



ORAL SURGERY

ORAL MEDICINE

ORAL PATHOLOGY

## REVIEW ARTICLE

## Three-dimensional craniofacial reconstruction imaging

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This review article aims to describe and discuss the imaging techniques most commonly used in medicine and dentistry to obtain three-dimensional images of the craniofacial complex. Three-dimensional imaging techniques provide extensive possibilities for the detailed and precise analysis of the whole craniofacial complex, for virtual (on-screen) simulation and real simulation of orthognathic surgery cases on biomodels before treatment, as well as for the detailed evaluation of the effects of treatment. Laser scanning in combination with the stereolithographic biomodeling seems to be a very promising combination for three-dimensional imaging, although there is still considerable room for improvement. Constant efforts should be made in the direction of developing and enhancing the existing techniques as well as exploring the potential for developing new methods based on emerging sectors of technology. (*Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2002;93:382-93)

Three-dimensional (3D) imaging is an innovative approach in the field of medical imaging that in a very short time has found a considerable number of applications throughout the medical and dental sciences, including orthodontics and maxillofacial surgery.

Although assessment of craniofacial morphology always requires a 3D approach, until the late 1970s, all the available techniques allowed the manipulation of data derived from radiographs and photographs only in 2 dimensions. With the aid of only 2-dimensional (2D) projection images, it is difficult to understand the precise anatomy or the morphology of an area under examination.

In the 1980s, attempts to overcome the drawbacks of the 2D techniques included the application of methods such as stereophotogrammetry<sup>1</sup> and the use of profile photographs and standard size radiographs of the head.<sup>2</sup> Since then, advances in computer and imaging technologies have made possible the generation and handling of precise 3D reconstructed images with routine clinical data.

Three-dimensional reconstructed images can provide precise and detailed information for the diagnosis of craniofacial structural problems, enhancing the specialist's perception of them and facilitating a more efficient treatment planning, thus making them preferable to the conventional 2D modalities. They are expected to help a specialist to select the most appropriate treatment intervention while also offering the possibility of preoperative treatment simulation, espe-

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cially in cases of craniofacial anomalies,<sup>3</sup> head and neck abnormalities,<sup>4-6</sup> craniofacial trauma surgery,<sup>7</sup> cranial bone defects,<sup>8</sup> and malocclusion problems.<sup>9</sup> Furthermore, the communication between specialists is made easier and more direct, and consultation with the patient becomes more interactive.

For the study of the craniofacial complex, as well as for other clinical applications, 3D imaging can be carried out (1) by simple and easily applicable techniques (3D cephalometric radiography, 3D occlusogram, laser scanning, automated infrared photogrammetry), (2) by sophisticated and advanced techniques that require the use of specialized equipment (3D ultrasound, 3D magnetic resonance imaging [MRI], 3D computed axial tomography [CT]), (3) by computer-aided manufacturing procedures (stereolithographic biomodeling), and (4) by combinations of 2 or more of the aforementioned methods. This review article aims to present and discuss these applications.

### SIMPLE 3D IMAGING TECHNIQUES

The simple 3D imaging techniques do not require complicated equipment, can be applied by the practitioner in a private practice, and are cost-effective. The images provided are of lower fidelity in comparison to the more advanced techniques and, therefore, are mainly used for clinical applications (treatment planning, prognosis, evaluation of treatment outcome). However, these simple techniques are not very reliable for recording measurements for research purposes.

#### 3D cephalometric radiography

This method is based on the basic principles described by Broadbent,<sup>10</sup> in 1931, regarding the simple and widely used technique of cephalometric radiography.<sup>11</sup> The requisites for this technique are those of routine cephalometric radiography, namely a cephalostat and an x-ray source, but with the addition of a personal computer.

Three-dimensional information is produced by combining and integrating the data received from the digitization of a posteroanterior and a lateral cephalometric radiograph by using predefined cephalometric norms. The data are processed in a personal computer with special software (3DCeph for Windows; Department of Orthodontics, University of Illinois at Chicago, Chicago, Ill), by which tracings of both cephalometric radiographs are produced. The lateral cephalogram is traced with the aid of 8 cephalometric landmarks (sella, nasion, anterior nasal spine, supradental, incisal tip of the maxillary central incisor, incisal tip of the mandibular central incisor, menton, and pogonion). All landmarks are conventionally considered to be on the median sagittal level. The tracing of the posteroanterior cephalometric radiograph is also used.

