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Clinical Application of Three-Dimensional Craniofacial Imaging in Orthodontics

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Since the inception of record keeping in orthodontics, clinicians realized that the best way to represent and record a patient's condition would be in three dimensions (3D). Several methods have been attempted, including facial moullages of every patient in order to capture a true representation of the patient's face, but the materials and technology available did not always allow a true registration in a practical or cost effective way. Photographic and radiographic methods were quickly adopted; however, using two dimensional methods to represent a three dimensional entity can result in misleading or incomplete diagnostic information. The present article reviews the need for the third dimension in orthodontic records, the available technology, and the possible trends for the future. The collection of 3D orthodontic records could be divided into face, craniofacial skeleton, and dentition. Direct and indirect methods can be used in order to end up with a 3D image. There are different ways to visualize and study the 3D images, they can be "printed" as a 3D object, they can be seen in a computer screen, or even in a holographic environment. The ideal patient record situation would be a complete 3D craniofacial record by using digital format to obtain individual as well as conjunctive access to soft tissue of the face, craniofacial skeleton, and dentition. The Cone Beam Computerized Tomography scanners show some potential of developing into the single source of 3D orthodontic records. If this occurs, an orthodontic records appointment could end up taking less than 10 minutes.

Key words: 3-D images, orthodontic diagnosis

INTRODUCTION

At the beginning of the 20th century, plaster was the primary material used to capture dentofacial morphology. Almost all practitioners used plaster to make casts of the teeth and alveolar bone. These dental casts, along with a careful clinical examination of the patient, formed the database for orthodontic diagnosis and treatment planning. One particularly ambitious practitioner, Calvin Case, even advocated the use of plaster facial moulages to record facial changes before and after treatment[1]. Although we tend to think that orthodontic records have steadily improved over the years, one factor that often is not appreciated is that these early records captured a patient's dentofacial morphology in three dimensions (3D). Technical difficulties in obtaining facial moulages and the practical problems of storage prevented most practitioners from adopting the technique. In addition, advances in photography and radiography changed the way practitioners recorded facial morphology. By the end of the 20th century, the combination of two dimensional (2D) radiographs and photographs and 3D dental casts was used to document the patient's morphology.

Recent advances in digital photography have reduced the cost and improved the quality of digital cameras. According to estimates by InfoTrends Research Group, global film camera shipments in 2004 shrank to 36 million units from about 48 million in 2003, while digital camera shipments rose to 53 million from 41 million units[2]. A similar trend in digital radiography also is occurring, but the acceptance of digital X-ray machines has not been as popular as digital photography, probably because of the hardware's price. Dental casts, the oldest and only remaining 3D record, also have a digital version. Since incorporation in the market about 5 years ago, 3D digital casts have steadily gained acceptance. This is due to clinicians's familiarity with the use of 3D digital models with Invisalign® (Align Technologies Inc, Santa Clara, CA, USA) and the practical problems associated with storage of dental casts. However, there remains some resistance to the digital model from practitioners accustomed to the touch and feel of this time-honored record. In addition, the current process used to

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generate digital study casts still requires dental impressions.

As these existing records become digital, the next logical step is to combine them to create an integrated digital record of the patient's dentofacial morphology. This combination would make the access, storage, and use of this record more practical. Interestingly, the amount of diagnostic information provided by this new digital record would not be increased. Because the two dimensional digital records (photographs and cephalograms) remain in 2D. The record could be improved if a hybrid digital record combined the lateral and frontal cephalograms to generate a 3D grid to register the dental models. However, this technique is time-consuming and not practical in a busy orthodontic office. Digital records definitely improve storage, access, conservation, communication, and duplication capabilities, but only a switch to a complete 3D image of the patient would also incorporate more diagnostic information.

WHY DO WE NEED A THREE-DIMENSIONAL RECORD?

The short answer to this question is that our patients are 3D and, therefore, the same format would be the most accurate representation of their morphology. In traditional cephalometry, 3D craniofacial structures are projected onto 2D radiographic film. This process creates cephalometric structures and landmarks that do not exist in the patient. Examples of such structures are the mandibular symphysis, articulare, the pterygoid fossa, and the "key ridge." Although orthodontists around the world constantly refer to these structures as anatomic landmarks, they are in fact artifacts of the cephalometric technique. Another problem arises when bilateral structures are averaged to create a unified anatomic outline. An example of this process is the averaging of the right and left inferior borders of the mandible to create the "mandibular plane." Such averaging of bilateral structures creates two problems. First, the "plane" that is created is really a line that is an abstraction based on the anatomy of the patient. Second, averaging the structures results in a loss of parasagittal information, and any true asymmetry of the patient is lost. It is impossible to determine how important this lost information is to diagnosis and treatment planning.

