SPECIAL ARTICLE

KOREA. J. ORTHOD.
2002. : 32(6) : 375 - 82

Advances of 3D Digital Imaging in Orthodontics

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Sophisticated methods in mapping both facial soft tissue and skeletal structures have been developed for different purposes in computerized craniofacial analysis. Various methods such as laser scanning, stereophotogrammetry, photographic systems, light digitizers, spatial digitizers, optoelectronic devices, and CT-Scans were utilized to derive 3D measurements and modeling of hard and soft tissue of the human head.

A non-invasive, economical, yet reliable method for measuring human facial skeletal structure has been developed in the past. Recently attempts to correlate the underlying skeletal structure with the facial soft tissue by means of 3D computer modeling has been developed and packaged in a computer software (3DCeph.NET$^{\text{TM}}$) .[1]

Laser surface scanner has become popular recently. By triangulating distances between reflecting laser beam to the scanned surface, the surface laser scanner is able to detect not only the length and width of an object but also it's depth. Its ease of use has opened various possibilities in laboratory research as well as clinical investigation. Assessment of the reliability of generating three-dimensional object reconstructions by utilizing the Minolta Vivid700 3D surface laser scanner was done.

Accuracy and reproducibility were tested for various orthodontic records such as facial scanning and study model scanning. Tests were conducted at varying distances between the object and the scanner.[2]

Starting few years ago, companies have shown interest in developing three-dimensional dental cast in order to simulate orthodontic treatment as well as "replacement" of plaster cast for ease of storage. Companies such as OrthoCAD$^{\text{TM}}$, GeoDigm$^{\text{TM}}$, SureSmile$^{\text{TM}}$ and Invisalign$^{\text{TM}}$ have making significant progress in developing computer algorithms to allow orthodontists manipulate three-dimensional digital data of the dentition in more precise manner. Yet works still have to be done in perfecting the integration between three dimensional digital data of skeletal, facial and dentition as well as incorporation of finite elements data of soft tissue characteristics, muscles tension and load under function in order to build a complete simulation of the patient.

With the rapid development of Internet Information Technology (IIT), connectivity between research centers / institutions and / or private sectors become more transparent. In August 2002, 75,000,000 hosts along 171,000,000 users were found in the United States alone, with 174 199 million hosts and 840 695 million users world-wide. Most physicians connect to the Internet on a daily basis, and 42% work in practices that have web sites, according to current research. IIT has become very popular in the medical and dental professions as a result of the introduction of new information technologies for browsing in journals and scientific literature, ordering equipment from suppliers, performing online consultations, accessing association

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websites, and communicating with other professionals. Physicians and dentists increasingly depend on computerization and the Internet.[3]

Most orthodontic cephalometric diagnostic system currently in the market works with the concept of plain client-server type of networking or just in a standalone computer. The software application will be installed in each terminal whereas data can be either stored in terminals or in the server (main computer). On the contrary, the model described in this article (3D Ceph.NET™) works with the concept of "metaframe" client-server. In this model both the software application and data reside in the main computer (server). Office administrator will have full control on both maintaining and securing the data which complies with HIPAA regulation (Health Insurance Portability and Accountability Act of 1996) in which patient data can only be access by an authorized personnel. The management office system described in this article was modelled after ASP (Application Service Provider) which enable both the management office application / software and its data be kept in secure system but at the same time allows authorized access from any computer terminals linked to intra / internet system. The ASP office management system only allows for every authorized terminal in the system to access both the 3DCeph.NET software application and the database without installing anything in the terminal itself. This feature will reduce installation time as well as setting up the application in each terminal in the network.

With the advantage of having the system easily adapted to both intra/ internet protocol allowing full integration of the orthodontic practice / office to grow and yet easily managed and increase in security by adopting the concept of integrated online ASP system facilitated by intra/ internet technology.[4]

MATERIALS AND METHODS

Three-dimensional imaging has progressed from the Bolton-Broadbent Cephalometer[5] and 3DCephalometric Computer Software to the advanced CT-Scan, MRI and ultrasound three-dimensional imaging. To fully reproduce patient anatomical structure three-dimensionally, technology formerly thought as science fiction, such as virtual reality, holographic projections, stereo-lithographs, now has potential in orthodontists' offices.