In this view the points supradental and the incisal tips of the incisors are visible. However, nasion, sella, anterior nasal spine, and pogonion are not so clearly visible, and their location is determined approximately.<sup>12-14</sup>

Data processing is carried out by the software as follows.<sup>12</sup> The lateral cephalogram is rotated 3-dimensionally so that the landmark that is situated midway between the 2 porion points is lined up with the point midway between the 2 infraorbitals. Simultaneously, the posteroanterior cephalogram is rotated so that the line that is defined by the 2 porion points is horizontal. Subsequently, there is a pairing of the landmarks between the 2 cephalometric images. In this way, 2 dimensions are received from the lateral cephalogram, and the posteroanterior one provides the data for the third dimension. This method is actually the electronic version of the method initially recommended by Broadbent<sup>10</sup> with 2 sources of x-rays, thus resulting in the on-screen 3D projection of the skull.

The acquired 3D images can be used in several ways. They may be used as provided by the computer for the detailed description of the head anatomy, the registration and study of head and neck development, diagnosis and treatment planning, the evaluation of treatment, and reexamination after treatment as well as for research purposes.<sup>15</sup>

A drawback of 3D cephalometry is that it requires the use of 2 cephalometric radiographs and therefore increases the x-ray dose received by the patient (total, 26 millirads). However, this x-ray exposure is still very small in comparison to other techniques (total dose of an average CT scan, 6.5 rad)<sup>16</sup>. Thus, this technique offers the possibility of extensive long-term repeatability, which makes possible longitudinal studies of the craniofacial complex. Moreover, it is readily applicable, has low cost in relation to other techniques, and the images provided facilitate the evaluation of treatment results (pretreatment and posttreatment condition).<sup>12,14,16,17</sup>

However, 2 basic disadvantages of this method are the need for relatively greater operator expertise and the greater margin of error in the evaluation of the exact position of cephalometric landmarks.<sup>12</sup>

Although 3D cephalometric radiography is a simple imaging technique, it cannot be used per se as a very reliable method for the precise assessment of the orthodontic or craniofacial patient. It presents no margin for further development; therefore, its role is limited to that of a complementary method for the study of the craniofacial complex and the planning of orthognathic surgery procedures.<sup>18</sup>

#### 3D occlusogram

This is a computer-aided technique introduced recently to contribute to the evaluation of teeth and

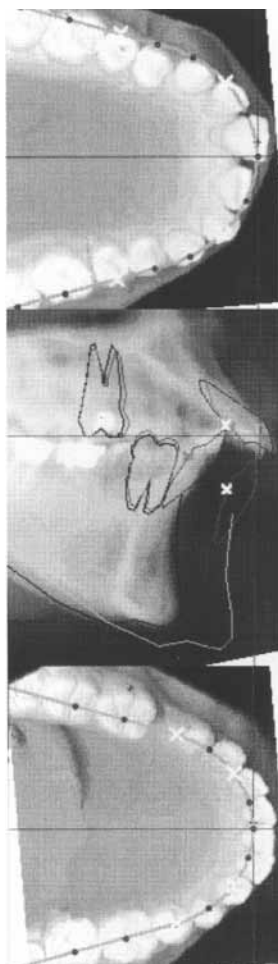


Fig 1. Three-dimensional (3D) occlusogram of a planned minor retraction of the upper front teeth, lower premolar extraction, and lower front teeth retraction, followed by a major surgical mandibular advancement. (Reprinted with permission, Fiorelli and Melsen<sup>9</sup>).

dental arches, the assessment of the direction and magnitude of orthodontic tooth movement, the selection of teeth to be extracted for treatment purposes, and the prediction of the final form of the dental arch as well as posttreatment occlusal relationships<sup>9</sup> (Fig 1).

Its application requires (1) dental impressions and the fabrication of study casts, (2) scanning of the occlusal plane of the casts (performed on a simple flatbed scanner), and (3) tracing and analysis of a lateral cephalometric radiograph. The computer operator simulates the desired position of the teeth on the lateral cephalogram (sagittal plane) as well as the transverse changes in the dental arches (sagittal and transverse planes). The calculation of the mesiodistal dimension of the teeth follows by using a computer or, more simply, by using a caliper on the dental cast. The latter is preferable because rotated or inclined teeth can

be more accurately measured. The combination of all data received by these procedures results in a complete 3D occlusogram of the patient, in which the clinician is able to test treatment hypotheses on the basis of orthodontic tooth movement.<sup>19</sup>

The 3D occlusogram is a simple, direct, and inexpensive technique. However, it is not as accurate as other techniques and it cannot be standardized, because the errors associated with the equipment (image magnification, distortion) vary according to the model and manufacturer.

### Laser scanning

This method is based on the use of a low-power nonhazardous laser surface scanner. Initially it was introduced by anthropologists for the quantitative assessment of anthropometric parameters.<sup>20-22</sup> It can also be applied in orthodontics and maxillofacial surgery for the registration of head morphology, and recent advances have also stimulated its use on dental casts.

