Craniofacial imaging in orthodontics: Historical perspective, current status, and future developments

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Abstract: Rapid and substantial advances in imaging methods and technology have not always been expediently or adequately communicated to the practicing orthodontist. In this review we highlight contemporary imaging techniques and innovations in imaging that, in the future, are likely to greatly improve the depiction of craniofacial structures for use in diagnosis and treatment planning. In order to provide an appropriate background for this topic, we first discuss the evolution of craniofacial imaging in orthodontics and review the limitations of current methods, including the two-dimensional representation of three-dimensional anatomy, depiction as a patchwork of site-specific images, associated geometric errors, and images that have a limited point of view and are static in space and time. Three-dimensional computed tomography can be considered a partial solution to these limitations, but imaging costs, radiation exposure, and lack of soft tissue representation may make it unacceptable for routine orthodontics. A more complete solution might be achieved through digital processing of contemporary imaging technologies that would extend their capabilities, overcome many of their limitations, and result in an increase in the amount of relevant information obtained. Digital processes are currently being developed that create accurate multidimensional models that integrate form and function. These models will be interactive, linked to knowledge databases, and will provide the clinician with answers to pertinent questions. These advances in imaging are likely to enhance the accuracy and reliability of orthodontic diagnosis and treatment planning, and will be of importance in both clinical practice and research.

Key Words: Craniofacial imaging, Cephalometrics, Three-dimensional imaging, Digital imaging

Over the years, diagnosis and treatment planning in orthodontics and dentofacial orthopedics have relied substantially on technological and mechanical aids. These technological aids include imaging, articulators, jaw tracking, and functional analyses. The goal in using these techniques is to accurately replicate or portray the "anatomic truth," to show the three-dimensional anatomy, both static and in function, as it exists in nature.

Imaging is one of the most ubiquitous tools orthodontists use to measure and record the size and form of craniofacial structures. Imaging has traditionally been used to record the status quo of limited or grouped anatomic structures. Despite the diverse image acquisition technologies currently available, standards have been adopted in an effort to balance the anticipated benefits with associated costs and risks. Because of these considerations, orthodontists routinely use an array of two-dimensional static imaging techniques to record the three-dimensional anatomy of the craniofacial region. For example, the anatomy is captured by site-specific images, including periapical radiographs and photographs for teeth, tomographs and magnetic resonance imaging (MRI) for temporomandibular joints (TMJs), and cephalometric radiographs for the facial skeleton. Although site-

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specific imaging enhances detail, it also segments the anatomy, creating a patchwork of separate images that represents an entire structure. This process results in related anatomic structures being differentiated arbitrarily on the basis of the point of view selected and the associated imaging geometry of that view. This anatomic segmentation places a troublesome, if not impossible, responsibility on the clinician to mentally reconstruct the true anatomy. The limitations of this approach have led to the design of many structured manual and computer-assisted analyses using linear and angular measurements between selected anatomic landmarks and constructed points to describe the anatomic information contained in the images. These measurements have often been incorporated into research databases for use in predicting growth and for evaluating treatment outcomes.

While the use of imaging in orthodontics has been relatively adequate, fulfillment of the imaging goal of "anatomic truth" has been limited by the available technology, the quality of the database, and tradition. These limitations have resulted in the use of a conglomeration of geometrically unrelated and inaccurate two-dimensional images for diagnosis and treatment planning. Ideally, multiple image sets would be fused into a common three-dimensional database to produce an accurate, interactive, and multidimensional model representing the patient's desired craniofacial structures and tissues. The interactive nature of this "smart" model would enable the clinician to manipulate static and dynamic three-dimensional images to retrieve any relevant information. The smart model would contain multidimensional information that includes three-dimensional space, time, and anatomic attributes, such as tissue resiliency, tissue type, and structural objects. The smart model could also provide time-dependent three-dimensional location and interrelationships of structural objects, including the jaws, landmarks, TMJ discs, teeth, and lips. The addition of functional attributes to this model, such as jaw tracking, electromyographic recordings, and bite-force measurements would allow computation of resultant stress/strain maps within the jaws and related structures. Stress/strain maps would help show the relationships between form, function, treatment outcome, and treatment stability. Such an approach to craniofacial imaging would provide a close replication of the anatomic truth and greater accuracy in diagnosis and treatment planning of orthodontic patients.

Although we are closer than ever to achieving the desired goals of craniofacial imaging, limited information on craniofacial imaging is available to the practicing clinician. Additionally, because of rapid and substantial advances in imaging technology, it has become increasingly difficult to keep abreast of recent developments that may be clinically relevant. Therefore, the objective of this review is to provide the clinician with background information on the evolution of craniofacial imaging in orthodontics, an overview of the limitations of currently used imaging methods, and a look at innovations in craniofacial imaging that are likely to greatly enhance the depiction of craniofacial structures.

Historical perspectives on imaging in orthodontics

The discovery of X-rays by Roentgen in 1895 revolutionized medicine and dentistry. Traditional cephalometry in two dimensions, known as roentgenographic cephalometry, was introduced to the dental profession approximately 36 years later by Broadbent,[1] and it remains relatively unchanged today. Cephalograms have been widely used, both as a clinical tool and as a research technique for the study of craniofacial growth and orthodontic treatment. However, because of the erroneous assumptions inherent in traditional two-dimensional cephalometry, use of this method for deriving clinical information as a basis for planning treatment has been called into question.[2-4] There are several reasons for the limited validity of two-dimensional cephalometry's scientific method and thus its application as outlined. First, and perhaps of most significance, is the fact that a conventional headfilm is a two-dimensional representation of a three-dimensional object. When a three-dimensional object is represented in two dimensions, structures are displaced vertically and horizontally in proportion to their distance from the film or recording plane.[5] Second, cephalometric analyses are based on the assumption of a perfect superimposition of the right and left sides about the midsagittal plane,[5] but this is observed infrequently because facial symmetry is rare and because of the relative image displacement of the right and left sides for reasons described above. The resultant discrepancies between the right and left sides do not lend themselves to an accurate assessment of craniofacial anomalies and facial asymmetries. Third, a significant amount of external error, known as radiographic projection error, is associated with image acquisition. These errors include size magnification and distortion, errors in patient positioning, and projective distortion inherent to the film/patient/focus geometric relationships as discussed below. Fourth, manual data collection and processing in cephalometric analysis has been shown to have low accuracy and precision.[6] Finally, large errors are associated with ambiguity in locating anatomical landmarks due to the lack of well-defined outlines, hard edges, and shadows, as well as variations in patient position.[5] Such landmark identification errors are considered a major source of cephalometric error.

Despite these limitations, many cephalometric analyses have been developed to help diagnose skeletal malocclusions and dentofacial deformities. However, several investigators have also questioned the scientific value of such analyses.[9-11] Vig[12] reported on the lack of validity that cephalometric analyses have as a diagnostic instrument, and demonstrated that conclusions drawn on the basis of the same cephalograms may vary significantly depending on the analysis used. Overall, the cumulative errors associated with traditional two-dimensional cephalometry have been significant enough to affect diagnosis and treatment planning.[3,13]

Hatcher recently reviewed and categorized sources of error inherent to traditional cephalometrics, including those due to internal and external orientation and those related to geometry and association as outlined below:

Internal orientation error: This refers to the three-dimensional relationship of the patient relative to the central X-ray beam or imaging device; it is assumed that the error is minimal when head position is specific and consistent. Since this is not always true, an internal orientation error is introduced.

External orientation error: This refers to the three-dimensional spatial relationship or alignment of the imaging device, patient stabilizing device, and the image-recording device. Minimal error is assumed when the X-ray source is 60 inches from midcephalostat, with the central ray passing through the ear rods and the beam horizontal to the horizon and perpendicular to the film plane. Furthermore, the distance from the midcephalostat plane to the film plane should be known and consistent between images. Any deviation from these assumptions will introduce errors into the final image.