The three dimensional orthodontic records could be divided into (A) face, (B) craniofacial skeleton, and (C) dentition.

THE THREE DIMENSIONAL FACE

There are basically two methods to capture 3D facial information: 1) light based, and 2) laser-based.

1). Structured Light:

The light-based method is also known as the shape camera or the stereo photogrammetric method. It uses conventional cameras mounted at different angles to provide different views of a subject. All cameras simultaneously are activated and all resulting views are combined into a 3D view of that subject. Usually only one or two of the cameras used is a color camera, and the image from that camera is the source of color for the 3D image.

The shape camera uses the principle of stereophotogrammetry, which is one of the primary ways humans perceive shape. The number of cameras used in a shape camera varies according to manufacturers. A vertical stripe or a grid pattern is projected on the subject at the moment the image is captured. The distortion in this pattern is captured by the shape lenses. These distortions are interpreted as 3D information by the computer software[3,4].

Multiple views are then obtained by using multiple cameras systems, or by taking a sequence of pictures when using single camera systems. The multiple views are then manually, semi-automatically, or automatically stitched together to produce a 3D facial model[4]. The alignment is done by designating three or more correspondent landmarks on overlapping images. After the alignment, a computer program merges the images, discards duplicate data, smoothes the model's edges, blends the colors evenly, and fills holes that may have occurred due to shadows or reflection.

2). Laser Scanners:

The laser-based methods use the same principles as do light-based systems. However, instead of a light pattern being distorted, a laser pattern is used, and its distortions are interpreted as 3D information. As with the light-based systems, laser-based systems are available that image one perspective at a time or in a panoramic fashion with the laser mounted on a revolving arm. An additional camera usually is necessary to obtain color information and texture maps[4].

Since the laser beam is a straight line, laser scanners cannot image undercut and apposed surfaces[5].

Analyzing the 3D Face:

Acquiring dimensionally accurate facial images using either structured light or laser approaches is particularly

demanding because of tissue reflectance, interference of hair and eyebrows, change of posture between different views (if necessary), and movement during imaging (more so with lasers because of longer exposure times). Certain structures like eyes, and ears do not image well because of extreme reflectance and/or undercuts where lights and laser cannot enter[4]. Image processing through software reduces these problems and is able to yelds relatively accurate images.

The 3D face can be analyzed by using linear measurements, area, perimeter, volumetric and symmetry analysis, all of which can be used for diagnosis and treatment planning, as well as for outcome assessment. Outcome assessments for soft tissue changes are usually done only in the profile view because of radiographic and photo limitations. A 3D model of the face allows a complete evaluation of the treatment outcome, which is information unavailable with 2D records.

To experience the capabilities of facial outcome assessment, we used a light-based system to capture 3D facial information simulating a pre- and a post-surgical mandibular advancement procedure. Two shape camera images were taken, one with neutral occlusion, and another with protrusive occlusion. Facial landmarks were identified in both images, preparing them for alignment. The landmarks were chosen around the orbit, around the nose, and forehead, where changes would not occur. After superimposing both images, two different analyses were performed. In the first one, the protrusive image was converted into a see-through wire frame so we could visualize the changes. The second analysis compares both images, turning them into a single image with different color intensity. The darker the shades of blue, the further apart are the pixels, hence the more change occurred. This analysis is called surface metric distance. The surface metric distance analysis showed a change mostly on the anterior midline region for this simulation. The area of change was easily evident. The outcomes of this simulation were satisfactory.

Current technology is available for the collection of 3D representations of the human face. Different methods and systems are available, and all seem to do a fairly accurate job recording the face as a time record. Diagnosis, treatment planning and outcome assessment analyses are possible by using the 3D face. Furthermore, the use of 3D images would give additional information beyond what is currently used in the majority of orthodontic offices.

THE THREE DIMENSIONAL CRANIOFACIAL SKELETON

The usual representation of the craniofacial skeleton in an orthodontic office consists of lateral and frontal cephalometric films. Both these images are 2D representations of a 3D objects, and thereby lead to enlargement and superimposition of structures.

Cephalometric research using only lateral film tracings was most widely used between 1950-1985[6-12]. Since the 1960s there has been moderate research interest in the use of the frontal film for asymmetry or three-dimensional studies[13-20] but the lack of consideration of frontal cephalograms risks missing the diagnosis of asym-metries, potentially resulting in treatment failures[21,22].

