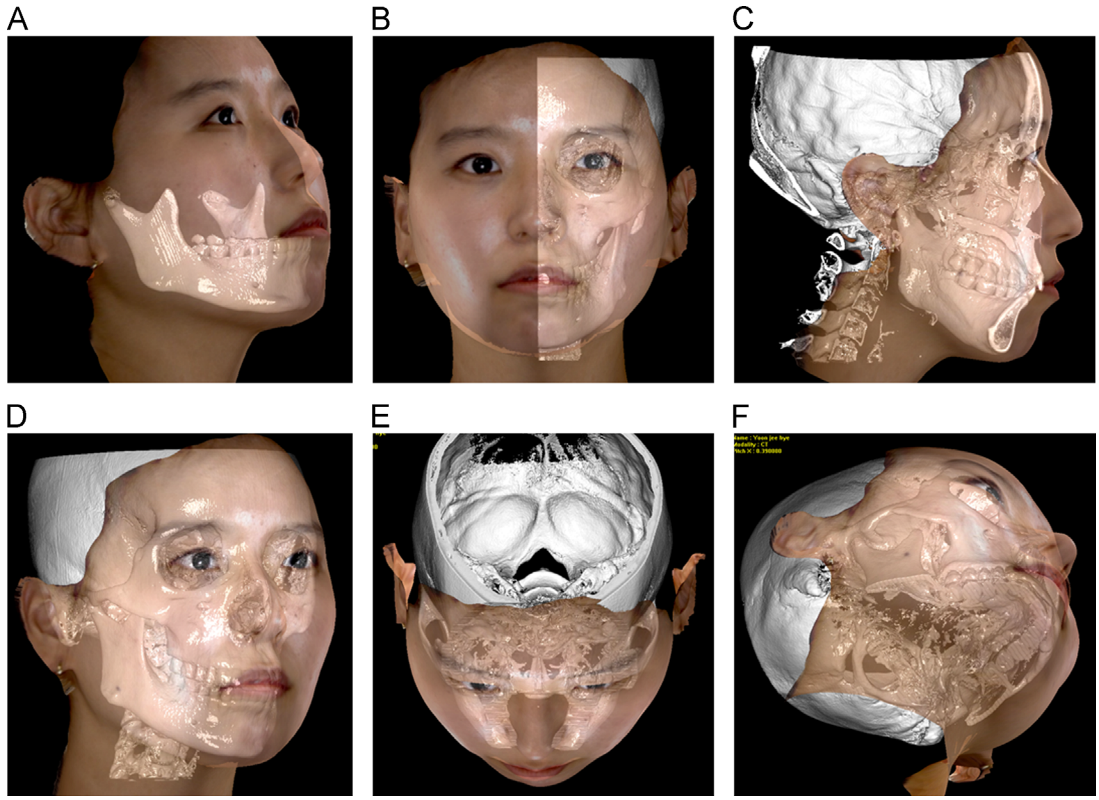

Figure. 6. 3D photograph superimposition over CBCT scan with Morpheus3D CT software (Morpheus). The 3D photographs superimposed over (A) volume rendered mandible, (B) mid-sagittal section of the CBCT (frontal view), (C) mid-sagittal section of the CBCT (lateral view), (D) full CBCT (¾ view), (E) superior view with anterior coronal section of the CBCT, and (F) inferior ¾ view with sectioned out mandible.

controversy in the literature. Most of the limitations of 3D superimposition techniques are related to imaging and landmark identification errors and software/hardware related errors. In addition, most of the methods that are currently being used in clinical settings are time consuming. Therefore, more research-based technological developments are required in this field to create more efficient and faster 3D superimposition techniques with higher accuracy and higher reproducibility.

Table 2. Photographs/digital models and CBCT superimposition

Methods	*Clinical applications*	*Advantages*	*Limitations*
Registration and superimposition of 3D digital models, and/or skin surface of facial 2D and 3D photographs over CBCT scans	Quantitatively assess 3D maxillofacial morphology, and evaluate the linear and angular changes in facial soft and hard tissues in clinical procedures Assessment of bone and soft tissue Advanced diagnosis and treatment planning in orthodontics and orthognathic surgery Provides a more accurate and reliable information for craniofacial growth, surgical outcomes, and treatment progress than conventional methods	Precise and dependable method	Expensive Limited evidence Time consuming Technique sensitive

Acknowledgment

The authors would like to thank Ms. Jennifer Huynh for her help with literature review.