Geometric error: This primarily refers to the differential magnification created by projection distance between the imaging device, recording device, and a three-dimensional object. For example, structures farthest from the film will be magnified more than those closer to the film. In addition, divergence of the X-ray beam from its source to the recording device will alter the anatomic truth.

Association error: This refers to the difficulty in identifying a point in two or more projections acquired from different points of view. The difficulty in identifying the identical point on two or more images is proportional to the magnitude of change in the angle of divergence between the projections.

When computers are used to assist in reducing these errors, they may introduce errors related to pixel size, loss of color and contrast information, and incomplete calibration. Therefore, in the hope of eliminating these random and systematic errors, methods have been developed to provide three-dimensional representations of the craniofacial complex. The first effort was proposed by Broadbent,[1] who introduced the roentgenographic cephalogram in 1931 and stressed its three-dimensional nature from the start. This study described the Orientator, which attempted to reduce association and geometric errors in lateral and posteroanterior headfilms. However, the Orientator did not overcome all the flaws and limitations inherent in two-dimensional cephalograms. The error of the Orientator method included variations in identification of identical landmarks from two different cephalograms and differential enlargements of the two views.[14] Contemporary efforts at minimizing errors and achieving accurate three-dimensional representation of the craniofacial complex have included computer-aided tomography (CT) and computer-aided design software,[15,16] which will be described later. However, the expense and dangers of radiation and the poor image rendering, respectively, of these techniques make them impractical for routine clinical use in orthodontics.

Another approach to the three-dimensional location of landmarks uses the principle of coplanar stereometry. This technique was adapted for cephalometric imaging from well-known principles used in stereo photogrammetry, and required the development of stereo cephalometric instrumentation that produced coplanar stereo pair images.[14,17] The limitation of this approach has been the expensive construction of the stereo photogrammetric machinery and the error introduced by patient movement during the acquisition of the two coplanar stereo films.

Goals and principles of craniofacial imaging

Despite the limitations of cephalometry, a large number of orthodontic databases have been constructed based on this imaging methodology.[5] In general, the purpose of craniofacial imaging is to help solve specific clinical problems. Craniofacial imaging is generally used either for deciphering any one of the following categories of information independent of the others, or more often, for synthesizing the information from two or more of the following categories.

(1) Assessment of pathology and any deviations from normal

(2) Comparison of outcomes of different treatment methods at different maturational stages and with different facial types

(3) Assessment of preceding growth or estimation of the direction and/or magnitude of expected growth

(4) Distinguishing the effects of treatment from the expected effects of unaltered growth

The ideal imaging modality maximizes the desired information and minimizes the physiological risk and expense to the patient. The underlying principle of ideal imaging is the determination of anatomic truth in terms of accurate portrayal of spatial orientation, size, form, and relationships of desired structures or features.[18] This requires assessment of the anatomy in three planes of space because craniofacial form is defined three-dimensionally and substantial and important information is lost when a three-dimensional structure is represented by a set of two-dimensional coordinates.[19]

Conventional craniofacial imaging modalities in orthodontics

When appropriately employed, many of the conventional imaging techniques can be used to meet the clinical objectives desired for orthodontic purposes. However, the information obtained from such imaging techniques should be correlated with all additional information to create a database for the purposes of arriving at a diagnosis and developing treatment options and a final treatment plan. Although cephalometric imaging has been and continues to be used to obtain important clinical information, in specific cases other types of imaging are equally important for orthodontic diagnosis and treatment planning. These include panoramic radiographs, full or limited mouth series, and various types of TMJ imaging as discussed in this section. In general, these image-acquisition techniques can be broadly grouped into those that primarily provide information on hard tissues and those that provide information on soft tissues. In some instances, information on both hard and soft tissues may be obtained together to varying degrees. There are many imaging modalities specifically designed to show hard or soft tissue structures, but this review will be limited to those most commonly used in orthodontics. Because many of the methods presented in this section rely on the use of X-radiation, we also provide a brief overview of imaging and safety patterns in orthodontics.

Hard tissue imaging techniques

Lateral and posteroanterior cephalograms

Despite the various limitations discussed previously, cephalometric radiography remains a vital clinical tool for gross inspection, determination of morphology and growth, diagnosis of anomalies, forecasting future relationships, planning treatment, and evaluating the results of growth and treatment.[4] Cephalometry's mainstay is that it is the only practical quantitative method that permits the investigation and evaluation of the spatial relationships between cranial and dental structures.[20] Although limited by their inability to show three-dimensional detail, cephalograms give a projectional resolution even greater that that of computed tomograms. Fine detail in bony anatomy is evident, and the trained eye can resolve structures smaller than 0.1 mm.[21] Of the cephalograms used in orthodontics, lateral cephalograms provide pertinent information on skeletal, dental, and soft tissue morphology and relationships, while posteroanterior cephalograms are primarily used to assess skeletal and dental asymmetries. In addition to the other errors associated with cephalometrics, posteroanterior cephalograms particularly have substantial limitations arising from internal orientation error linked to variations in the three-dimensional position of the head relative to the instrumentation.

As a research tool, cephalometry has been the most widely used imaging modality in orthodontic investigations, having been used to quantitate craniofacial parameters in individuals or sample populations, distinguish normal from abnormal anatomy, compare treated and untreated samples, differentiate homogeneous from mixed populations, and assess patterns of change through time.[5]

Panoramic radiography

Panoramic radiography is an excellent imaging technique if used with the realization that it has greater value for screening than for diagnostic purposes. Panoramic radiographs provide useful information about mandibular symmetry; present, missing, or supernumerary teeth; general root parallelism; dental age; eruption sequence; as well as limited information about gross periodontal health, sinuses, and TMJs. A panoramic projection can also reveal, to some degree, the presence of pathology and variations from normal. It must be stressed, however, that panoramic radiography has many shortcomings related to the reliability and accuracy of size, location, and form of the images created. These discrepancies arise because the panoramic image is made by creating a focal trough or region of focus within a generic jaw form and size. The best images are obtained when the anatomy being imaged approximates this generic jaw, and any deviations from this generic jaw form will result in a structure that is not centered within the focal trough; the resultant image will show differences in size, location, and form when compared with the actual object[18] (Figure 1).

Limited or full-mouth series (FMX)

A limited or full-mouth series consists of bitewings and periapical projections. There is more controversy regarding the routine use of this series than perhaps any other radiographic method used in orthodontics. Serious consideration should given to the cost/benefit ratio that takes into account radiation exposure, diagnostic value, and the need for medicolegal documentation. It is generally recommended that this imaging technique be selected on a case-by-case basis, since the potential risks due to ionizing radiation are real.[5] Obviously, there are many indications for the use of these radiographs, particularly to assess periodontal status and root morphology and length in adult patients. However, in most of these cases, a limited series often proves to be the most prudent choice. Communication with the general dentist is advisable in order to select the most appropriate time and series, and to discuss sharing of periapical and/or bitewing radiographs. From a strict orthodontic perspective, these images provide several benefits, including the ability to assess overall dental and periodontal health; root length, shape and form; presence of periodontal ligament space to help rule out the possibility of ankylosis; positions of impacted or erupting teeth; and root parallelism. Periapical radiographs are also used in conjunction with some mixed dentition analyses.