The need for three-dimensional cephalometry was recognized in the 1960s by Savara[23], and has been confirmed by many[8,9,11,16,19,24-28]. Altobelli[28] specifically called attention to the lack of three-dimensional standards for pediatric and adult craniofacial patients. Dean et al[29]. noted that normative 3D cephalometric data would be an important tool in the study of craniofacial variation, as well as diagnosis, treatment planning, stereotactic treatment, prosthetic and appliance design, and outcome assessment.

Various manual techniques for abstracting three-dimensional coordinate data from biorthogonal head films have been developed[19,23,26,30-35]. Until recently, this work remained impractical because of the time-consuming nature of pencil tracing of films and computer mouse-based landmark identification from tracings.

The use of computer-readable digital films will have an important role in reinitiating three-dimensional cephalometrics. However, the importance of computer-based cephalometry was long ago recognized by Ricketts, who wrote: “Cephalometrics, when computerized, becomes the most powerful tool of information yet devised for the practicing orthodontist.”

There are different ways to obtain a 3D representation of the craniofacial skeleton. Basically, the method can be divided into a 1) constructed method, or indirect creation of a 3D image, and 2) direct capturing of the 3D image.

1). Construction of a 3D Craniofacial Skeletal Image:

The construction of a 3D craniofacial skeleton image uses the principles of stereometry[27,36]. Using this principle, we can combine two radiographs with different views of the same object to create a 3D image. Nevertheless, requirements that must be met to create an accurate image include: 1) availability of homologous landmarks, 2) knowledge of the enlargement used, 3) no movement of the

patient's head during the taking of both radiographs, and 4) knowledge of distances between X-ray cassette and subject.

In 1975, Broadbent et al[37]. introduced the Broadbent Orientator. The Orientator uses the information obtained from biorthogonal plane film radiographs to create 3D data points. In order to use the Orientator to acquire 3D data, one must assume that the beams of the posterior and lateral tube heads orthogonally intersect in the center of the head. However, manual use of the Broadbent Orientator for 3D data collection is cumbersome[27]. Therefore, 3D data collection was not routinely attempted. Recent advances in computer graphics allow easier collection and interpretation of 3D data, using a computerized version of the original Broadbent Orientator[34]. Therefore, the Broadbent cephalometer is equipped to adjust to all necessary requirements, and it has been used on several occasions to create 3D images[35,38-40].

The creation of a 3D landmark frame consists of (1) film alignment, (2) entry of ML and P+ distances (these are the specific head to film distances for the lateral and frontal view respectively), and (3) landmark identification. A 3D landmark frame can be constructed from the 2D coordinate of bi-planes. The frontal view (x, y) provides all x (width) coordinates, the lateral view (z, y) provides all the z (depth) coordinates, and both lateral and frontal views provide the y coordinates.

2). Direct 3D Craniofacial Skeletal Image:

There are different methods and hardware available that allow us to obtain a 3D representation of the craniofacial skeleton. Different file formats can be used to describe a 3D image. The Digital Imaging and Communications in Medicine (DICOM) standard was created by the National Electrical Manufacturers Association (NEMA) to facilitate the viewing and distribution of medical images, such as CT scans, MRIs, and ultrasound. The DICOM standard allows software companies developing imaging applications to concentrate on processing the DICOM format rather than trying to address the wide variety of proprietary formats prevalent throughout the industry. Most imaging manufacturers with proprietary file formats provide a conversion utility to produce DICOM files.

Magnetic Resonance Imaging:

Magnetic Resonance Imaging (MRI) has been applied to craniofacial imaging for several years; however, its use in dentistry is limited mostly to evaluation of the temporomandibular joint and of airways[41]. Possible reasons for the lack of wider use of MRI are cost, access, and orthodontists' lack of experience in interpretation. Nevertheless, MRI does not use ionizing radiation and allows for dynamic imaging. Those capabilities may give MRI a role in future craniofacial imaging[4].