Radiography has been used to study craniofacial growth, but radiation is potentially harmful. CT-Scans are better for acquiring three-dimensional information about the craniofacial complex, but the level of radiation is too high for routine use. Other three-dimensional devices such as ultrasonic machines and three-dimensional cameras require calibration and additional attachments. The procedures can become quite a challenge in clinical trials.

Assessments of facial asymmetry in living individuals have been performed two-dimensionally, resulting in lost data because complex three-dimensional structures were projected onto flat two-dimensional surfaces. Improvements on classic anthropometric linear and angular measurements include optoelectronic systems, moiré stripes, stereophotogrammetry, and laser scanners; these enable us to analyze three-dimensional data involving surface area with mathematical methods such as the Fourier series, Euclidean Distance Matrix and Ferrario's Asymmetry Vector.[6] Three-dimensional facial landmarks used by Ferrario[6] and Weeden[7] include supraciliary points above the most superior aspect of the eyebrow, midnose point located on the midline of the nasal bridge, middle interciliary point, nasal tip, commissure point, cheek point and chin point. Data can be gained for studying asymmetrical facial structures, functional and facial soft tissue movements and also differential facial growth. Berkowitz[8] and Ishikawa[9] (1999) studied the development of the cleft lip and palate repair, via a three-dimensional approach. They utilized a scanning device that analyzes movement of the cleft segments in space.

The Minolta Vivid700 3D Laser Surface Scanner operates by using a Class II laser λ=685 nm at 25mW,

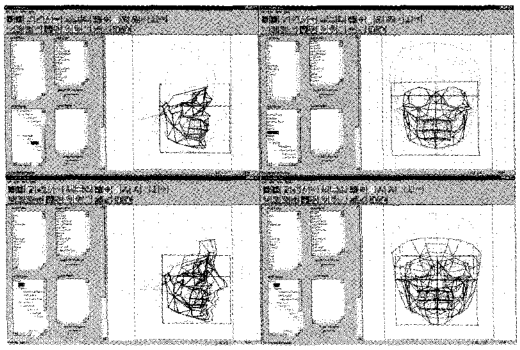

Fig. 1. 3DCeph. NET™ Integration Module

Beam Spread Angle (2σ) of 21° horizontally and 0.1° vertically, object to scanner distance from 0.6 m to 2.5 m with the field of view 70 mm to 1100 mm, and scanning time of 0.6 seconds. The scanner utilized ½ inch frame transfer CCD 380,000 pixels for its 3D data and similar specification for the color CCD data. The scanner's output data are 200x200x256 for 3D and 400x400 for the color data. The total weight of the device is 9 kg.[10] Spatial Linear measurements were measured manually, using a caliper accurate to 0.5 mm. Each measurement was conducted twice on two different times, two days apart, and the average value was used.

1. Testing of the calibrated geometrical cylinder

A calibrated geometrical cylinder with the height of 141 mm and width of 46 mm was used and tested at two different times (T1 and T2) at exactly the same distance between the object and capture lens of the scanner (90 cm at zoom level 4/ 25 mm lens). At each time point, data were obtained from 10 trials and average values were calculated. At T3, the object was zoomed at zoom level 5 (46 mm lens) and 10 trials were obtained. At T4, object was zoomed at zoom level 4 (25 mm lens) with 70 cm object to capture lens distance.