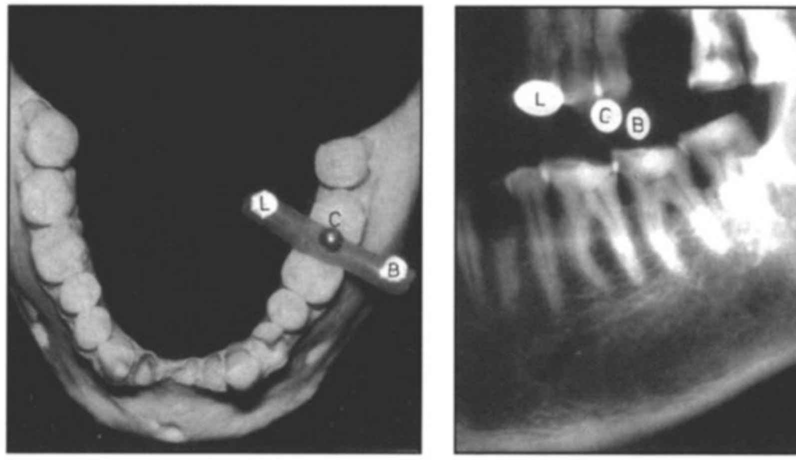

Figure 1A Figure 1B

Figure 1

Effects of the focal trough on image output. Three ball bearings of equal size were embedded in wax and aligned parallel to the occlusal plane and the embrasure between molars. The buccal (B) ball bearing was located near the lateral region of the focal trough, the central (C) was near the center of the focal trough, and the lingual (L) was near the medial region of the focal trough. The panoramic image shows deviations in size, shape, and location of the ball bearings that are not located at the center of the focal trough. The lingual ball bearing appears enlarged, displaced anterosuperiorly, and has an oval shape, while the buccal ball bearing appears diminished in size, displaced posteroinferiorly, and altered in form. Only the central ball bearing had adequate image representation.

Hand-wrist radiographs

Growth spurts during the adolescent period can influence the type and outcome of orthodontic treatment.[22] The ability to predict the amount and timing of growth facilitates planning the optimal time for interceptive treatment and potentially for redirecting growth using orthopedic appliances. This information is also critical for assessing the expected future growth in individuals with discrepant maxillomandibular growth, and for determining whether growth is near completion prior to performing orthognathic surgery. Hand-wrist radiographs aid in providing an estimate of remaining growth, since a positive correlation between skeletal growth assessed by this method and facial growth has been reported.[22,23] It has also been shown that skeletal development of the hand and wrist can be used to help predict the onset of peak height velocity.[24,25] However, in general, hand-wrist films must be used in conjunction with other indicators of overall body growth and development, with the understanding that their predictive value varies greatly among individuals. Several useful textbooks[26,27] have been written on the assessment of skeletal maturity and development of the hand and wrist to which the reader is referred for additional information.

Tomography

Tomography is a general term for a technique that provides an image of a layer of tissue. The layers or planes can be oriented to conform to a desired slice of the anatomy under study. The versatility of this technique makes tomography highly desirable for accurate imaging of a wide variety of maxillofacial structures, including the TMJ, and for cross-sectional imaging of the maxilla and mandible. Modern complex-motion tomographic units can be optimized to image any selected region of the facial skeleton.

TMJ and soft tissue imaging

Imaging of the TMJ is a broad field and makes up a separate subset of oral and maxillofacial radiology. Several methods exist for imaging the TMJs either two-dimensionally or three-dimensionally.[28] Two-dimensional imaging includes conventional radiology (transcranial, transpharyngeal, transmaxillary, submental-vertex, or reversed Towne's projection), arthrography, and fluoroscopy. Three-dimensional images include MRI, computed tomography (CT), and most recently, dynamic stereometry derived from three-dimensional imaging and tracking data.[28]

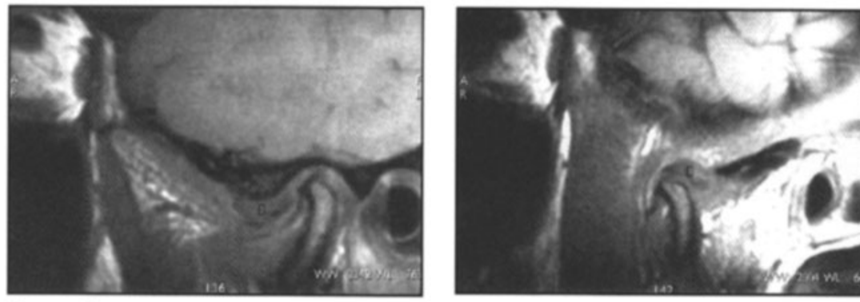

Figure 2A Figure 2B

Figure 2

T1 weighted axially corrected MRIs of the TMJ in the closed (A) and open (B) positions. The articular disc (D) is located anterior to the condyle in the closed position. The intermediate zone of the disc is interposed between the condyle and opposing eminence in the open position. This sequence therefore demonstrates a reducing anteriorly displaced disc.

Corrected tomography of the TMJ

Because of its ability to image the TMJ quickly and relatively inexpensively, corrected tomography has been one of the most widely used techniques for examining the hard tissue of the jaw joint. Axially corrected TMJ tomography refers to the alignment of the tomographic beam with the mediolateral long axis of the condyle to produce image layers that are parallel or perpendicular to the mediolateral long axis of the condyle. The laterosuperior and mediosuperior surfaces of the condyle are more difficult to image using sagittal tomography than the central two thirds of the condyle, and axially corrected coronal plane images are therefore recommended for viewing these surfaces.[18] The value of this technique is limited a priori by its two-dimensional nature, as well as by its inability to show the disc.

Computed tomography

CT differs from traditional tomography in the use of a computer to aid in generating the image, and in allowing multiple CT slices to be stacked to give an idea of the three-dimensional form. CT, while better than traditional radiography, is inefficient at producing suitable soft tissue contrast.

Magnetic resonance imaging

As our understanding of the biology and function of the TMJ increases, soft tissue imaging of this area has become increasingly valuable. Because X-ray tomograms are unable to show soft tissues adequately, MRI is the preferred imaging technique when information regarding the articular disc (Figure 2), or the presence of adhesions, perforations, or joint effusion is desired. MRI has the advantage of creating an image without using ionizing radiation, but it is not in wide use by orthodontists due to its expense. While it excels at imaging soft tissue, distinguishing between soft tissues of similar signal intensity, such as synovial tissue and the adjacent joint fluid, requires the injection of a paramagnetic contrast material.[29] Other regions of similar signal intensity, such as bone and air, also appear very much the same on an MR image and may be difficult to distinguish. Because of this, if information regarding the soft tissues directly adjacent to the jaws is required, then both MRI and CT scans should be considered.[18]

Arthrography

Arthrography relies on radiographic image acquisition following intra-articular administration of an iodinated contrast agent, which is placed under fluoroscopic guidance. Arthrography has contributed greatly to the understanding of disc position, but in recent years MRI has almost completely replaced TMJ arthrography for clinical use. Arthrography has an advantage over MRI in identifying the presence of perforations between the superior and inferior joint compartments and adhesions, but has the disadvantages of increased patient risks related to radiation dosage, percutaneous injection into the TMJ, and potential for allergic reaction.

Summary of TMJ imaging methods

The American Academy of Oral and Maxillofacial Radiology recently presented a position paper on imaging of the TMJ.[30] The reader is referred to this comprehensive review for further TMJ imaging protocols and selection criteria. This position paper discusses currently available imaging techniques and their respective indications, as well as their advantages and limitations. It should be emphasized that, since there is a wide spectrum of TMJ imaging modalities available, the subtlety of the expected findings should dictate which of these techniques is most appropriate for individual cases. Consultation with an oral and maxillofacial radiologist is encouraged when any question about imaging procedures or interpretation arises.