**Registration of head morphology.** Laser scanning of the head and neck can be applied as follows. The patient's head is immobilized with a cephalostat, and a laser scan of the whole head and neck is performed with the scanner. The scanner consists of 2 sources of fanned laser beams and functions as a system for acquiring the surface coordinates of the facial form. The 2 beams are projected vertically onto the scanned surface from an oblique angle and observed from the front with a simple video camera. A computer processes the acquired image and registers the coordinates. By connecting the registered points to their neighbors, small triangular elements (facets) are generated. This way the scanned surface is represented by these facets, which are used because they simplify the subsequent computational procedures. Reconstruction of these facets from a computer equipped with proper software generates a 3D image of the scanned surface.<sup>23,24</sup>

It is a relatively simple and low-cost technique that is mainly used for clinical purposes. It provides the clinician with data that enable more precise treatment outcome prediction, prognosis, treatment planning, and the evaluation of treatment results.<sup>25</sup> Research applications of laser scanning are limited to the determination of the median profile of subjects of the same race, the quantitative assessment of the facial soft tissue mass, and is a useful tool for comparative anthropometric research studies.<sup>20-22,26</sup>

**Registration of dental casts.** Similarly, laser scanning can be used on dental casts. The data received from the dental casts are very useful for the diagnosis and determination of treatment plans in orthodontics. However, dental casts as diagnostic material present 2

main disadvantages. First, they are bulky, voluminous, and difficult to store. This is a major disadvantage—especially when dealing with a large number of patients. As a consequence and because of limited storage space, many institutes have to periodically purge dental cast collections of previously treated cases, with the consequent loss of valuable research material.<sup>27,28</sup> Second, they are fragile. Statistics have shown that almost 50% of the study casts handled by nonspecialized personnel reach the clinical site fractured.<sup>29</sup> For these 2 reasons, efforts have been made toward the substitution of the dental casts with their numeric holograms created by laser scanning, maintaining their valuable advantages while simultaneously eliminating their disadvantages.

There are many devices that can provide 3D images of dental casts. A very simple one uses the Denisyuk setup (an elementary layout for the creation of a hologram), which permits the presentation and study of holograms even under the light produced by a halogen lamp.<sup>27</sup> The holograms produced by this device (it is similar to a slide projector) lack quality and fidelity. Similar results but of better quality have been achieved by Harradine et al<sup>29</sup> with the use of the slightly more advanced holographic camera, Holocam System 70 (Holofax Ltd, Rotherwas, Hereford, United Kingdom). A much more sophisticated device is recommended by Kuroda et al.<sup>28</sup> It consists of (1) a central unit for taking the necessary measurements (3D-VMS250R; UNISN INC, Tokyo, Japan), (2) a personal computer of at least 16-bit as an overall program manager (the original layout of the device included the PC-9821Ap, NEC Inc, Tokyo, Japan), and (3) the main processing unit for the electronic data (Titan Vistra 800X; Kubota Computer Inc, Tokyo, Japan).

Most of the devices used in this technique cost relatively little. This method becomes even more cost-effective when space economy is taken into account. Moreover, the data received are very easily handled, stored, and electronically exchanged, and the operator needs no special training. Laser scanning is a quite reliable technique that could also be applied to data exchange programs operated by various institutions.<sup>28,30</sup>

A disadvantage of this technique is the considerable time still required to complete the 3D scanning of dental casts. This could be reduced in the future as new, faster, and more accurate scanning equipment, which is now under development, becomes available.

#### **Automated infrared photogrammetry**

The use of infrared light as an imaging modality was originally introduced by anthropologists<sup>20</sup> for anthropometric studies. It could be also used in the clinical

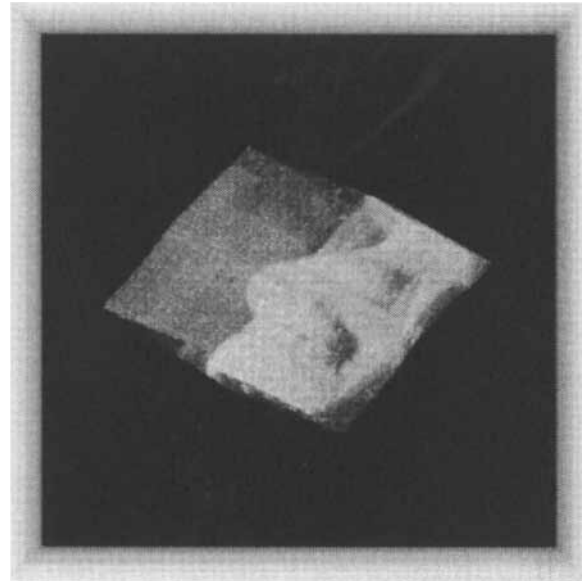


Fig 2. 3D visualization (volume visualization) of a 3D ultrasound data set of the nose (gradient-weighted projection).

practice of orthodontics and maxillofacial surgery to create 3D images of the head and neck.

