Application and Development of Three-dimensional Technology in Orthodontic Cephalometry

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Abstract: Cephalometry is a key technique in orthodontic clinics for diagnosis, treatment planning, evaluating and tracking treatment results, and academic research. However, several limitations remain in its reading and processing of craniomaxillofacial three-dimensional spatial structural data. Cephalometry has progressed from a two-dimensional plane to a three-dimensional plane with the introduction of CBCT and other three-dimensional technologies, and more clinicians and researchers have contributed valuable research results for the development of three-dimensional technology in orthodontics. This review will focus on the application of three-dimensional technology in cephalometry as well as other three-dimensional assisted orthodontic technologies.

Keywords: CBCT, Cephalometry, Orthodontics, Three-dimensional

Introduction

Orthodontists analyze craniomaxillofacial soft and hard tissue characteristics from lateral cephalometric radiographs, which may be utilized as a valuable reference for malocclusion diagnosis and treatment. Since the introduction of cephalometry in the 1930s, the lateral cephalometric radiograph has been the most traditional and dependable diagnostic technique in orthodontics. However, there are some problems with lateral cephalometry: the overlap of bilateral landmarks leads to inaccuracy, and the asymmetry between bilateral structures is sometimes difficult to be differentiated effectively, making it hard to truly reveal the three-dimensional craniomaxillofacial structures1. One of the challenges in orthodontic and orthognathic treatment is determining to quantify the interaction between tooth movement and skeletal growth2. Many orthodontists began to use three-dimensional imaging technology for diagnostic scanning and image superposition before and after treatment in order to more correctly measure the data. Cone beam computed tomography has increasingly been used to head and neck imaging during the last decades, producing three-dimensional views of craniomaxillofacial anatomy. It has less artifacts, a lower radiation dosage, structural overlap error reduction, quick imaging, and high quality2. Three-dimensional cephalometry research is currently being conducted. This review will cover three-dimensional cephalometry in the reference plane, landmark identification, linear and angular measurement, reference value establishment, new landmark introduction, and three-dimensional photogrammetry.

1. Research progress of reference plane in 3D cephalometry

For analysis, traditional two-dimensional cephalometric radiograph typically employs lateral and anteroposterior cephalometry. One crucial component is determining the orientation of the head through the reference plane. The Frankfort horizontal (FH) plane, composed of orbitale (or) and porion (Po), is used as the conventional horizontal reference plane in lateral cephalometry to orientate the head position. Anteroposterior cephalometry mostly use the midsagittal plane (MSP) to assess face asymmetry. The methods of constructing the reference plane to orientate the head position in three-dimensional cephalometric analysis is still based on classical 2D cephalometry, but there is no overlapping problem of craniomaxillofacial landmarks in the three-dimensional analysis3. In recent years, the topic of whether three-dimensional cephalometric reference plane landmarks can follow conventional cephalometry has become a research hotspot.

Some studies have reported that the FH plane formed by orbitales and porions in traditional cephalometry can be used for three-dimensional cephalometry4-6. Because of the asymmetry of the craniomaxillofacial area, it is difficult to place these four landmarks on an identifical plane in three-dimensional measurement3. Oh Suseok1 formed the

FH plane by randomly selecting three landmarks from bilateral orbitales and porions, resulting in four FH plane composition modes. The results demonstrated that the concordance between four FH planes and the traditional FH plane from 2D cephalometry was confirmed, but considering the repeatability of the orbitales, bilateral orbital points and one porion can be utilized to define the FH plane in three-dimensional measurement. Jin's3 research showed that there is no statistical difference between the four FH planes constructed by the above methods, among which the FH plane defined by the right porion and bilateral orbitales is the most reasonable for clinical use. Gauthier7 believed that a more dependable FH plane could be built using bilateral porion and left orbital points. Pittayapat5 discovered that traditional FH plane landmarks have poor repeatability in the x- axis direction, as do porion in three-dimensional measurement, which is similar to the findings above. The researchers also recommended two new landmarks: the internal acoustic foramen (IAF) instead of the porion, which has better repeatability, and the zygomatic maxillary suture (ZyMS), which has lower repeatability than the orbitale.