Imaging and safety patterns in orthodontics

In 1978, the cost of dental radiographic examinations was estimated to be more than $730 million.[31] Twenty years later, national expenditures for such procedures may exceed $2.5 billion per year. Such changes have led to a real concern in public health regarding the biologic and economic cost of maxillofacial radiology.[32] As a consequence of these concerns, and prior to the introduction of digital radiology, several important cephalometric radiation exposure reduction methods have been proposed.[33] These methods include rare earth screen/film systems, rare earth filtration, the use of grids, and the use of prepatient filtered soft tissue enhancement methods. Additionally, given that the radiation dose of cephalometric and panoramic films is equivalent to a single periapical or bitewing radiograph, in addition to their other diagnostic uses, these imaging methods may function well in a screening capacity prior to deciding on the need for additional radiographs.[34]

Contemporary and evolving imaging techniques

Digital imaging

Images are points of information that can be produced either by the conventional analog process or by a more contemporary digital one. Interest in digital imaging has grown for a number of different reasons. In terms of necessity, use of digital imaging allows the operator to manipulate data on a computer, facilitating the complex analyses and organization that are required in three-dimensional CT and MR imaging. In terms of biology, recently introduced techniques may reduce patient radiation exposure by 30% to 98%.[35] In terms of practicality, the elimination of hard-copy X-ray film may decrease storage needs and enable teleradiology, or the transmission of images over the phone and Internet.

In the digital process, a collection of digital or binary information is used to construct a computerized image. In most types of digital radiography, electromagnetic energy (X-radiation) is converted to an electrical charge by an X-ray sensor. These sensors include charge-coupled devices (CCDs), amorphous silicon, and amorphous selenium. CCDs are small sensors, like those found in video cameras. Because of the impracticality of creating large CCDs, these chips are arranged in an array when used in large X-ray applications. Amorphous silicon and amorphous selenium are flat panel sensors that, unlike CCDs, can be quite large. Another method of converting X-rays into an electrical charge for digital use is the storage-based phosphor plate. These plates are thin, wireless, and flexible, similar to intensifying screens. Reusable phosphor plates store the energy from the X-ray beam and are then "read" by a laser scanner that detects the intensity and location of the stored energy. The obvious advantage of this technique is that it can be retrofitted to an existing X-ray machine while maintaining a work flow very similar to film-based imaging.

Once X-ray energy has been converted to an electrical charge, a computer with a frame-grabber circuit board (digitizer) samples the photosensor values (voltage) and converts (digitizes) them into a picture element array (pixels). The series of horizontal arrangements of pixels on a computer monitor are called raster lines. On a cathode-ray tube (CRT) or computer monitor, these raster lines collectively make up the displayed matrix of pixels termed a bitmap. A pixel, or the image space unit, has a height and width to define its size, as well as a gray scale or color value. The number of different color values or intensities that each pixel can hold is measured in bits/pixel. For instance, an 8-, 10-, or 12-bit/pixel digitizing system can produce 28, 210, or 212 shades of gray, respectively. The same 8-, 10-, or 12-bit/pixel digitizing system will give 256, 1,024, or 4,096 different colors, respectively. The total bits of information in an 8-bit image file with a size of 1,024 x 768 pixels will be the product of these three numbers, or 6,291,456 bits. Since 8 bits of information require 1 byte of memory, this 8-bit, 1,024 x 768 pixel image will require a total of 786,432 bytes of memory. The number of bits per pixel determines how much information can be stored in the image. It has been suggested that periapical X-rays might require as little as 6 bits,[36] while larger X-rays may demand up to 12 bits.[37] Such detailed information requires large amounts of storage space. Optical tape, with the ability to store 1 terabyte (a million megabytes) of data could provide much of the storage needed. Additionally, more efficient storage can be obtained by compressing digital information. Compression ratios of 3:1 result in no loss of information, but ratios of up to 20:1, which lose some information, may still be clinically acceptable,[35] since the uncompressed and compressed images may appear the same to the observer.

In recent years, digital imaging has been used to complement or even replace conventional imaging of the maxillofacial structures. In order to determine the suitability of digital imaging as an alternative to conventional imaging methods, the most important criteria that must be considered are spatial resolution and gray-scale resolving power. While gray-scale resolution is determined by the bits/pixel as discussed previously, spatial resolution depends on the relative difference between the number of pixels available in the image capturing device and the size of the object being imaged as described below. The data collected from imaged structures are stored in computer memory as either a two-dimensional pixel or a three-dimensional voxel (Figure 3). The height and width dimensions of these picture display units are inversely proportional to the area being scanned (field of view), and the depth is proportional to the cut thickness. An image produced with smaller pixels and voxels (small field of view and cut thickness) has more detail, or higher resolution, than those produced with larger pixels or voxels. A technique called targeting, or matching the field of view as closely as possible to the size of the area of interest, produces images with the best detail because the pixels are kept small. A fixed number of pixels are available, and that number is determined by the matrix size of the scanner (e.g., 512 x 512 or 1,024 x 1,024 pixels). All the pixels can be assigned to an area of varying size. Thus, for example, when similar numbers of pixels are assigned to a periapical view and a panoramic view, the resultant periapical image will be of a much higher resolution than the panoramic image.

Finally, digital imaging offers additional advantages since the image data can be enhanced by processing it through desired algorithms to achieve specific imaging objectives. For example, anatomic structures or tissue details can be enhanced by employing various algorithms that offer three-dimensional display, multiplanar reformatting, edge enhancement, sharpening, smoothing, and subtraction of successive data sets. However, it should be understood that, despite the usefulness of these functions, they do not add information to the digital image, but instead work by suppressing unnecessary information from the image.[38]

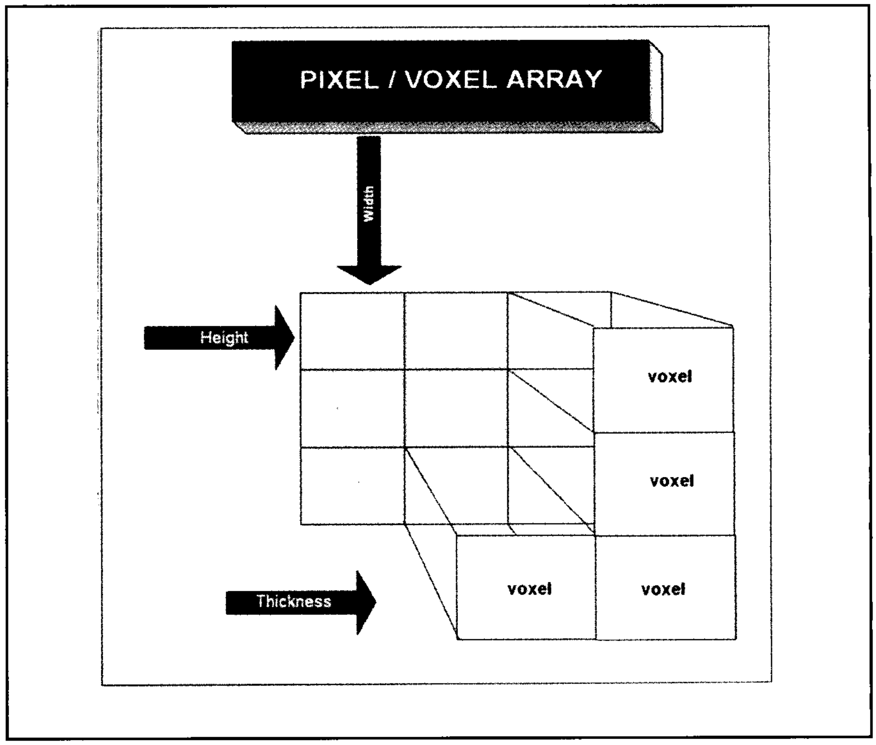

Figure 3
Pixel/voxel array: A two-dimensional pixel array, when extended into a third dimension, is termed a voxel. Each pixel possesses a unique location in the two-dimensional array and has a height, width, and gray scale or color value. In addition to these characteristics, a voxel has a thickness dimension.