Table Specification of the currently available cone beam CT machines approved for use in dental medicine

Trade Name	NewTom	i-CAT™ Cone beam 3-D Dental Imaging System	CB MercuRay™	3D Accuitomo XYZ Slice View Tomograph
Manufacturer	Quantitative Radiology, Verona, Italy	Imaging Sciences, Hatfield PA, USA	Hitachi Medical Corporation, Tokyo, Japan	J Morita Mfg Corp, Kyoto, Japan
Model	Newtom 3G	i-CAT	MercuRay	MCT-1
Main Unit Dimensions	2,000(W) x 2,413 (D) x 2,000 mm (H)	1,040(W) x 1,120 (D) x 1,830 mm (H)	1,840(W) x 1,900 (D) x 2,250 mm (H)	1,620(W) x 1,200 (D) x 2,080 mm (H)
Weight	480 kg		950 Kg	400 Kg
Tube Voltage	110 kVP	120 kVP	60-120 kVP	60-80 kVP
Tube Current	15 mA	3-8 mA	10-15 mA	1-10 mA
Scan Time*	36 seconds	10-40 seconds	10 seconds	17 seconds
Image Detector	Image intensifier CCD	Amorphous flat panel detector	Image intensifier CCD	Image intensifier CCD
Grayscale	12 bit	12 bit	12 bit	8 bit
Field of View	100mm (6") 150mm (9") 200mm (12")	250 (Diameter) x 200 (Height)mm	102.4mm (6") 150mm (9") 190 mm (12")	40(Diameter) x 30(Height) mm
Voxel Size	0.2–0.4 mm	0.2–0.4 mm	0.2–0.376 mm	0.125 mm
Reconstruction Time	2 minutes	1.5 minutes	6 minutes	5 minutes

*Scan time is how long the machine takes to take an image, and does not represent exposure time. For example, in the NewTom even though the scan time is 36 seconds, the actual exposure time is only 5.4 seconds.

Computerized Axial Tomography and Cone Beam Computerized Tomography:

Traditional Computerized Axial Tomography (CAT) scanners are relatively large, expensive, and use a considerable amount of ionizing radiation to create a 3D image. A better option for craniofacial imaging is the Cone Beam Computerized Tomography (CBCT) or Cone Beam Volumetric Tomography (CBVT) scanners. Comparing both types of scanners, the CBCT uses a conventional low energy X-ray tube, similar to the one used in panoramic dental devices, whereas the CAT scan uses a high energy X-ray source with rotating anode. The CBCT features a reduced chamber volume allowing a significant reduction in radiation. Additional reductions result from the cone-beam projection of X-rays, which produces a more focused

beam and much less scatter radiation compared to the conventional fan-shape projection of conventional CT devices[4]. Total radiation of CBCT units is approximately 20% of conventional CT and equivalent to a full mouth series[4,42-44].

There currently are four main system providers in the world market. Three CBCT scanners image the patient in the seated position (CB MercuRay - Hitachi Medical Corporation - Tokyo, Japan; I-CAT - Imaging Sciences International - Hatfield - PA, USA); and 3D Accuitomo (J Morita Mfg Corp, Kyoto, Japan). One scanner images the patient in the prone position (NewTom 3G - Quantitative Radiology, Verona, Italy). The available CBCT machines differ in size, possible settings, area of image capture (field of view), and clinical usage. (Table)

A less than 10 seconds exposure gives more diagnostic and treatment plan information than a panoramic X-ray, full mouth periapical series, lateral and frontal cephalograms, and occlusal radiographs. All those views can be produced from the original capture, and also some views that were impossible to obtain with regular radiographs (Fig.1). The use of CBCT technology could have an important impact in treatment planning and diagnostic record taking. With relatively low radiation and the ability to collect 3D data in less than 10 seconds, the CBCT may become the ideal craniofacial skeleton imaging option for the orthodontic office. If the CBCT technology continues to evolve and is able to achieve the potential it seems to have, it would be the replacement of the current X-ray machines.

THE THREE DIMENSIONAL DENTITION

The use of digital dentition has not been as widely accepted from its beginning as the other digital records. The patient's orthodontic record representing the dentition has traditionally been the only 3D record used. The clinician got used to "feeling" the occlusion.

Invisalign® (Align Technology, Inc Santa Clara - CA, USA) probably played a significant role in familiarizing clinicians with digital dental casts. They, in a sense, made the transition easier.

Converting the dental casts to a 3D computerized image yields no proven additional diagnostic and treatment planning information, but there are several advantages of a computerized 3D dental cast. Superimposition of pre- and post-treatment lateral cephalograms is an accepted and currently used method of outcome assessment. There are dental cast outcome assessment methods, but the actual superimposition of pre- and post-treatment casts cannot be performed unless digital 3D images are used. Using the ClinCheck® with Invisalign® models, we are able to use superimpositions[45] to aid in treatment planning decisions. Actual treatment outcome analyses, however possible, are not currently widely used. Specific techniques and methods are yet to be developed and tested.