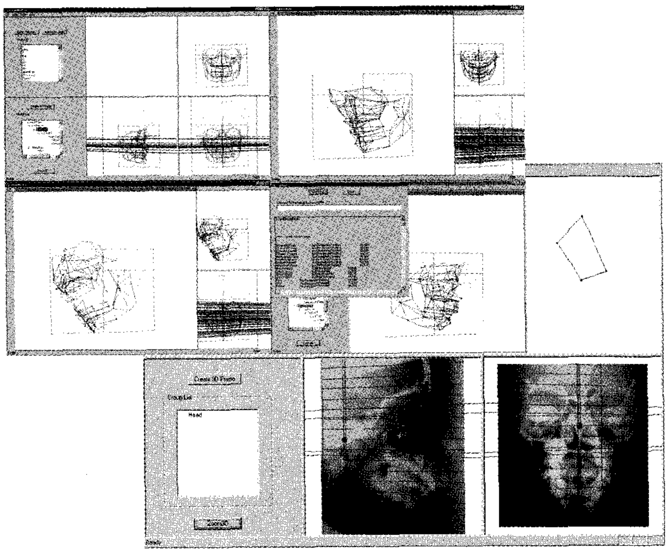

Fig. 2. 3DCeph. NET™ Vector Intercept and Landmarks Aligner

2. Testing on a dental study cast

A dental study cast was scanned at two different times and two different object to scanner distances (T1 at 70 cm and T2 at 90 cm) both with the zoom level 4/ 25 mm lens (Figure 2). The inter molar width was measured from the intersection of upper first molar palatal groove and the palatal gingival margin (point iL and iR for left and right side respectively), and was repeated 10 times for both T1 and T2. Palatal vault depth was measured as a perpendicular distance from midpoint between iL and iR to the midpalatal raphe (mr). For each time T1 and T2, the measurement was repeated 10 times. Black markers were placed in point iL, iR and mr to eliminate landmarks identification error of the measured distances. For every scanning, we dismantle the scanning setting and recreate it again to be able to measure the error in the whole method thus providing us with overall accuracy of the method. For each exposure, three different angulations (−45°, 0° and 45°) relative to the occlusal surface were taken in order to overcome the undercut surface. Vivid700 3D software was then used to merge the three views and produce full three−dimensional data of the model.

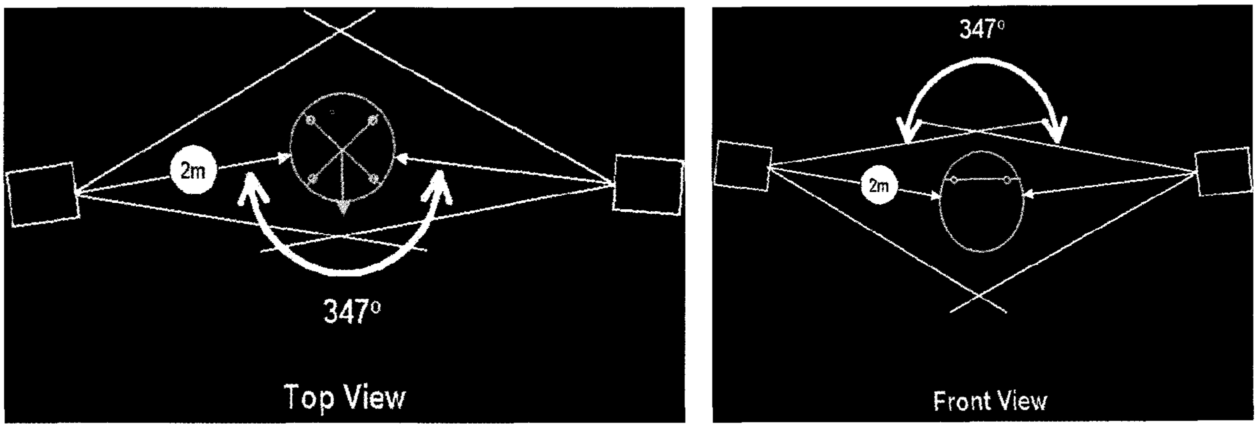

Fig. 3. Coverage area on the facial laser surface scanning

3. Testing on a plaster facial model

A plaster facial model was made by taking an alginate facial impression of a human face. The model was also used to assess the reliability of 3DCeph 2000™ software to assess the 3D soft tissue thickness in order to relate the soft tissue to the hard tissue in space. Twelve soft tissue landmarks (A–L) were used. In each landmark, 15 mm long nails were implanted, representing the normal surface line 10 mm above each corresponding landmark. Those landmarks are : A. Right Supraorbitale at the level of soft tissue glabella; B. Soft Tissue Glabella; C. Left Supraorbitale at the level of soft tissue glabella; D. Nasal Tip; E. Upper Lip; F. Lower Lip; G. Soft Tissue B; H. Soft Tissue Pogonion; I. Right maxillary points located on the cheek one–fourth of the distance between between the right and left alar and right and left TMJ, respectively; J. Right cheek point located on the cheek one–quarter of the distance between the right and left commissure and right and left TMJ points; K. Left maxillary points located on the cheek one–fourth of the distance between the right and left alar and right and left TMJ; L. Left cheek point located on the cheek one–quarter of the distance between the right and left commissure and right and left TMJ points. The facial model was scanned from three different views (–45°, 0° and 45°) to eliminate undercuts and merged with Vivid700 3D software (see figure 3).