The establishment of mid-sagittal plane (MSP) as a reference plane in three-dimensional cephalometry is of great significance for the evaluation of craniomaxillofacial asymmetry8. The nasion-basion-incisive foramen (N-Ba- IF) plane might be utilized to define the MSP, according to Green et al.9, because the central landmark on the skull center was more coplanar and accurate than the midpoints of bilateral pairs. Zhang10 believed that the basicranial structure changes little in the process of craniomaxillofacial growth and development, and the accuracy of establishing MSP with sella (S), nasion (N) and basion(Ba) is the best. The MSP, which consists of the nasion, anterior nasal spine (ANS), and posterior nasal spine (PNS), is thought to be a valuable reference plane for assessing facial asymmetry, according to Shin11. Different thresholds between soft and hard tissues in three-dimensional measurement may result in the loss of some information and low reliability due to the positioning of ANS and PNS in the surrounding soft tissue with low density12. As a result, further investigation into the reliability of MSP as defined by N-ANS-PNS is required. The MSP perpendicular to the FH plane and going through the crista galli and basion, according to some studies8, best approximated the genuine symmetrical MSP. However, the software does not have the function of autonomously identifying the crista Galli in three dimensions. As a result, using the crista galli in the construction of MSP landmarks should be done with caution.

2. Difference, reliability and repeatability of landmarks in 3D cephalometry

In clinics and experiments, traditional 2D cephalometry is extensively used. The definition and identification of common landmarks has resulted in the formation of a mature system. Each landmark must be defined appropriately in three planes (sagittal plane, coronal plane, and axial plane) of complicated craniomaxillofacial anatomy in 3D cephalometry, and landmark definition must be reliable, repeatable, and accurate. Physical identification and three-dimensional cephalometric identification on the dry skull were undertaken by Lascala et al.13 and Periago et al 4., with the finding that there is a difference but it is not clinically significant. On 46 patients, Grauer et al.14 identified landmarks on homologous cone-beam computed tomographic–generated cephalograms and traditional 2D cephalograms, and found that the majority of the landmarks showed statistically significant differences but did not reach clinical significance. Ludlow2 examined the accuracy of landmarks identification on multi-planar reconstruction (MPR) and traditional 2D cephalogram in 20 patients, concluding that MPR is more accurate, especially in terms of all bilateral landmarks. The accuracy of three-dimensional cephalograms in clinical applications has been tentatively proven, and study into the differences between three-dimensional and traditional cephalometry is still ongoing.

The midline landmarks including nasion, sella, and basion on the cranial base, as well as nonconventional landmarks such the fronto-zygomatic suture, condyle, and mental foramen, were found to be highly reliable by Joorok et al.15 on CBCT cephalogram markers before and after treatment in 22 patients. The foramen spinosum and temporal fossa, on the other hand, showed larger errors, while the gonion (Go) was the least reliable. Bilateral bone landmarks, on the other hand, were less reliable than midline structure, and dental landmarks were more reliable than skeletal landmarks. Neiva et al.16 used a 3D virtual image model (3D reconstruction) and multiplanar reconstruction of axial, coronal, and sagittal slices from 12 CBCT images to identify landmarks, and they discovered that MPR showed more reliability than 3D reconstruction. The landmarks on the midsagittal plane, such as the supramental (B), pogonion (Pog), menton (Me), and ANS, were more reliable for each landmark, whereas the landmarks on the condyle, such as the condylion (Co), were less reliable. This is comparable to Joorok's conclusion, and De oliveira et al.17 also verified the result that the reliability of condylion was poor. Chien et al.18 discovered that 3D imaging in CBCT improved interobserver and intraobserver reliability of various landmarks, such as the subspinale (A), ANS, midramus (Xi), orbitale, sigmoid notch, and maxillary central incisor root, among others, as compared to 2D cephalogram.