In the workshop report by Hans[46] in 1993, it was agreed that the space required to store models was a universal problem for all orthodontists. The digitization of the dental cast allows for easy storage, fast access, and conservation of the dental casts. This saves physical space, time, conserves the records in an intact form, and for longer time, because old records would not need to be trashed due to storage needs. The digitization of the dental casts allows measuring, dental cast analyses, and provides views that would not be possible without destruction of the dental cast.

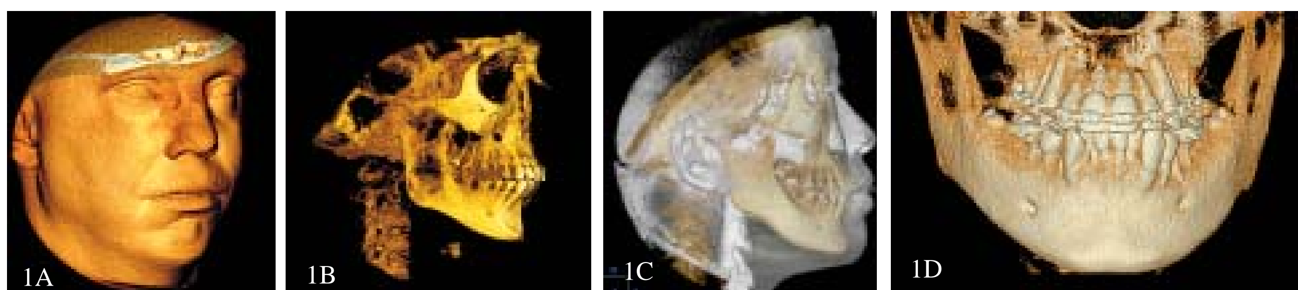
Digital 3D dental casts can be produced either directly or indirectly.

1). Direct Method:

A direct method of producing 3D digital images of the dentition is made possible by using a scanner to capture both dental shape and information. Orametrix (Orametrix, Inc Dallas - TX, USA) uses a structured light intraoral scanner to directly produce a 3D image of the dentition. After isolating the dentition and application of an opaquing agent, small images of the dentition are taken with a video camera while a light pattern is projected onto the teeth. The images are streamed to a computer where they are registered. The complete dental arch is imaged in approximately 90 seconds[4]. A clear advantage of this method is the elimination of the impression and pouring/trimming needs. Nevertheless, the contact points between teeth do not image well, and segmenting the teeth can be challenging[4].

2). Indirect Method:

The indirect method requires an accurate dental impression with alginate or polyvinyl siloxane. The 3D digital dental cast can be produced by scanning the impression, or scanning the poured cast resulted from the impression. The scanning of the dental cast can be either destructive or non-destructive. Destructive methods involve the removal of a thin layer of material, alternating with image capture to generate a stack of images that are rendered in 3D. Non-destructive methods involve the use of a laser based system with a multi axis robot to obtain several perspectives of the plaster model that are combined to form a complete 3D model[4]. Another approach to non-destructive methods includes the use of Micro CT to image the dental cast or impression.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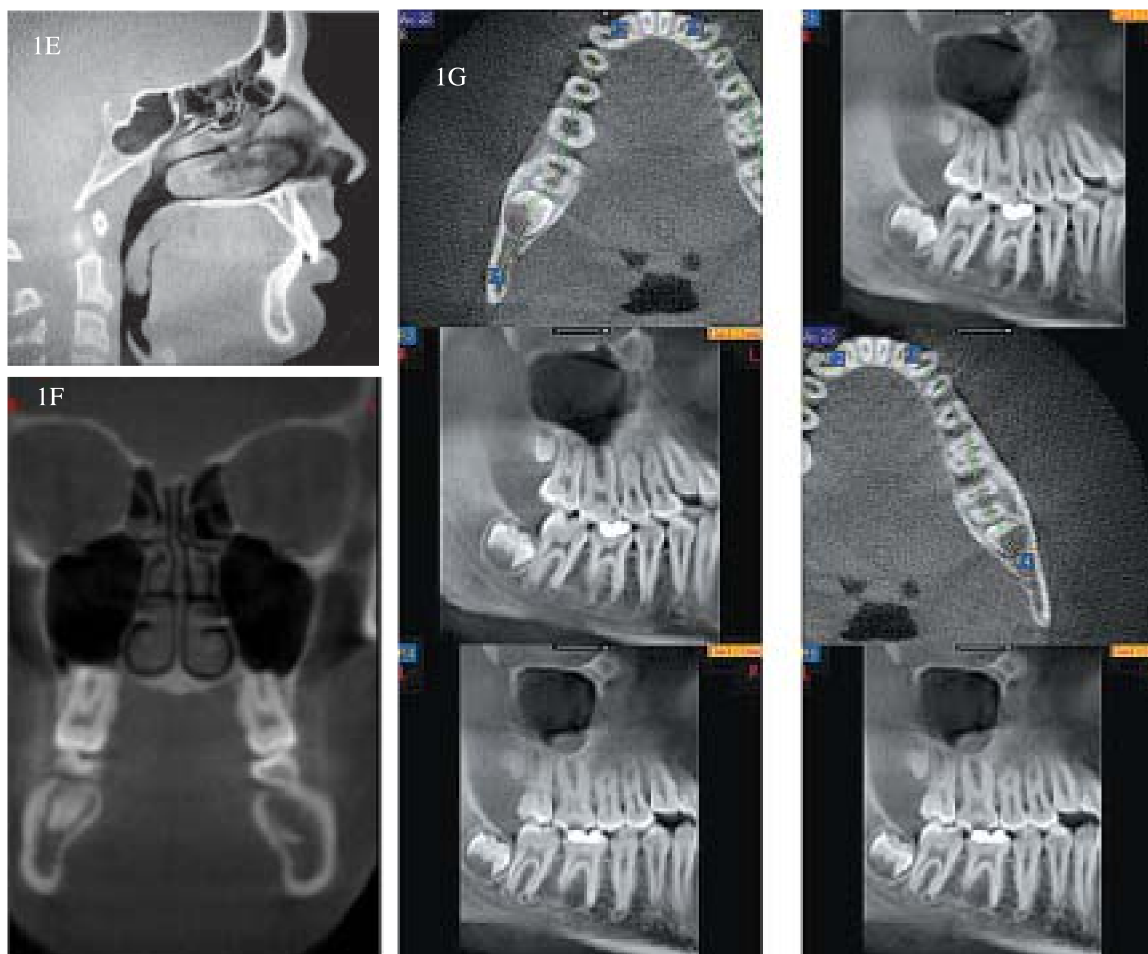
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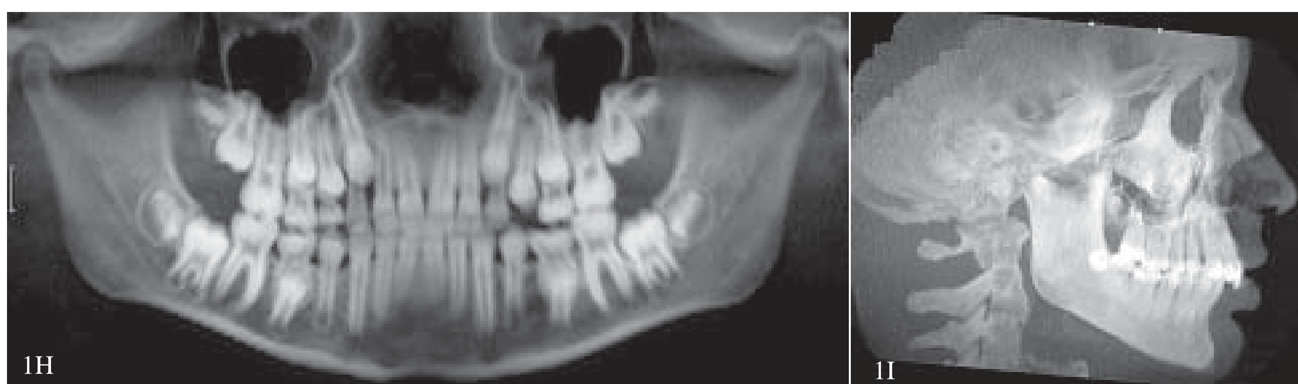
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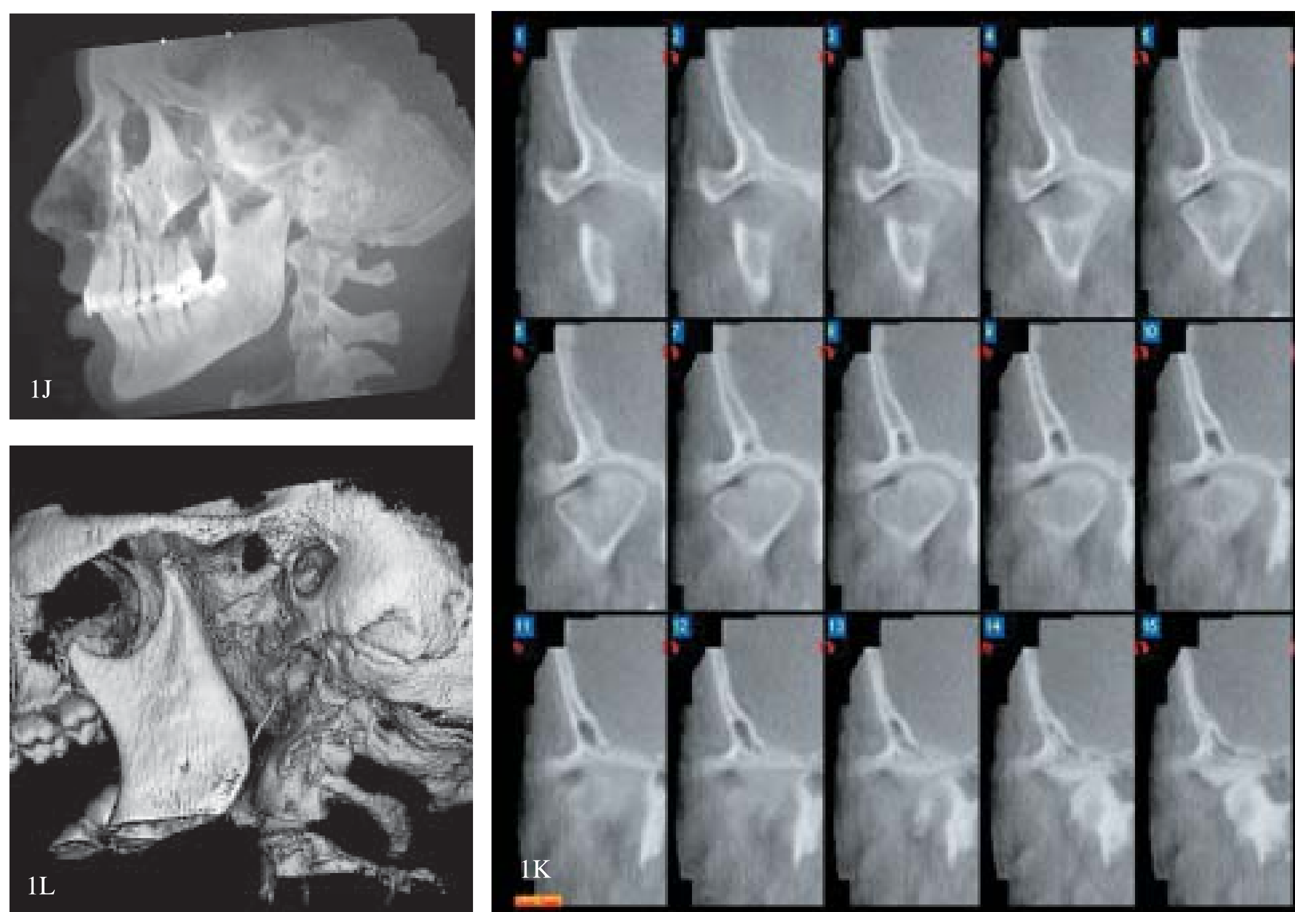