Computerized and automated systems

Digital imaging has been a welcome addition to evolving computerized office management systems. Additionally, considering the time, tediousness, and systematic error associated with manual cephalometric data collection and processing, automated landmark identification and computerized cephalometric analysis systems have also received major attention.[39] It has been suggested that human error associated with anatomic landmark location may be significantly reduced or even eliminated with the development of fully automated cephalometric systems.[40] This process requires a scanner or frame grabber for image acquisition and advanced software that performs contour and contrast detection for automated landmark location. Although such methods and software systems programmed for landmark detection have been designed and show high reliability,[41] to date they are still unable to match human operators in their accuracy.[42]

While the validity of any single cephalometric analysis as a diagnostic measure has been questioned,[5] and the conclusions drawn on the basis of the same cephalograms may vary according to the analysis chosen,[12] computerized cephalometry offers an advantage in that it allows for multiple cephalometric analyses to be performed simultaneously. Automated systems also facilitate the performance of repeated digitizations of landmarks in an effort to increase the reliability of the analysis.[7,43,44]

Another important advantage of computerized cephalometry is that since the information is in digital form, it can be integrated with other digital information, such as intraoral and extraoral digital photographs and tomographs, to form composite profiles of patient records. The clinical and research implications of this possibility have been the focus of some investigations.[9] The usefulness of such computerized cephalometry as a basis for shared data sets for research purposes, including the establishment of true cephalometric norms and sound biologic parameters in craniofacial research, has also been stressed by other investigators.[4] Finally, computerization of cephalometric and other images offers distinct advantages in teleradiology, which is the transmittance of images over the telephone and Internet.

Teleradiology

Early 1982 marked the initial meeting of the First International Conference and Workshop on Picture Archiving and Communications Systems (PACS) for Medical Applications. The thought was that if digital imaging is to be fully used, there must be an efficient and universal method of storing and transporting the digital information. Unrealistic expectations and inadequate technology prevented the universal implementation of PACS.[45] Since that time, the goal has been to establish standards such that different manufacturers could interface their equipment with PACS networks, and therefore allow images to be transferred and read between locations and platforms. Currently, the American College of Radiology and the National Electrical Manufacturers Association have developed a standard known as Digital Imaging and Communications in Medicine (DICOM) and have adopted Ethernet TCP/IP as a network protocol.[46] This electronic transport of images will continue to meet challenges as new technology surfaces and as legal questions about interstate medical and dental practice arise.

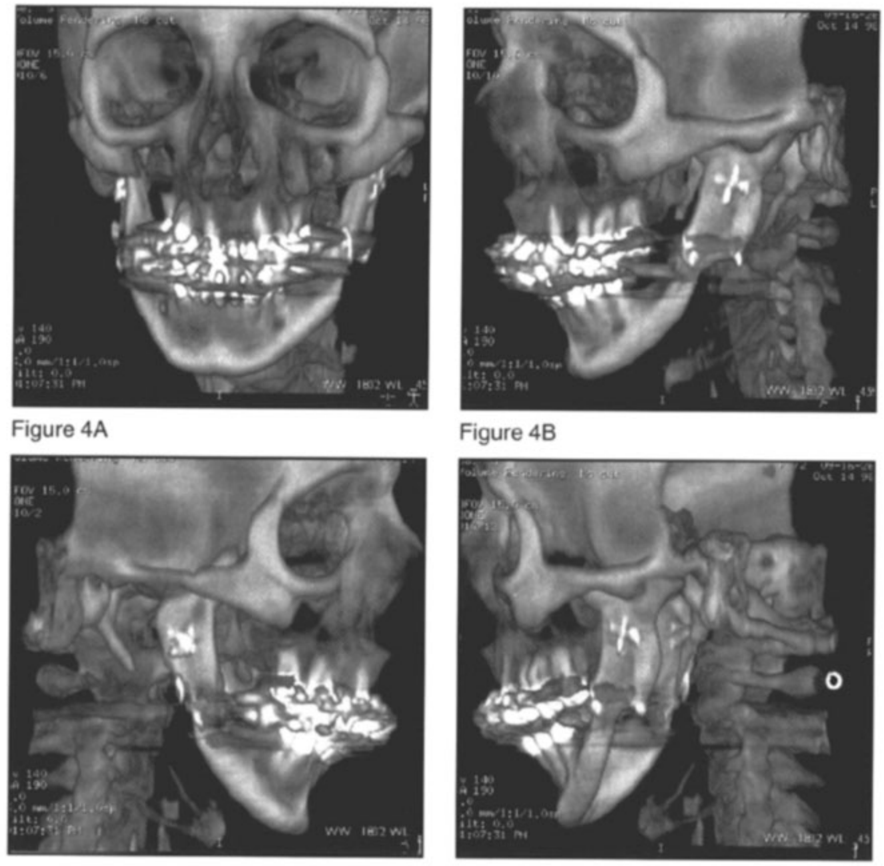

Figure 4A

Figure 4B

Figure 4C

Figure 4D

Figure 4

A three-dimensional reconstruction of a CT scan of the head using a GE 9800 helical scan. The data were processed using a volume-rendering algorithm in a bone window showing a patient from several points of view displaying an altered mandibular anatomy due to bilateral sagittal split osteotomies and a right side condylectomy.

Developments in craniofacial imaging

One of the most significant limitations of conventional imaging modalities in maxillofacial radiology has been the lack of practical, cost-effective, and low-risk methods to represent the anatomic truth. The future of craniofacial imaging lies in the generation of efficient, inexpensive, and detailed three-dimensional images for diagnosis and treatment planning. Current and evolving technologies, including CTs, microCTs, tuned-aperture CTs, and MR spectroscopy aim to achieve many of these objectives.

Computed tomography

In conventional stereo cephalometry, identification of identical points in two or more projections is difficult and results in an association error that is proportional to the magnitude of the divergence angle between the projections. CT scans automatically solve this problem by sampling a large number of small angle increments around the object, after which any given feature is correctly located as a result of the mathematical image reconstruction process. Although CT scans are too expensive and have too high a radiation dose to be appropriate for most orthodontic applications, in certain situations the benefits outweigh the risks. The treatment of craniofacial deformities, where the asymmetries render traditional two-dimensional diagnostic records inadequate, is one example.[21,47] Additionally, the outcome of surgical procedures may be visualized using sophisticated CT techniques (Figures 4 to 6). For these patients, CT images can be manipulated to undergo a three-dimensional reconstruction of the image. The final image can be fed through a computer-aided design system and either viewed on a computer screen or processed into plastic via milling machines or laser stereolithography.[21] Furthermore, the technique is sophisticated enough to allow the extraction of an element, such as the mandible, in order to view it in isolation from other structures.

CT scans produce a very dense data set that contains three-dimensional information about the soft tissues and bone that can be extremely valuable for diagnostic purposes. The CT scans acquire 12-bit data (4,096 shades of gray) for each voxel. The anatomic data sets can be processed or reformatted to show anatomic features of interest. The anatomy can be reformatted and displayed in three dimensions (Figures 4 and 5), or in specified points of view, windowed and leveled to optimize the gray scale for the tissues of interest (i.e., soft or hard tissues, Figure 5) or shown in thin (1 mm thick) sections (Figure 6). An alternative to surface rendering of conventional three-dimension CTs is a technique called volume rendering. In volume rendering, a volume of tissue is windowed and leveled to optimize for the tissue types of interest and an