Between the midline structure and the bilateral structure, there are some discrepancies in the reliability of CBCT cephalometric measurement. The reason for this difference could be that bilateral structures have a large radius of curvature, making them difficult to be identified, and the operator's proficiency as well as methods of identifying bilateral landmarks in CBCT will also affect the reliability. Another reason could be that the sagittal slice image of the midline region is thinner and has no overlapping effect, making it easier to be identified. Furthermore, the degree of identification may be related to the data entry method and identification sequence19,20. In 2D lateral cephalometry, the operator usually estimates the position of landmarks based on the density difference of adjacent anatomy18, whereas in 3D cephalometry, the operators identify the landmarks in three planes in MPR view to make the identification clearer, but differences may appear in 3DR view due to the different visibility of bone density in the view16.

Another significant factor to consider when evaluating the quality of 3D cephalometry is the repeatability of landmarks. To compare the repeatability of the two methods, Fuyamada et al.21 had 18 stomatologists plot landmarks on the dry skull on CBCT, which were based on traditional 2D cephalometry and novel landmarks proposed for 3D cephalometry, respectively. The results showed that the novel landmarks for 3D cephalometry were more reliable. In addition to considering the appropriate use of traditional identification methods when utilizing 3D cephalometry, the position of landmarks in each plane of the three-dimensional image should be precisely determined to increase repeatability. Titiz et al.22 performed CBCT 3D reconstruction on 20 patients and found the high repeatability of landmarks except that the small standard deviations of nasion and infradentale (ID). The glabella (g) and nasion (n) showed poor interobserver and intraobserver repeatability in a study by Toma20, but the repeatability of most landmarks was within clinical use. It's possible that the poor repeatability of landmarks in diverse studies is due to major morphological changes in the anatomical structure of these landmarks, making their localization in 3D images unclear, which can be decreased mistake by strictly controlling the 3D slice identification error 2,22.

3. Research progress of measurement items in 3D cephalometry

The majority of available researches compare 3D cephalometry results to physical measurements of the dry skull and traditional 2D cephalometry, whose differences play an essential role in the clinical application of 3D cephalometry. There was no statistical difference between CBCT cephalometric linear measurement and direct measurement on dry skulls, according to Gribel et al.23, however there was a significant statistical difference between traditional cephalometric linear measurement and direct measurement on dry skulls. Cavalcanti et al.24 also found that there was no significant difference between 3D-CT imaging measurement and physical measurement on dry skulls, demonstrating a high accuracy of 3D-based linear measurements. Many linear measurements on a 3D volumetric surface and anatomic dimensions have statistical differences, according to Periago et al.4, but most measurements can be clinically accurate for craniofacial analysis. Hassan et al.25 assessed that the radiographic measurements on 3D surface-rendered images were closer to the physical measurements on dry skulls than the 2D slices and 2D projection images, indicating that the linear measurements based on 3D CBCT surface-rendered images were accurate in the clinics.

Jodeh et al.26 obtained small differences in angular measurements between 2D cephalometry and 3D CT reconstruction on 62 skulls. The measurements of SNA, SNB, MP-FH, U1-SN, and U1-L1 showed statistically significant but low clinically significant differences among the 12 angular values. Zamora et al.27 found that there was no statistical difference in both angular and linear measurements between the two CBCT analysis software (NemoStudio and InVivo5), and there was no statistical difference between the two CBCT software packages and the 2D cephalogram. In 10 dry cephalometric cases, Kumar et al.28 measured linear and angular values on CBCT cephalometry and conventional 2D cephalometric measurements, CBCT orthogonal cephalometric measurements, and CBCT transmission cephalometric measurements, and found no statistical differences between the measurements of the orthogonal CBCT projections, perspective CBCT, and conventional cephalometry, except for values of Co-Gn, and Orthogonal CBC Except for the angles that included the anatomic landmarks involving the sella, Yitschaky et al.29 concluded that the compatibility of most commonly used conventional cephalometric measurements in 3D cephalometry was confirmed.