Initially, an *in situ* marking of a predefined number of landmarks (15 to 25) is performed by means of a special ink visible under the infrared light. The position of the selected landmarks is registered, and a preliminary framework of the face is assembled in the computer. The image is obtained by using a pair of infrared digital cameras placed at 90 degrees on the horizontal plane. The framework is completed with the addition of scanned photographic images of patients, enabling the formation of the 3D image of the head and neck.<sup>20-22,26</sup>

This technique does not require the use of potentially harmful radiation, and the images received are considered more than satisfactory for anthropometric analyses. However, they are of low fidelity and are not very suitable as a basis for more detailed study of the craniofacial complex. In addition, the patient has to remain absolutely still for a long time during the procedure. This makes the use of this method impractical for very young or hyperkinetic patients.

#### **ADVANCED 3D IMAGING TECHNIQUES**

The advanced 3D imaging techniques require the use of advanced and very sophisticated equipment. The acquired 3D images are of very high quality and are very reliable for both clinical and research purposes. However, the necessary equipment is not accessible to the average practitioner, and because of their high cost these techniques are limited to selected cases.

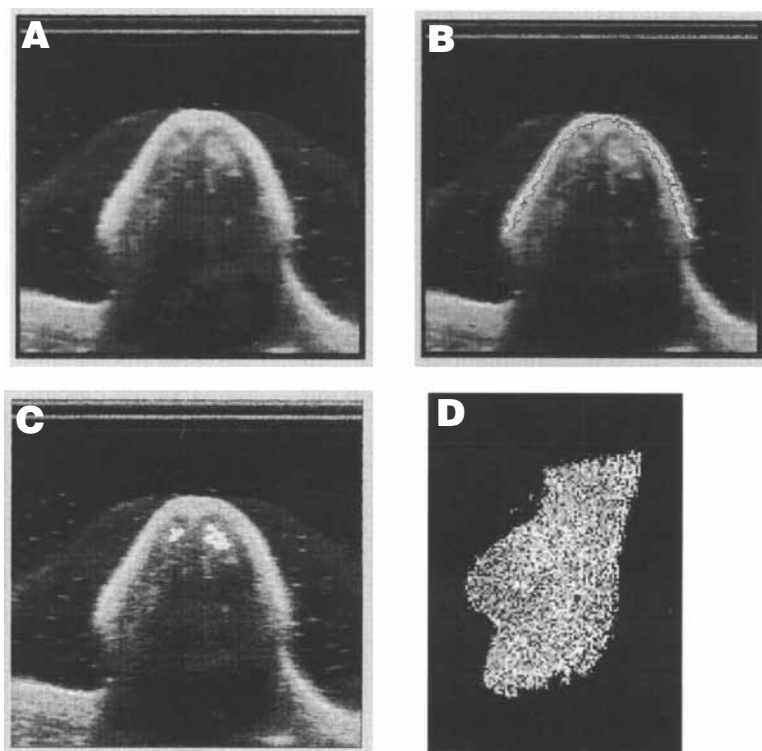


Fig 3. 3D segmentation of the soft tissue structures of a nose. **A**, Sonographic cross section of the nose; **B**, segmentation of skin surface; **C**, segmentation of cartilage; **D**, segmented 3D data set.

### 3D ultrasound (ultrasound holography)

3D ultrasound is a newly developed imaging technique. It is mainly used for fetal visualization and diagnosis in obstetrics,<sup>31-35</sup> but some applications have been reported in maxillofacial surgery for diagnostic and treatment planning purposes<sup>36,37</sup> as well as for the investigation of temporomandibular disorders.<sup>38-41</sup> For its application, very high frequency sound waves of a wavelength between 3.5 to 7.0 MHz are emitted from a special probe, a transducer, placed in contact with the area of interest. Repetitive arrays of ultrasound beams scan the area in thin slices and are reflected back onto the same transducer. Special software is used to accumulate and render the acquired data into 3D images. The acquisition of an entire 3D hologram through this technique is not time-consuming.

In clinical practice it is used by maxillofacial surgeons for the 3D visualization of abnormalities of soft tissues and organs adjacent to the maxillofacial complex (salivary glands, nose, tongue)<sup>36,37,42</sup> (Figs 2 and 3).

Three-dimensional ultrasound can facilitate the immediate diagnosis of minor defects (cleft lip and palate) or major craniofacial malformations of the fetus, thus providing the opportunity for in situ treatment planning.<sup>43</sup>

A disadvantage of this technique is that ultrasound images can be distorted or present artifacts. Artifacts and image distortions can be defined as false, multiple, or misleading information introduced by the imaging system itself or by interaction of ultrasound with the adjacent tissues. The most common errors are the false-positive and false-negative images produced during the process of diagnostic ultrasound that sometimes can be so intense that they mislead the clinician in the diagnosis. Hull et al<sup>44</sup> have observed on the imaging of 20 fetuses that although the initial imaging showed an apparent limb defect in 55% of the cases, a real birth defect was present in only 18% of the newborns. This error was caused by the physical properties of the adjacent fetal and maternal anatomic structures, whereas shadowing by acquiring data from more than one orientation avoided this artifact.