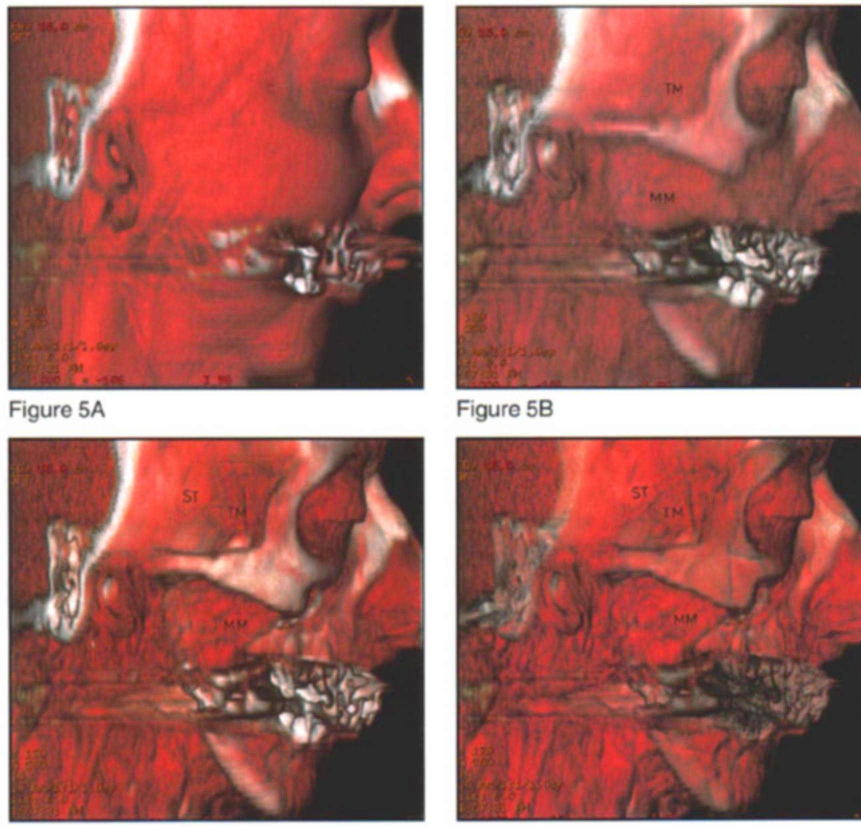

Figure 5A Figure 5B Figure 5C Figure 5D

Figure 5
A series of three-dimensional volume-rendering techniques that show various combinations of soft tissues and bone. The soft tissues have been assigned a relatively high opacity in figure A, with decreasing levels of opacity assigned in figures B through D. The superficial masseter muscle (MM) and portions of the temporalis muscle (TM) can be seen in figures B through D, and the superficial temporalis artery (ST) is observed in figures C and D.

opacity level assigned to various displayed tissues. This allows the simultaneous display and visualization of layered tissues (Figure 5).

Microcomputed tomography

MicroCT is principally the same as CT except that the reconstructed cross sections are confined to a much smaller area. The future of microCT lies in its ability to sample data over a much smaller volume than full body, significantly reducing the radiation exposure. Current microCT scanning of bone has revealed accurate and precise information about bone stereology and microarchitecture. This technique can now be used to measure bone connectivity in all three dimensions and even to record anisotropy, neither of which are possible even with histology.[48] This method has been used clinically to evaluate osteoblastic/osteoclastic alveolar remodeling as well as bone dehiscences and root resorption.[49]

Tuned-aperture computer tomography (TACT)

Because of the limitations of current radiographic techniques and the need for three-dimensional imaging, the National Institute of Dental Research elected in 1990 to support the development of a system for generating three-dimensional images tomosynthetically from a machine consisting of a multitube X-ray and an X-ray CCD

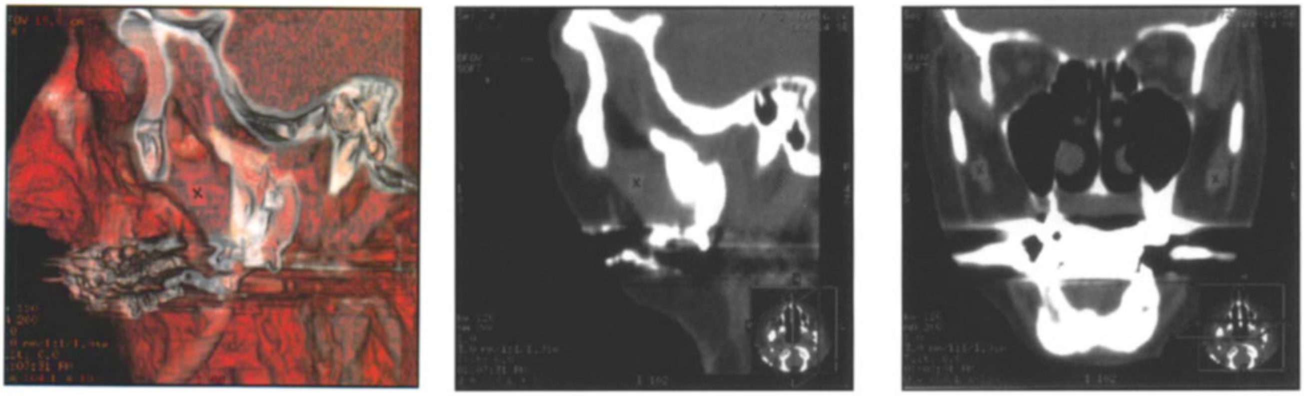

Figure 6A Figure 6B Figure 6C

Figure 6
Three-dimensional volume-rendered images of thick section (A) combined with thin section images of the left side in parasagittal plane (B) and coronal plane (C). These images show an aberrant muscle or scar band (marked X) that extends from the anterior border of the base of the ascending ramus to the posteroinferior region of the zygomatic extension of the maxilla. This tissue may represent a reattachment of the temporalis muscle following mandibular osteotomies.

screen. The most contemporary result of this endeavor has been the TACT system, which is able to convert multiple two-dimensional images created from multiple arbitrary projection source positions into a three-dimensional image.[50] TACT and tomosynthesis require the acquisition of several transmission radiographs of the target anatomy, each acquired from a unique point of view. A feature in a three-dimensional object is uniquely displaced on each resultant image, depending on its location relative to the imaging source and film. The feature and corresponding image plane can be reconstructed by stacking all the images so that the feature of interest is superimposed. This approach enables the end-user to reconstruct the desired image plane from a small number of original images. The TACT technique places a calibration or reference marker in the field of view to allow for synthetic reconstruction of the desired image plane, but it eliminates the need for precise control and knowledge of the imaging geometry. This technique does require that the image sensor and imaged object remain fixed, and the location of the X-ray source can be arbitrary. The calibration marker allows for the determination of the imaging geometry used to produce the final visualization from the resultant image. This technique permits the mapping of all the resultant images into a three-dimensional volume. For practical clinical application of this technique, the image is acquired with a digital sensor, such as a CCD or amorphous silicon sensors.

TACT appears to have a higher diagnostic value than traditional radiographs in its ability to detect dental caries.[50] The future of TACT for orthodontists will lie in its ability to assist in the evaluation of dentoalveolar bone, the detection of root resorption, and evaluation of the TMJs. TACT technology can be used for other orthodontic purposes as well, using existing hardware devices to provide CT-like images. This would involve retrofitting amorphous silicon plates to traditional cephalometric headfilm cassettes, grabbing images at 30 frames/second which, when combined with TACT software algorithms, would generate images that offer an effective and practical replacement of craniofacial CT.

MR spectroscopy

MRI works by obtaining a resonance signal from the hydrogen nucleus, and therefore is essentially an imaging of water in the tissue. MR spectroscopy works in a similar manner, but allows the imaging of any molecule or compound in the tissue.[51] MR spectroscopy is useful for the study of skeletal muscle physiology, tumors, and the healing of grafts.[52] This approach has been used to compare phosphate metabolism in muscles of bruxing subjects with nonbruxing controls[53] (Figure 7), and may have applications to a better understanding of the changes in muscle functions of patients with temporomandibular disorders.

Structured light

Because much of what is diagnosed in facial esthetics need not be related to the deeper structures of muscle and bone, it may be possible to analyze the face at its surface level only. Structured light scanning enables the topology of the face to be digitized simply and without ionizing radiation.[54] The result is a three-dimensional "shell" of the patient's face, viewable on a computer monitor. Three-dimensional facial analyses are now a possibility, and three-dimensional superimposition revealing treatment effects and treatment outcomes will soon be a reality. The eventual goal of this technique is to merge the facial shell and underlying X-ray data from other sources to complete the three-dimensional structure for diagnosis, treatment planning, and assessment of treatment outcomes. Structured light patterns, when combined with stereo photogrammetry to accurately measure the light pattern, result in the generation of an accurate three-dimensional map of the lighted structure.