All data were processed statistically for average value, standard deviation, maximum and minimum distortion and differences. Differences were assessed by paired t–tests with $p=0.05$.

The computer software using stereophotogrammetry[11,12] with a vector intercept algorithm[13] and was found to be accurate to less than 1.0 mm for linear measurements.[14] Fifty one hard tissue and sixty soft tissue landmarks were used in our previous study. From those landmarks, 97 vectors in hard tissue and 159 vectors in soft tissue were derived and the accuracy was determined to be less than 1.0 mm in measuring soft tissue thickness.[1]

The 3DCeph™ computer software running on a standard PC was able to correlate digitized landmarks seen from different perspectives / projections and convert the 2D location of each landmark into its 3D spatial coordinates (x, y, and z). From those landmarks and their spatial coordinates, 3D wireframe meshes can be established by connecting those landmarks in triangular fashion creating multiple unit surfaces. Finite element modeling can be obtained following the creation of the wireframe meshes.

Soft tissue thickness can be measured from any hard tissue landmark to the corresponding soft tissue landmark within 1.0 mm accuracy comparable to CT–Scan measurements. Unlike CT scans which requires at least 50–60 slices of x–rays projections, 3DCeph™ is

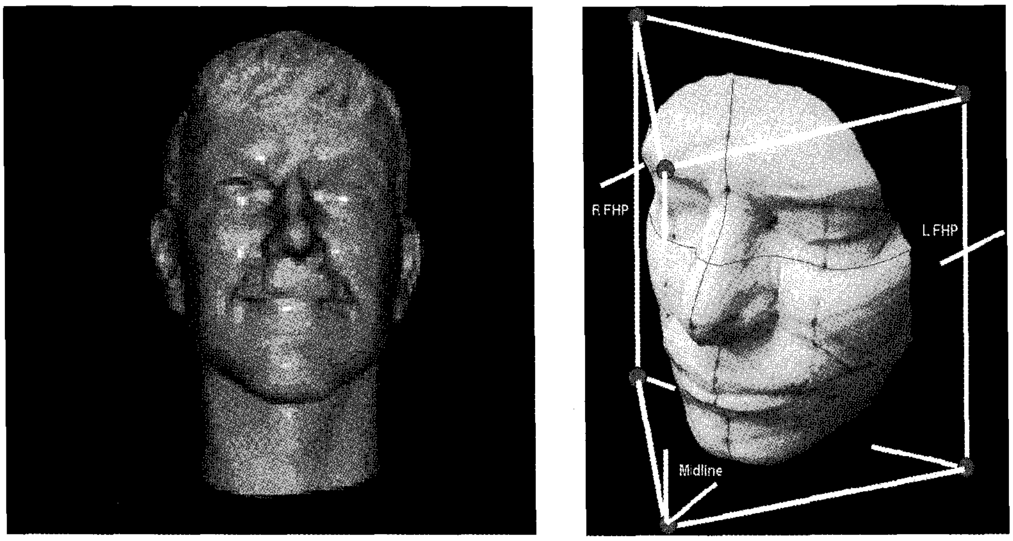

Fig. 4. 3DCeph Head Aligner with Cephalostat Adapter

able to aid in generating a 3D wireframe model of a human skull with sufficient accuracy by utilizing two standard x-ray projections (lateral and PA). The automatic computerized landmark alignment module of 3DCeph™ enables the software to improve precision in locating any cephalometric landmarks and thus improve the overall accuracy of the 3D computer modeling.