By comparing the results of 3D cephalometric measurements with conventional 2D cephalometric measurements and physical measurements, the reliability of 3D cephalometry applied to the measurement of common items in clinical orthodontics was further established. The distinctions between 3D cephalometric landmarks are more finely defined; for example, CBCT analysis software can automatically identify the landmarks of the sella in three reference planes, which cannot be done with 2D cephalometric software, and 3D cephalometric software can superimpose and magnify the small differences in craniomaxillofacial anatomy. Besides that, in 3D cephalometric measurement, the linear distance and angle are no longer the same as the projection point measurements of landmarks in traditional 2D images but in actual 3D space, implying that the differences between the two analysis methods must account for the fact that certain measurements cannot be applied directly from 2D to 3D in addition to improving identification accuracy29. Although studies24,29-31 have shown that 3D cephalometric measurements are more accurate than traditional lateral cephalometric measurements, the factors influencing their accuracy and the method of control, such as the quality of the 3D image (voxel size), the instruments used to perform these measurements, the accuracy of the software, and the setting of reference landmarks, still need to be clarified before they can be used in clinical settings23.

4. Research progress of normative reference database in 3D cephalometry

Three-dimensional treatment planning for orthognathic surgery based on computer-assisted simulation has become popular in recent years32. When only conventional 2D cephalometric reference values are available for diagnosing, establishing treatment plans, and analyzing treatment outcomes, 3D cephalometry may be erroneous. The use of three-dimensional cephalometry to assess morphology or deformity has become commonplace. The use of normal reference values in craniomaxillofacial 3D cephalometric measurements not only quantifies age, gender, and race-specific maxillofacial type variances, but also acts as a guide for developing restorative procedures33.

To determine the range of 3D cephalometric normal values, several researchers measured, analyzed, and tallied the normal occlusion population of different races and ages. Cheung34, Wong35, and Wang33 developed a normative database based on CBCT of the Chinese adult's population in Hong Kong, Taiwan, and southern China. Gao obtained templates and reference values for adolescents with normal occlusion in Beijing by analyzing craniofacial growth three-dimensionally. Bayome36 obtained the normative values of maxillary and mandibular curve length by 3D cephalometric measurement of 38 Korean adults with normal occlusion. Vahdettin37 created a database by 3D rendering software program focusing on Turkish Cypriot's craniofacial anatomy about 38 angular and linear values. Further research should be done with a broader sample of people of diverse genders, ethnicities, and ages to assess measurement reliability, operation accuracy, and predictability of the correlated reference, facilitating universal clinical validation of 3D cephalometry35.

5. Introduction of new reference points for three-dimensional cephalometric measurements

Due to its characteristic of identifying in three-dimensional space, 3D cephalometry can be more selective in landmarks. The basicranial region is recommended to avoid the overlap problem of 2D cephalometry and to obtain reference landmarks that stay stable with pubertal growth or treatment38. Kim et al.39 evaluated 51 candidate reference planes consisting of landmarks from the basicranial region for the construction of the MSP for three-dimensional CT, and found that the planes formed by the nasion, foramen cecum (FC), sella, basion, and opisthion (Opi) could be used for craniofacial analysis in 3D CT images, so two new landmarks for the basicranial region, the foramen cecum and opisthion, were introduced in this study. Lagravere et al.38 revealed that foramina spinosum, ovale, and rotundum, and the hypoglossal canal all provided high reliability and accuracy in 3D cephalometric measurements and could also be applied to establishing reference coordinates for 3D superimposition analysis before and after treatment.