Stereo photogrammetry

Stereo photogrammetry dates back to long before the structured light method was developed and involves photographing a three-dimensional object from two different coplanar views in order to derive a three-dimensional reconstruction of the images. Modern stereo photogrammetry can be applied to solve accurate three-dimensional skull mapping. Using a bundle adjustment method, both the geometric calibration and three-dimensional mapping functions can be elegant and accurate.[55] The bundle adjustment method is basically a self-calibration method that uses a large number of measurement points simultaneously to estimate the position of the imaging device and three-dimensional coordinates of the anatomic features.

The identification of landmarks in three dimensions allows for independent three-dimensional tracking of the relative changes in location of the landmarks as a result of growth, development, mandibular movement, injury, skeletal malformation, and treatment. The techniques used in the spatial correlation of multiplanar images can be applied to other clinical data collection methods, such as three-dimensional motion, as well as photographic and X-ray images. By combining X-rays with the principles of stereo photogrammetry, changes in bone density can be tracked temporally in three dimensions. The determination of three-dimensional motion of the mandible relative to the maxilla can be accomplished with a timed sequence of video images using a surveyed set of spatial markers that are linked to the maxilla and mandible. One set of markers can be tracked to define the three-dimensional movement of the mandible, while the other can track the relative location of the maxilla. This same tracking technology can be applied to tomographic, photographic, CT, and MRI images. The spatial and temporal referencing of

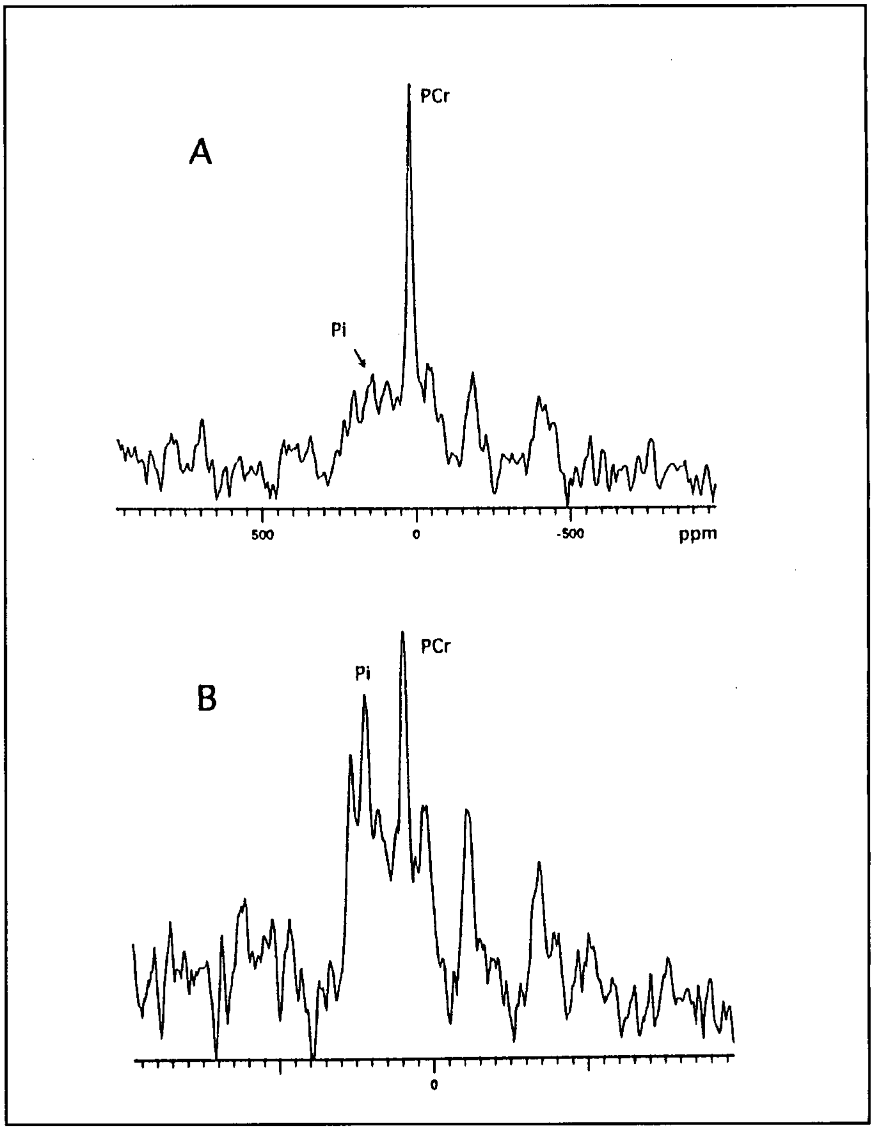

Figure 7
Phosphate-31 nuclear magnetic resonance (^{31}P-NMR) spectroscopy of a resting (A) and contracting (B) human massetter muscle showing dramatic changes in levels of inorganic phosphate (Pi) and phosphocreatinine (PCr) during muscle function. Metabolism of the phosphocreatinine into inorganic phosphate by the contracting muscle causes a substantial increase in the Pi:PCr ratio. Deviations from normal changes in the Pi:PCr ratios may be an indicator of aberrant muscle function such as that occurring in patients with temporomandibular disorders (courtesy of Dr. Arthur J. Miller).


Figure 8A


Figure 8B

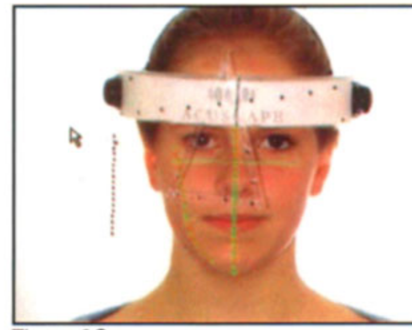
Figure 8C


Figure 8D


Figure 8E

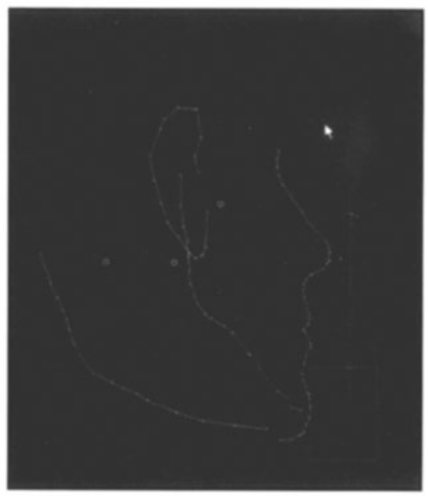
Figure 8F

Figure 8
Utility of new hardware and software (Acuscape Sculptor) for three-dimensional reconstruction and measurements of soft and hard tissue images. (A) Frontal photograph showing calibration frame worn by subject. Calibration frame contains calibration targets that are registered on photographic and radiographic images (black and radiopaque spheres in A and B, respectively). Known geometric arrangement of calibration targets provides the opportunity to compute geometric effects of head position relative to camera or X-ray source. Three-dimensional measurements can be made on images when precise geometry between object, film, and imaging source is known and combined with two or more images of the subject. (B) Lateral cephalometric projection and frontal (C) and lateral (D) photographs provide images that can be cross-calibrated to allow for three-dimensional measurements of any features on these images. Cross-calibrated images are fused into the same database allowing simultaneous measurement of hard and soft tissues. (E) By tracing an area of interest, such as the right ear, right and left posterior and inferior borders of the mandible, and soft tissue midline of the face in three dimensions, the three-dimensional location (x,y,z) of any given point on a tracing can be stored in a database and point-to-point distances computed. (F) Three-dimensional images can be rotated and tilted to provide desired point of view. (Courtesy Acuscape International Inc.)

these independent data sources will create the opportunity for data fusion or calibration of these data sets to a common set of surveyed reference markers. Fusing data to a common set of coordinates or image registration points creates a composite image with the spatial attributes of each of the input devices. For example, visible light images and X-ray images can be combined into a single composite image if they can be registered to a common three-dimensional coordinate system. These techniques would overcome problems created by the currently used patchwork of two-dimensional images acquired from a selected point of view.