### 3D MRI

Although MRI per se is a technique for 2D imaging of body structures, with the advances in image processing systems it has become one of the most valuable 3D imaging techniques. The device used for MRI is the magnetic tomograph. It consists of a large cylindrically shaped electromagnet, equipped with coils along with transmitters and receivers of radio waves.

The patient is placed inside the electromagnet, which generates a powerful magnetic field around the patient. This magnetic field causes the polarization of the hydrogen atoms contained in the tissues. Their subsequent depolarization is accompanied by the emission of radiation, similar to the radio waves, which is received by the receivers. Subsequently, the data from these receivers are processed by computer software to produce MR images. Because of the low hydrogen concentration in bony tissues, their visibility in these images is limited.<sup>45</sup>

MRI offers a variety of clinical applications in the field of orthodontics, maxillofacial surgery, and related disciplines. It allows a thorough examination of the soft tissues and the components of the temporomandibular joint, which is especially useful in cases of temporomandibular disorders.<sup>46</sup> When used for the examination of the tongue, it enables the precise estimation of its volume and has rendered other methods obsolete.<sup>47-51</sup> Recently, as the interest in the intrauterine treatment of myelomeningocele has increased, MRI has also been used as a diagnostic tool for the assessment of the fetal central nervous system anatomy because of its noninvasive nature and its potential to produce more accurate imaging of the central nervous system in comparison to ultrasonography.<sup>52</sup>

Software that takes advantage of the high-quality MR images and transforms them into 3 dimensions has been recently developed.<sup>53</sup> With this program, the slices received by means of MRI can be rotated in space, geometric calculations can be performed, and particular areas of interest can be highlighted, magnified, or further analyzed. All slices can be reassembled, resulting in the on-screen display of a 3D image of the head and neck of the patient.

MRI is a safe technique (the magnetic field does not seem to affect humans), it is noninvasive as long as x-radiation is not used, and it is eminently suitable for long-term studies on human beings. Because of its nature, it provides data for the indirect diagnosis of several soft tissue abnormalities, including the temporomandibular joint,<sup>54-59</sup> and it can be applied to the preoperative planning of tumor resection, particularly in lesions close to the base of the skull,<sup>60</sup> as well as for the assessment of maxillary sinus volume for the sinus lift operation.<sup>61</sup>

This technique is not indicated for patients with metallic implants, osteosynthesis plates and screws, metallic prostheses, and fixed orthodontic appliances, because they interfere with the magnetic field producing artifacts in the image. Moreover, the magnetic field may change their position, damaging the surrounding tissues and undermining their therapeutic role.<sup>62-65</sup> Finally, the high cost of MRI mitigates its use in routine clinical examination.

### 3D CT

This is considered to be an excellent method for the study of the craniofacial complex, as well as for treatment planning in maxillofacial surgery. It derives from CT, which is a 2D technique. With proper enhancement from computer software, high-quality 3D images can be produced.

A CT scan of the head and neck is performed in thin contiguous slices (1- to 1.5-mm thickness). The images are processed and assembled by the computer, resulting in on-screen 3D visualization of the scanned structures.

With these images the clinician can perform an overall evaluation and diagnosis of the case as well as prognosis, treatment planning, and an estimation of the final treatment outcome. More specifically, 3D CT has already been applied in maxillofacial surgery in cases of craniofacial malformations and acquired defects, as a planning tool for the surgery of skull base abnormalities,<sup>4</sup> for surgical planning of head and neck cancer,<sup>5,66</sup> for the measurement of the volume of oral tumors,<sup>6</sup> for the analysis of primary nasal deformity in cleft lip and palate infants,<sup>67</sup> for assessment of naso-orbitoethmoidal fractures,<sup>68</sup> and for evaluation of airway changes,<sup>69</sup> as well as for in vitro experimental validation of 3D landmark measurement in craniofacial surgery planning.<sup>70</sup>

This method can be also used in clinical practice for the evaluation of temporomandibular joint abnormalities<sup>66,71</sup> and of the postsurgical condylar displacement after mandibular osteotomies,<sup>72</sup> in orthodontics for patients with severe tooth anomalies, such as impacted canines,<sup>73</sup> and in periodontology for the analysis of alveolar bone morphology of bone defects caused by periodontal disease.<sup>74</sup>

This method has been used in research for the determination of root canal geometry,<sup>75</sup> and some studies have successfully demonstrated an association between craniofacial growth patterns with the dental and skeletal characteristics of the mandible.<sup>76</sup> Some of the present authors have used this method for experimental purposes to evaluate bone healing in the intrauterine treatment of surgically created cleft lip and underlying alveolar defect<sup>77</sup> (Fig 4).