Fig. 1. Images taken with a CBCT scanner (courtesy of Aperio Services LLC - Sarasota - FL, USA; and Hitachi Medical System America Inc. - Twinsburg - OH, USA). A) Soft tissue face, B) Maxillofacial skeleton with braces in maxillary posterior dentition, C) soft tissue face and maxillofacial skeleton in the same view, D) image of patient with braces, E) sagital view of maxillofacial complex, F) coronal view of the posterior dentition, G) image equivalent to bite wing series, H) image equivalent to panoramic radiograph, a 2 mm slice was used, I) and J) image equivalent to traditional cephalograms, but with CBCT both left and right sides can be analyzed and traced separately (an image equivalent to a traditional cephalogram can also be achieved by superimposing right and left structures into a single image), K) a study series on a mandibular condyle, and L) TMJ area.

The use of a digital representation of the dentition currently gives as much information as a plaster dental cast would, with some added benefits. Nevertheless, some clinicians do not want to give up the ability to “feel” the occlusion and maneuver the dental casts in different positions. There are different methods to create a digital representation of the dentition. Some of these methods allow the use of dental casts by the clinician, and eventual digitization for storage and retrieval advantages. A direct digital image of the dentition can also be “printed” creating a dental cast. These options give the clinicians the advantages of both digital and analog worlds.

THREE-DIMENSIONAL PRINTED MODELS AND HOLOGRAMS

A 3D image of a 3D object is clearly the most accurate representation possible. The visualization of a 3D image can be done in more than one way. Using a computer screen gives the operator the ability to rotate the image and see it from different angles. The depth information of the object can be captured by measurements, but not visually. Two other possible ways of seeing a 3D object in 3D space are printing the actual image in 3D, or as holograms.