References

1. Mah JK, Huang JC, Choo H. Practical applications of cone-beam computed tomography in orthodontics. *J Am Dent Assoc*. 2010;141(suppl 3):7S–13S.
2. Smith BR, Park JH, Cederberg RA. An evaluation of cone-beam computed tomography use in postgraduate orthodontic programs in the United States and Canada. *J Dent Educ*. 2011;75:98–106.
3. Heon JC. Three-dimensional superimposition. *PCSO Bull*. 2010;82:23–26.
4. Danforth RA, Peck J, Hall P. Cone beam volume tomography: an imaging option for diagnosis of complex mandibular third molar anatomical relationships. *J Calif Dent Assoc*. 2003;31:847–852.
5. Vishwanath AE, Sandesh SP, Nandini SN, Neelima A. CBCT—an advanced diagnostic tool for orthodontics and other specialties in dentistry—a systematic review. *Orthod Cyber J*. 2012.
6. Hatcher DC, Aboudara CL. Diagnosis goes digital. *Am J Orthod Dentofacial Orthop*. 2004;125:512–515.
7. Harrell WE Jr, Hatcher DC, Bolt RL. In search of anatomic truth: 3-dimensional digital modeling and the future of orthodontics. *Am J Orthod Dentofacial Orthop*. 2002;122:325–330.
8. Miller AJ, Maki K, Hatcher DC. New diagnostic tools in orthodontics. *Am J Orthod Dentofacial Orthop*. 2004;126:395–396.
9. Agrawal JM, Agrawal MS, Nanjannawar LG, Parushetti AD. CBCT in orthodontics: the wave of future. *J Contemp Dent Pract*. 2013;14:153–157.
10. Cevidanes LH, Styner MA, Proffit WR. Image analysis and superimposition of 3-dimensional cone-beam computed tomography models. *Am J Orthod Dentofacial Orthop*. 2006;129:611–618.
11. da Motta AT, de Assis Ribeiro Carvalho F, Oliveira AE, Cevidanes LH, de Oliveira Almeida MA. Superimposition of 3D cone-beam CT models in orthognathic surgery. *Dent Press J Orthod*. 2010;15:39–41.
12. Scarfe WC, Farman AG, Sukovic P. Clinical applications of cone-beam computed tomography in dental practice. *J Can Dent Assoc*. 2006;72:75–80.
13. Periago DR, Scarfe WC, Moshiri M, Scheetz JP, Silveira AM, Farman AG. Linear accuracy and reliability of cone beam CT derived 3-dimensional images constructed using an orthodontic volumetric rendering program. *Angle Orthod*. 2008;78:387–395.
14. Farman AG, Scarfe WC. The basics of maxillofacial cone beam computed tomography. *Semin Orthod*. 2009;15:11.
15. Kapila S, Conley RS, Harrell WE Jr. The current status of cone beam computed tomography imaging in orthodontics. *Dentomaxillofac Radiol*. 2011;40:24–34.
16. Stratemann SA, Huang JC, Maki K, Hatcher DC, Miller AJ. Evaluating the mandible with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2010;137:S58–S70.
17. Stratemann SA, Huang JC, Maki K, Miller AJ, Hatcher DC. Comparison of cone beam computed tomography imaging with physical measures. *Dentomaxillofac Radiol*. 2008;37:80–93.
18. Motta AT, de Assis Ribeiro Carvalho F, Cevidanes LH, de Oliveira Almeida MA. Assessment of mandibular advancement surgery with 3D CBCT models superimposition. *Dental Press J Orthod*. 2010;15:45e1–45e12.