3D CT enables high-fidelity images and detailed visualization of the bony tissues of the head and neck. The radiation used during the application of this technique does not interact with metallic devices; therefore, it can be used on patients with metallic implants, osteosynthesis plates and screws, and fixed appliances or on patients under orthodontic treatment. Some artifacts can be created on images of patients with metallic prostheses, but there is the possibility of overcoming these difficulties with more sophisticated image processing software.

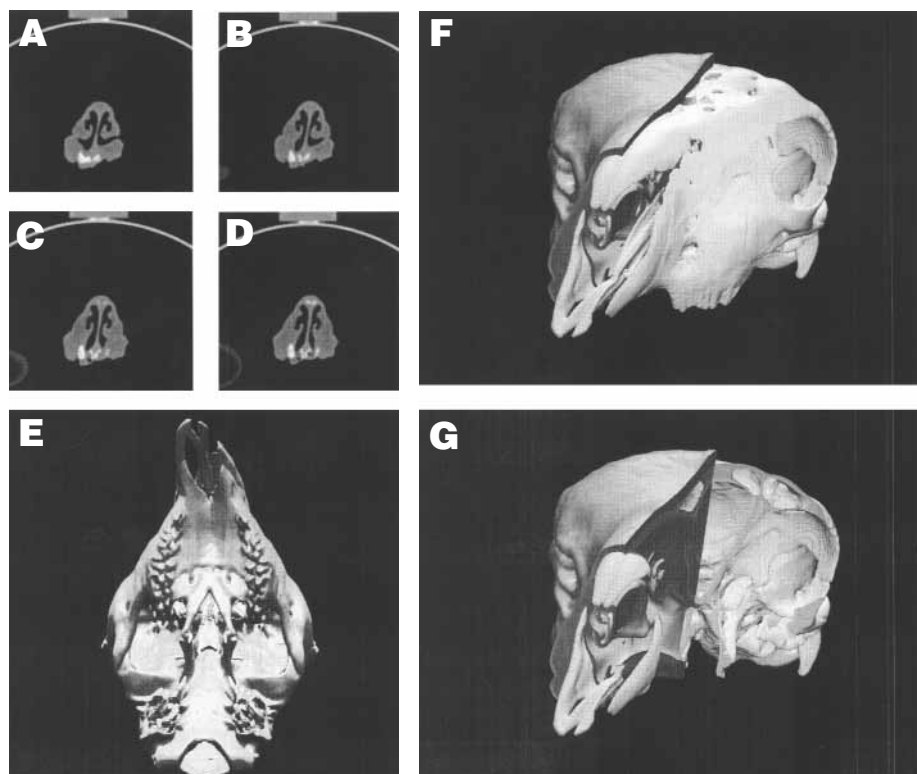


Fig 4. 3D visualization of 3D CT data set of a cranium of a sheep fetus at 142 days of gestation. **a, b, c, and d**, Slices of 2D CT images of the frontal region of the cranium of the fetus; **e**, ventral view of a 3D CT reconstruction of the bony cranium with unhealed maxillary alveolar defect; **f and g**, frontolateral view of a 3D CT reconstruction of the cranium of the same fetus together with a layer of soft tissues. All 3D CT reconstructions were rendered within VOXEL-MAN software (Department of Computer Science in Medicine, University Hospital, Eppendorf, Germany).

The extensive exposure to radiation is the main disadvantage of this technique. The quantity of radiation received by the patient in an average scan is approximately 6 rad, quite a high quantity; therefore, its long-term repeatability is limited to experimentation on cadavers or animals. Furthermore, the high cost, as well as the psychologic stress induced on the patient during the procedure, has to be taken into consideration.

### COMPUTER-AIDED 3D IMAGING MANUFACTURING TECHNIQUES

The computer-aided 3D imaging manufacturing techniques provide a "hard copy" of all 3D information received. The only technique that has been applied in the medicodental field is stereolithographic biomodeling.