Computerized stereophotogrammetry utilizing 3DCeph™ in combination with good radiographic, photographic and laser surface scanning technique can be used as a non-invasive, economical, yet reliable technique in determining soft tissue thickness. (3DCeph™ demo can be found in http://128.248.179.34/prod 01.htm)

Based on the model applied in 3DCeph™, the development of 3DCeph. NET™ was started to fully integrate with both 3D dental cast and 3D facial surface scanning as a non-invasive method of generating "The 3D virtual" patient for improved accuracy in diagnosis and treatment planning. Furthermore, it utilizes the current Microsoft.NET technology, allowing easy, reliable and secure transmission of data through internet channels. The combination of 3DCeph™ (see Figure 1 and 2) and Microsoft.NET technology will extend the orthodontic diagnosis ability over internet channel. The .NET technology offers services such as delivery software on the web, a framework for universal services, a server centric computing models, run on any browser on any platform, and .NET is based on the newest web standards.[4,15]

In conjunction with the software development, a head band equipped with electronic magnetic sensors will also be developed to ensure proper head positioning and standard calibration for all three-dimensional images involved in this study (cephalometric radiographs, 3D scanning of the face and dental cast). The calibrated head band will act as a registration plane based on these landmarks while taking different projection of the x-rays, as well as merging 3D scans of multiple plane of a subject. The predecessor of this head band, the facebow, has been found to improve accuracy of the 3D system, but was found to be cumbersome in clinical application. By integrating an electronic magnetic sensor into the specially designed head band one can ensure proper head positioning when subject needs to be repositioned from one position (lateral) to another (PA). Thus head positioning error can be minimized. The built in electronic magnetic sensor can be linked directly to the x-ray machine to trigger the exposure when the three points represented by three magnetic sensor placed on the left, right side and frontal part of the head band are aligned with the sensor (Figure 4).

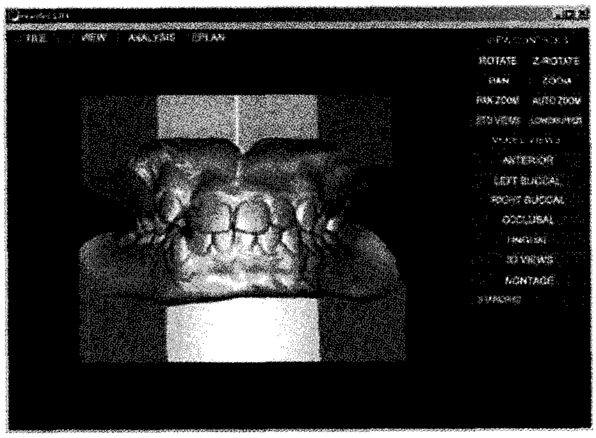

Fig. 5. Sample of Three-Dimensional Model

This device was designed to increase accuracy in repositioning the subject after head positiong change while taking one projection (ie. Lateral) to another projection (ie. PA) to get an orthogonal projection (biplanar) as described in previous research on stereo-photogrammetry. In addition, this device will also act as registration points and planes while integrating multiple three-dimensional data obtained from subject by utilizing 3D laser surface scanner. The limited scanning field of the scanner force users to take multiple section of scanning (at least two) to be able to produce a full 3D facial / head structure. The proposed device can also be utilized as registration points / planes when integrating 3D facial scanning to 3D wireframe underlying skeletal structure which later can act as registration points for the 3D scanning of the dental cast (Figure 5).

DISCUSSION

The laser surface scanner generates accurate three-dimensional data. The availability of a light-weight, user-friendly surface laser scanner in the field of orthodontics makes it possible to analyze growth, soft tissue changes, treatment simulation, appliance designs, and treatment effects in three-dimensions. Three-dimensional computerized data derived from laser scanner can also be transformed by utilizing Computerized Aided Manufacturer (CAM) and stereolithography techniques to produce orthodontic appliances such as splints, computerized wire bending, e-models, and surgical simulation models. The self corrected mechanism of the laser scanner in adjusting for image distortion give flexibility for clinical research. The software can be utilized to merge images taken from different perspectives, thus eliminating undercuts. Interestingly, due to the nature of the laser beam spread, it was found that the smaller the object the more accurate the measurements.