Lee et al.40 also introduced a novel measurement index, the M measurement, in which two points of the maxilla and mandible centroids projection in the MSP are each perpendicular to the horizontal plane, and the distance between the two perpendiculars is measured as the M measurement. The M measurement can be used to assess the degree of sagittal development of the patient's maxilla and mandible instead of the ANB and anterior-posterior dysplasia indicator (APDI), but it has limitations. M measurements, which combine two- and three-dimensional cephalometry, can serve as a bridge for future orthodontic research and analysis, moving away from simple linear distance and angular measurements and toward the study of overall bone structure, including the maxilla, mandible, and cranial base, and their relationship.

Liberton41 defined a set of landmarks for 3D cephalometric measurement that includes 7 new landmarks on the cribriform plate, the foramen ovale, the anterior cranial fossa, the optic canal, the internal acoustic meatus, the glenoid fossa, and the hypoglossal canal, as well as the traditional 2D cephalometric landmarks. They have a high level of consistency and accuracy, and would provide more valuable information.

6. Application and development of three-dimensional photogrammetry in orthodontics

Despite significant progress between traditional and 3D cephalometric measurements, cephalometric values are still insufficient in combining craniomaxillofacial soft and hard tissues to provide a full range of objective considerations from function to aesthetics for orthodontic diagnosis and clinical outcome assessment. What's more, the use of cephalometric measurements as a radioactive diagnostic tool has been restricted in some countries42. Nonradiographic three-dimensional photogrammetry measurements are gradually making their way into the ranks of orthodontic devices as a new generation of computerized stereophotogrammetry that is faster, simpler, and more accurate in capturing and constructing image data, allowing orthodontists to quantify dentofacial differences and assess treatment progress and outcomes with nonradiographic devices43.

Castillo et al.44 compared the relationship between conventional cephalometry and 3D photogrammetry and found that the measurements relating the jaws to each other and incisor orientation had strong positive Pearson correlation coefficients such as ANB, mandibular plane angle (MPA), lower 1/3 height of the face, angle of U1-SN, angle of U1-NA, lower incisor position and axial inclination, implying that the interrelationship between jaws and incisor orientation in 3D photogrammetry has a strong positive correlation with conventional cephalometric measurements, and can be used as a predictor of cephalometric measurements by predicting the relationship between jaws and incisor orientation from the corresponding 3D photogrammetry. Manosudprasit et al.43 applied two 3D photogrammetric devices to acquire extraoral 3D facial and intraoral dental images, and compared the measurements with conventional cephalometric measurements, the diagnostic parameters and results of each method were basically consistent, concluding that there was good agreement between cephalometry and photogrammetry methods when patients with malocclusion required extraction for orthodontic treatment or orthognathic surgery. Masoud et al.45 concluded that 3D photogrammetry could also use eye and natural head orientation as a reference to provide different gender non-radiographic maxillofacial and dental diagnostic reference, to help the surgeon determine the relative position and orientation of the patient's teeth and craniomaxillofacial structures.

The 3D photogrammetry technique is still under development, which is a new method using customized devices, and the familiarity of the examiner affects the consistency of the measurement. Secondly, the reference values of the 3D photogrammetry are based on different samples that are collected in a way fundamentally different from traditional cephalometric measurements, which leads to diagnostic differences between the two methods43.
Although further extensive investigations of measurement methodologies and reference values are needed for clinical use of this diagnostic program, it may become the preferred choice for orthodontic-orthognathic clinical diagnosis and assessment in the future.

7. Conclusion

The accuracy and reliability of 3D cephalometric measurements will be improved further with continued research and development of 3D technology, as will the unification and updating of landmarks and measurement items, the improvement of measurement methods and evaluation systems, and the establishment of databases. 3D photogrammetry and morphometry46 will also be included to the list of orthodontic treatment methods. It is thought that 3D technology has taken a prominent role in orthodontic clinical and research.

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