19. Cevidanes LH, Heymann G, Cornelis MA, DeClerck HJ, Tulloch JF. Superimposition of 3-dimensional cone-beam computed tomography models of growing patients. *Am J Orthod Dentofacial Orthop*. 2009;136:94–99.
20. Mah JK, Yi L, Huang RC, Choo H. Advanced applications of cone beam computed tomography in orthodontics. *Semin Orthod*. 2011;17:57–71.
21. Cevidanes LH, Oliveira AE, Grauer D, Styner M, Proffit WR. Clinical application of 3D imaging for assessment of treatment outcomes. *Semin Orthod*. 2011;17:72–80.
22. Nguyen T, Cevidanes L, Paniagua B, Zhu H, Koerich L, De Clerck H. Use of shape correspondence analysis to quantify skeletal changes associated with bone-anchored Class III correction. *Angle Orthod*. 2014;84:329–336.
23. Choi JH, Mah J. A new method for superimposition of CBCT volumes. *J Clin Orthod*. 2010;44:303–312.
24. Maes F, Collignon A, Vandermeulen D, Marchal G, Suetens P. Multimodality image registration by maximization of mutual information. *IEEE Trans Med Imaging*. 1997;16:187–198.
25. Cevidanes LH, Bailey LJ, Tucker GR Jr., et al. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. *Dentomaxillofac Radiol*. 2005;34:369–375.
26. Tai K, Park JH, Mishima K, Shin JW. 3-Dimensional cone-beam computed tomography analysis of transverse changes with Schwarz appliances on both jaws. *Angle Orthod*. 2011;81:670–677.
27. Tai K, Park JH, Superimposition of 3-dimensional cone-beam computed tomography for 2-dimensional image analysis,. In Park JH: Computed Tomography: New Research, ed Nova Science Publishers, Inc., Hauppauge, NY, 2013, 457–475.
28. Rayapudi N, Padmalatha C, Gandikopta CS, Yudhistar PV, Tircoveluri S. A comparative study of linear measurements of facial skeleton using computed tomography and traditional cephalometry. *APOS Trends Orthod*. 2013;3:7.
29. Naudi KB, Benramadan R, Brocklebank L, Ju X, Khambay B, Ayoub A. The virtual human face: superimposing the simultaneously captured 3D photorealistic skin surface of the face on the untextured skin image of the CBCT scan. *Int J Oral Maxillofac Surg*. 2013;42:393–400.
30. Tai K, Park JH, Mishima K, Hotokezaka H. Using superimposition of 3-dimensional cone-beam computed tomography images with surface-based registration in growing patients. *J Clin Pediatr Dent*. 2010;34:361–367.
31. Tai K, Hotokezaka H, Park JH, et al. Preliminary cone-beam computed tomography study evaluating dental and skeletal changes after treatment with a mandibular Schwarz appliance. *Am J Orthod Dentofacial Orthop*. 2010;138:262.e1–262.e11.
32. Heymann GC, Cevidanes L, Cornelis M, De Clerck HJ, Tulloch JF. Three-dimensional analysis of maxillary protraction with intermaxillary elastics to miniplates. *Am J Orthod Dentofacial Orthop*. 2010;137:274–284.