Studies involving dental casts can be performed with ease since computerized three dimensional wireframe diagrams allow models to be cut, superimposed and measured in the computer. Measuring changes in area as well as length of curvatures gives more insight for many data sets. In the area of craniofacial anomalies, various studies could be derived about cleft lip repair, asymmetrical facial growth, change of head shape, nasal molding procedures (see Figure 7). It was found that in all cases that the scanner produced more accurate measurement in height (x) and width (y) but less accurate in depth (z). In measuring intermolar width, the scanner tends to produce smaller value than the manual measurement, on the contrary it produces bigger value when measuring palatal depth. The increase accuracy in measuring height (x) and width (y) is due to the horizontal laser beam source that was used in the unit. The depth (z) was acquired while the horizontal laser beam moves from top to bottom of the scanned objects, time discrepancy occurs between the emitting part of laser beam to the photosensitive censor while scanning object's depth which causing slight increase in the z coordinates (enlarged).

The need for 3D reconstruction as a diagnostic tool led to the development of sophisticated technology such as the computed tomography. Despite the many applications of the CT and its versatility, it has disadvantages. The high cost to perform a 3D CT-scan reconstruction is far greater than the cost of several ordinary cephalograms. The radiation exposure from the CT survey is also much higher than the total radiation of several ordinary cephalograms. Moreover, with new developments in digital x-ray film, the amount of radiation exposure for cephalograms can even be reduced further by 90%.

The use of special aligner in this study will facilitate the use of 3D modeling for most orthodontists. The user does not have to have a special research cephalometric radiography unit with two perpendicular x-ray sources installed. The facebow enables the operator to use an ordinary single x-ray source unit with good precision. However, when available, an x-ray unit with two x-ray sources is preferable for ease of use, speed of procedure and further lowering the risk of head positioning error. Even though it was not yet assessed in this study, it is possible to apply the aligner to produce integrated three-dimensional model consists of three-dimensional wireframe of the skeletal structure generated by stereophotogrammetry, three-dimensional laser facial scanning and three-dimensional scanning of the dental cast for greater detail and accuracy of the dentition. The prototype computer program used in this study, 3DCeph. NET™, provides a feature which enables the user to generate 3D modeling using any combination of lateral, frontal and basilar projections. This does not mean that all cases will need all three cephalograms routinely. Selected cases such as surgical cases, cases with significant posterior or anterior crossbites or syndrome cases having significant asymmetry (both dental and/ or skeletal) will definitely benefit when assessed in three dimensions. Even in such cases, not all of them will need three projections (lateral, frontal and basilar). Most cases can be reconstructed in 3D with adequate accuracy by using lateral and frontal projections. But when any surgical simulation involving asymmetric movement, the use of basilar projection will be very helpful. For example, it is possible to locate the new mandibular dental and skeletal midlines in a hemifacial microsomia patient, because lengthening one side of the mandibular ramus will affect the other side as the whole mandible is repositioned.

Longitudinal evaluation of human craniofacial growth and development will definitely benefit from using 3DCeph. NET™, not only it is inexpensive but also less radiation exposure for the individual participating in the study as well as its ability to integrate other kinds of digital three-dimensional data and its "internet web-enabled" ability.

Lastly, despite the ease of having integrated three-dimensional data and computer simulation, data security and authenticity has to be anticipated a prior to any use of computerized medical records. The use of secured channel as well as secured file format integrating both compression and encryption technology should be encouraged and adopted by whoever utilized these digital data as legal documents.

CONCLUSIONS

It was anticipated that in the near future, the data gathered from the 3DCeph.NET™ collectively from the authorized online users can be used to record any 3D growth norms and patterns in 3D and incorporated with 3D CT data. In longitudinal studies, researchers will only need to take beginning and ending 3D CT, whereas the annual growth rates can be derived mathematically using data from bi-planar radiographs analyzed by 3D Ceph. Bone surface contours can be derived from CT study and morphed to different sizes as growth occurs and recorded annually by the 3DCeph.

Combined with three-dimensional cephalometry techniques and software packages, a complete three-dimensional simulation can be obtained and gives both the orthodontist and surgeon a better control in designing a treatment plan for the patient. Its application intraorally can also be valuable for clinical research, not only for saving time but also for patient comfort.

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