A direct digital image can be printed in 3D. There is technology available to create 3D models out of CT based

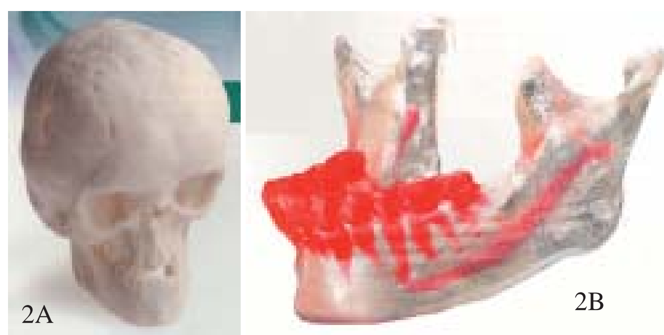

Fig. 2 3D Models created out of CT images. A) Craniofacial complex printed in RapidView® mode, B) model of the Mandible printed in ClearView® mode showing the use of stereolithography (courtesy of Medical Modeling LLC - Golden - Co, USA).

images (Fig. 2). These models can be useful for treatment planning and surgical simulations, and provide a 3D representation of the patient that can be held and seen in 3D space.

Another way of seeing a 3D image in 3D space is by using holographic technology. Transparent images provide "X-ray vision" for radiologists, surgeons, and patients. This yields a clear visual understanding of the critical relationships between and within anatomical and pathological structures. This true holographic perspective allows surgeons to be efficient, more precise, and more confident during pre-surgical planning, in the operating room, and for post-surgical assessment and follow-up.

A COMPLETE 3D PATIENT RECORD

The ideal patient record situation would be a complete 3D craniofacial record in which there would be individual as well as conjunctive access to soft tissue of the face, craniofacial skeleton, and dentition. The only way we can have such a record is in a digital format.

Several attempts have been made to create a complete 3D craniofacial record. Most of the attempts involved the collection of individual digital images for face, craniofacial skeleton, and dentition, and then combining them into a single image (Fig. 3). The process is not very accurate because the records are constructed 3D images out of 2D images, and the records were taken at different times with the patient in different positions. Currently, the process of constructing a complete 3D Patient record as a single file is possible, but it is not user friendly or practical in a clinical environment.

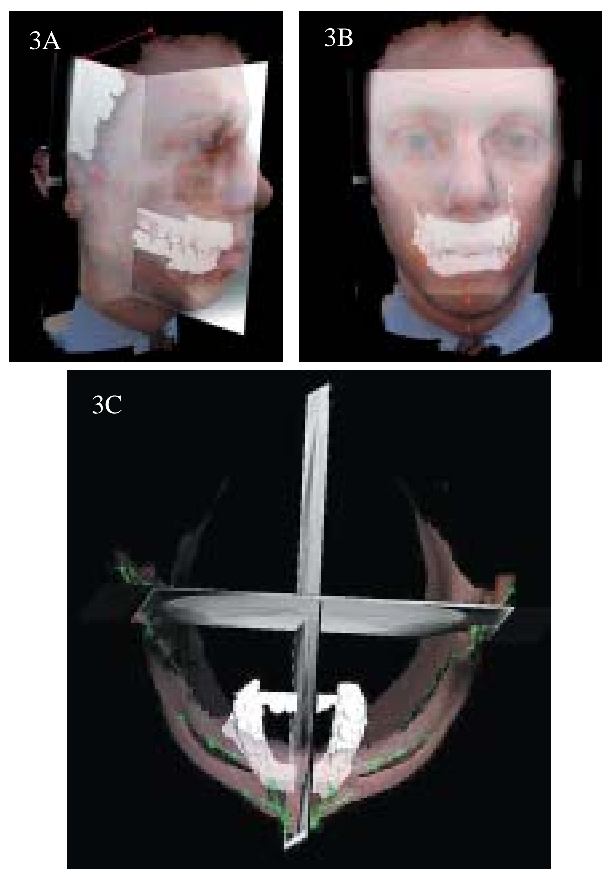

Fig. 3 Constructed complete 3D patient record using frontal and lateral cephalograms, digital 3D dental casts, and a 3D stereophotogrammetric image of the face. A) Lateral view, B) frontal view, and C) view from the top.

The new Cone Beam Computerized Tomography scanners show some potential in that arena, and could develop into the single source of orthodontic records. If this eventuates, an orthodontic records appointment could end up taking less than 10 minutes.

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