33. Swennen GR, Mollemans W, De Clercq C, et al. A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning. *J Craniofac Surg*. 2009;20:297–307.
34. RM, Maal TJ, Breuning KH, Berge SJ, Mostafa YA, Kuijpers-Jagtman AM. Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches. *PLoS One*. 2011;6:e16520.
35. Cevidanes LH, Motta A, Proffit WR, Ackerman JL, Styner M. Cranial base superimposition for 3-dimensional evaluation of soft-tissue changes. *Am J Orthod Dentofacial Orthop*. 2010;137:S120–S129.
36. Gianquinto JR, Tuncay OC, Sciote JJ, Yang J. A method of superimposition of CBCT volumes in the posterior cranial base. *The Temple University Digital Library*. The Temple University; 2011.
37. Kau CH, Olim S, Nguyen JT. The future of orthodontic diagnostic records. *Semin Orthod*. 2011;17:6.
38. Sun Y, Luebbers HT, Politis C. Three-dimensional virtual model surgery to fabricate the digital intermediate splint. *J Craniofac Surg*. 2013;24:563–565.
39. Kau CH. Creation of the virtual patient for the study of facial morphology. *Facial Plast Surg Clin North Am*. 2011;19:615–622.
40. Park TJ, Lee SH, Lee KS. A method for mandibular dental arch superimposition using 3D cone beam CT and orthodontic 3D digital model. *Korean J Orthod*. 2012;42:169–181.
41. Farman AG, Scarfe WC. Development of imaging selection criteria and procedures should precede cephalometric assessment with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2006;130:257–265.
42. Chenin DL, Chenin DA, Chenin ST, Choi J. Dynamic cone-beam computed tomography in orthodontic treatment. *J Clin Orthod*. 2009;43:507–512.
43. Spin-Neto R, Marcantonio E Jr, Gotfredsen E, Wenzel A. Exploring CBCT-based DICOM files. A systematic review on the properties of images used to evaluate maxillofacial bone grafts. *J Digit Imaging*. 2011;24:959–966.
44. Lee JY, Kim YI, Hwang DS, Park SB. Effect of setback Le Fort I osteotomy on midfacial soft-tissue changes as evaluated by cone-beam computed tomography superimposition for cases of skeletal Class III malocclusion. *Int J Oral Maxillofac Surg*. 2013;42:790–795.
45. Efstratiadis S, Baumrind S, Shofer F, Jacobsson-Hunt U, Laster L, Ghafari J. Evaluation of Class II treatment by cephalometric regional superpositions versus conventional measurements. *Am J Orthod Dentofacial Orthop*. 2005;128:607–618.
46. Ghafari J, Engel FE, Laster LL. Cephalometric superimposition on the cranial base: a review and a comparison of four methods. *Am J Orthod Dentofacial Orthop*. 1987;91:403–413.
47. Cevidanes LH, Bailey LJ, Tucker SF, et al. Three-dimensional cone-beam computed tomography for assessment of mandibular changes after orthognathic surgery. *Am J Orthod Dentofacial Orthop*. 2007;131:44–50.
48. Grauer D, Cevidanes LS, Proffit WR. Working with DICOM craniofacial images. *Am J Orthod Dentofacial Orthop*. 2009;136:460–470.
49. Cho HJ. A three-dimensional cephalometric analysis. *J Clin Orthod*. 2009;43:235–252.
50. Park SB, Kim YI, Son WS, Hwang DS, Cho BH. Cone-beam computed tomography evaluation of short- and long-term airway change and stability after orthognathic surgery in patients with Class III skeletal deformities: bimaxillary surgery and mandibular setback surgery. *Int J Oral Maxillofac Surg*. 2012;41:87–93.
51. Engelbrecht WP, Fourie Z, Damstra J, Gerrits PO, Ren Y. The influence of the segmentation process on 3D measurements from cone beam computed tomography-derived surface models. *Clin Oral Investig*. 2013;17:1919-27.
52. Terajima M, Yanagita N, Ozeki K, et al. Three-dimensional analysis system for orthognathic surgery patients with jaw deformities. *Am J Orthod Dentofacial Orthop*. 2008;134:100–111.
53. Jayaratne YS, McGrath CP, Zwahlen RA. How accurate are the fusion of cone-beam CT and 3-D stereophotographic images?*PLoS One*. 2012;7:e49585.
54. Lin HH, Chiang WC, Lo LJ, Sheng-Pin Hsu S, Wang CH, Wan SY. Artifact-resistant superimposition of digital dental models and cone-beam computed tomography images. *J Oral Maxillofac Surg*. 2013;71:1933–1947.
55. Cevidanes LH, Tucker S, Styner M, et al. Three-dimensional surgical simulation. *Am J Orthod Dentofacial Orthop*. 2010;138:361–371.
56. Jayaratne YSN, McGrath CPJ, Zwahlen RA. How accurate are the fusion of cone-beam CT and 3-D stereophotographic images? *PLoS One*. 2012;7.
57. Tsao J. Interpolation artifacts in multimodality image registration based on maximization of mutual information. *IEEE Trans Med Imaging*. 2003;22:854–864.
58. Lee JH, Kim MJ, Kim SM, Kwon OH, Kim YK. The 3D CT superimposition method using image fusion based on the maximum mutual information algorithm for the assessment of oral and maxillofacial surgery treatment results. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 2012;114:167–174.
59. Lagravere MO, Major PW, Carey J. Sensitivity analysis for plane orientation in three-dimensional cephalometric analysis based on superimposition of serial cone beam computed tomography images. *Dentomaxillofac Radiol*. 2010;39:400–408.
60. Ludlow JB, Gubler M, Cevidanes L, Mol A. Precision of cephalometric landmark identification: cone-beam computed tomography vs conventional cephalometric views. *Am J Orthod Dentofacial Orthop*. 2009;136:312.e1–312.e10.