#### Stereolithographic biomodeling

This technique was initially developed in the engineering sciences to manufacture prototype models. It has been applied to the fabrication of human skull models for treatment planning in maxillofacial surgery,<sup>78</sup> as well as in anthropometric research

studies.<sup>79,80</sup> For its application the study area is initially scanned by means of MRI<sup>81</sup> or conventional CT.<sup>82</sup> A computer with a special manufacturing software package guides a special device to manufacture a study model. In the simplest form, the "printer" is a device that cuts and shapes pieces of aluminum or plastic according to the acquired data. This version is limited to very small areas of the cranium, and it lacks precision because of the nature of the material used.<sup>83</sup>

A variant of the biomodeling was applied by Fuhrmann et al.<sup>84</sup> It involves the molding and shaping of a special polyurethane foam to form a precise and detailed reproduction of the elements of the viscerocranium. In addition, dental imprints of the patient and gnathologic data are used to mold dental casts and adapt them on the polyurethane cranium. In this way, the polyurethane teeth that are derived initially are substituted because they wear out easily and do not represent the exact occlusion, leading to erroneous conclusions.

Zeilhofer<sup>82,85</sup> and D'Urso et al<sup>86,87</sup> have developed an even more sophisticated modification of this tech-

nique, in which the acquired data are used to guide a laser beam that selectively light cures a special composite, resulting in the construction of a total or partial model of the skull (Nordcom Medical Systems GmbH, Kiel, Germany). With a color-coding technique, specific structures such as teeth and nerves can be displayed, facilitating more detailed surgical planning on the model (Fig 5).<sup>88-90</sup>

The manufactured biomodels improve the quality and the precision of essential diagnostic measurements, facilitate the communication between specialists when dealing with cases needing an interdisciplinary treatment approach, and allow simulation of surgical procedures<sup>91</sup> (Fig 6).

Nowadays, stereolithographic biomodeling is mainly used for clinical purposes in maxillofacial surgery for the evaluation of craniofacial anomalies,<sup>3</sup> for surgery planning,<sup>92</sup> for reconstruction of cranial bone defects,<sup>8,93</sup> for primary reconstruction in craniomaxillofacial trauma surgery,<sup>7</sup> for custom cranioplasty,<sup>94</sup> and for accurate, preoperative adaptation of reconstruction plates or osteosynthesis devices.<sup>95</sup> The technique can also be used for ear<sup>96,97</sup> or orbital reconstruction<sup>98,99</sup> and could be potentially applied in anthropologic studies<sup>100</sup> or in the study of facial aging.<sup>101</sup> It has the added advantage of making the consultation with maxillofacial patients easier.

The disadvantages of this technique are mostly those inherent in MRI and CT. In addition, the necessary equipment is quite costly, and the cost of fabrication of a composite skull model is at present, and likely to remain, very expensive. Although the use of stereolithography in routine cases is quite rare, it is already used in various universities and institutions with very satisfactory results especially in severe cases of maxillofacial deformities.<sup>37,82,102</sup>

## COMBINATIONS OF 3D IMAGING TECHNIQUES

There are a number of possible combinations of the 3D imaging techniques described in this article. Very few of them are applicable in practice, either because they are time-consuming or because it is difficult to handle the necessary devices. For these reasons the emphasis must be on easy and speedy applications as well as on limiting the need for special training for operators and/or technicians.

### Laser scanning and 3D CT

This combination has been reported by Moss et al<sup>24</sup> for use in patients undergoing orthognathic surgery. The 2 techniques are applied separately. The data are combined and assessed by computer. By means of a computer-aided design program, the simulation of the



Fig 5. Stereolithographic model of a maxilla and a mandible of a patient during the mixed dentition stage; shaded area represents the teeth and the mandibular nerve.

orthodontic and orthognathic procedure is feasible. This combination allows the design of various interventions in the maxillofacial complex, it is not time-consuming (only 6 seconds are required for a full reconstruction of the 3D image), the communication between specialists is simplified, and the stored data are easily handled. The disadvantages of the technique are the high purchase value and operating costs of the necessary equipment, as well as the exposure of the patient to ionizing radiation implicit in the use of the tomograph.<sup>23,24</sup>

### Laser scanning and 3D cephalometric radiography

This combination can be applied immediately with technologically advanced radiographic devices. It provides the on-screen digitizing option in which there are a scan and digitization of the head and neck surface. The data are processed by computer software and subsequently combined with those of the pair of cephalometric images necessary for 3D cephalometric radiography. The result is a 3D image of the head of the patient with a simultaneous description of the radiographic anatomy of the head together with the overlying soft tissue morphology. Therefore, the planning of the soft tissue thickness and the expected post-treatment morphology can be calculated during treatment.<sup>103</sup> Unfortunately, this technique is unavailable to the vast majority of clinicians, because access to such modern radiographic apparatus is, for the time being, very limited because of equipment shortage.