An innovative approach to three-dimensional craniofacial imaging using conventional imaging methods

Digital technology has recently given an impulse of validity to cephalometry by eliminating much of the error associated with image acquisition and landmark identification in traditional cephalometry. By combining digital technology with modern stereo photogrammetry, it is now possible to create a digital replica of a patient, using computer-aided fusion of radiographic and photographic images (Figure 8). This image acquisition process includes an inherent calibration technique that automatically corrects for errors of geometry created by the location and three-dimensional orientation of the image source, image sensor,

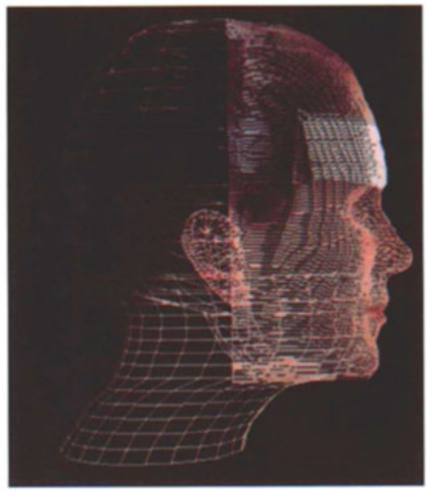

Figure 9A

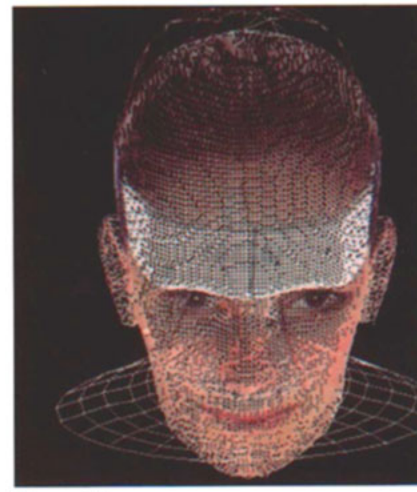

Figure 9B

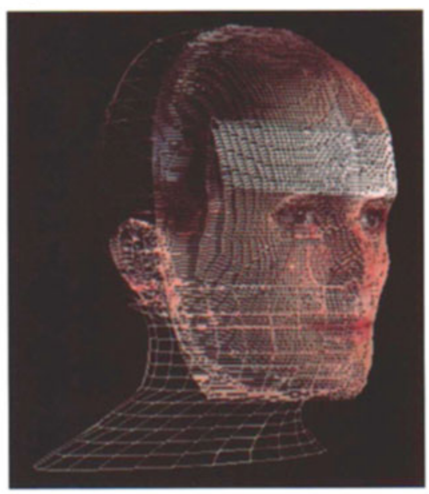

Figure 9C

Figure 9D

Figure 9
Three-dimensional reconstruction of the face by using new hardware and software (Acuscape Sculptor). Figures A to C show a dot contour of facial soft tissue construct of a subject made from a series of cross-calibrated photographs. Three-dimensional measurements of the subject's facial anatomy have been used to construct a subject specific model that can be viewed from any desired point of view (A - C), and potentially used for diagnosis, treatment planning and treatment simulations. The dot contour construct can also be photo-textured to a photo-realistic appearance (D). (Courtesy Acuscape International Inc.).

cephalostat, and patient's head. In addition, this technology can assist in identifying the same feature on more than one image, and it allows accurate three-dimensional modeling of hard and soft tissue anatomical landmarks from multiple cephalometric films and photographs. Recent software (Acuscape Sculptor™, Acuscape International Inc, Glendora, Calif) developed as a result of this technology, combines modern digital photogrammetry with image analysis in a PC Windows environment. The software computes accurate three-dimensional landmark locations and cephalometric traces, including three-dimensional curving forms such as jaws, orbital rims, mandibular canal, cranial base, sella turcica, temporomandibular joints, and alveolar ridges (Figure 8). It merges two or more cephalometric-type headfilms acquired at approximately prescribed head orientations into a single, accurate, three-dimensional database of anatomical structures. The computed traces and landmarks are then displayed in virtual view with the ability to interactively change the viewing angle. This software also provides a self-calibration feature based on advanced digital imaging and photogrammetry algorithms, which eliminates the need for a head fixation mechanism in the cephalostat while compensating for all magnification and rotation effects. This calibration technique further allows geometric cross-calibration of the visible band images, such as digital color photographs and video frames, with the scanned cephalometric films. Such manipulations enable the superimposition of three-dimensional hard tissue landmarks and tracings onto digital photographs or captured video frames of the face with accurate registration to the photographic view. Finally, using a series of cross-calibrated photographs, this software can be used to reconstruct a three-dimensional dot contour of facial soft tissues (Figure 9). Such a reconstructed image of the face can be viewed from any desired point of view and has potential uses in diagnosis, treatment planning, and simulation of treatment outcomes.

The advantage of the system is that it can use existing low-cost X-ray imaging equipment and a standard flatbed scanner. Its graphical user interface allows the user to control the analytic functions. The on-line analysis results are graphically displayed for confirmation and editing on multiple image windows. The relational database behind the software keeps track of the anatomical structures, images, three-dimensional landmark coordinates, and calibration data in a unified framework. These features may make this approach an important interim clinical and research method in the evolving field of craniofacial imaging.

Standardization and practicality of novel craniofacial imaging techniques

In August 1998, the American Dental Association adopted DICOM standards that address biomedical imaging. Similar standards have been adopted and are currently in use for medical imaging devices, such as CT scans and MRIs. These standards address digital interface communication protocol to allow communication between disparate types of equipment, transmission of data, data compression, archiving of data, and coding of imaged anatomic regions and patient attributes, such as name, age, and date of birth. Currently, most manufacturers of digital equipment have not complied with these standards, but it is expected that over time these will be widely adopted.

The majority of currently available three-dimensional software applications have been designed for a variety of software platforms that range from personal computers (PCs) to UNIX workstations. Due to improvements in PC performance, an increasing number of these software applications are being designed for PCs. In general, there is a potential for three-dimensional software applications to be more complicated to operate than simple imaging programs, thus requiring more than average computer savvy. While the ease of using different three-dimensional computer software applications may vary substantially, ideally, software for the orthodontic office would be designed to operate on commonly available and configured PCs and would look and feel similar to other commonly used software applications. Therefore, although all software programs require some learning, the learning curve may be reduced when the graphical user interface tools and functions become more familiar and intuitive. Overall, the ease-of-use or simplicity of these software programs, which are under the control of the company that writes the software, should improve over time.

Conclusions

Although current imaging methods used in the orthodontic specialty continue to provide adequate information for diagnosis and treatment planning, several of these methods, including cephalometry, have important limitations. A critical limitation of most of these methods is associated with their two-dimensional representation of a three-dimensional object. However, exciting innovations in digital imaging are likely to change the way these current imaging methods are used in diagnosis and treatment planning. More importantly, new techniques, such as microcomputed tomography and tuned-aperture computed tomography, will conceivably provide information on the imaged object not available with current methods. These advances in imaging will substantially enhance our ability to identify conditions that are not detectable with currently available imaging techniques, and will help improve the accuracy and reliability of diagnosis and treatment. These advances in imaging techniques will be of great importance, both in clinical practice and in research.

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