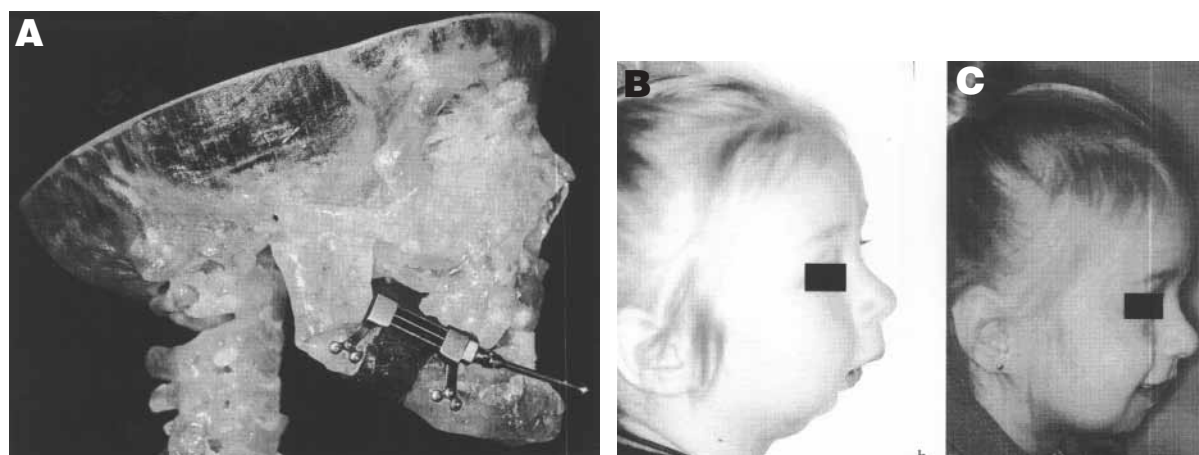


Fig 6. Simulation of orthognathic surgery by means of a stereolithographic model created from a 3D-CT data set of the cranium of a patient with callus distraction. **a**, The distraction osteogenesis surgery simulation; **b**, lateral view of patient before surgery; **c**, lateral view of patient after surgery.

### Laser scanning of the head and scanning of dental casts

This requires laser scanning of the head and the scanning of dental casts. The overall result, although satisfactory, is of inferior quality compared with those obtained by the other methods, because the resulting images are of low fidelity, rendering attempts at treatment planning extremely difficult.<sup>104</sup>

### 3D CT and color portrait photography

Xia et al<sup>105</sup> presented this technique very recently in an attempt to develop a 3D virtual reality surgical planning and simulation workbench for orthognathic surgery. The surgical planning and simulation are based on 3D CT reconstructions, whereas soft tissue prediction is based on an individualized, texture-mapped, color facial soft tissue model.

### 3D CT and stereolithographic biomodeling

This technique is very promising and has the potential to become a standard routine in maxillofacial surgery. The 2 techniques are applied consecutively so that the stereolithographic model is used as the solid printout of the 3D image obtained by 3D CT.<sup>82-89</sup> It is by far the most useful technique for treatment planning and the evaluation of the consequences of severe craniofacial malformations. However, the high cost of the biomodels along with the irradiation of the patient limits its use only to severe malformations.

## DISCUSSION

In recent years, application of 3D imaging has become a pressing priority because of its advantages over the 2D techniques used in everyday practice. It is

considered to be a useful tool in the hands of the clinician, providing diagnosis in 3 spatial planes, simulation of every orthodontic and/or surgical intervention that has to be performed, better prognosis, and more effective treatment planning. 3D imaging techniques offer enormous possibilities for the accurate and precise study of the whole craniofacial complex, for the evaluation of treatment results (through the comparison of pretreatment and post-treatment conditions), as well as for virtual on-screen simulation and the real simulation on biomodels of surgical-orthognathic treatment cases. The data obtained from the various 3D imaging techniques are in electronic form, thus simplifying data exchange among clinicians, researchers, and institutions, opening up new possibilities for open distance consultation and virtual simulation of maxillofacial patients.

At present there is no ideal technique for 3D imaging. Some existing methods (3D cephalometric radiography) lack precision and can give very variable results depending on the skill of the operator. Some others (3D CT) require the exposure of the patient to radiation, and others (3D cephalometric radiography, laser scanning, automated infrared photogrammetry) have not yet been sufficiently developed.

An ideal 3D imaging method should fulfill the following requirements: (1) it should be simple and easy to use, (2) the patient should not be exposed to any hazard, (3) it should be fast, (4) the form of the data must be easily handled, (5) it should help visualize and simulate the planned treatment procedure, and (6) it should not be of high cost.

The extensive advantages of 3D imaging will probably establish the use of these techniques in virtual, as

well as in open distance, applications. At the Technical University of Munich, significant applications of telemedicine have been developed in maxillofacial surgery. Up until now, telemedicine has been limited to consultation and the sharing of knowledge between surgeons. Usually with the help of a 3D graphics computer platform and an Internet connection, they can simulate surgical procedures and enable speculation on the result immediately before the application of a procedure. With the optimization of data transfer methods and the development of additional and more sophisticated surgical equipment, the next challenge for surgeons will be robotic surgery during which patients will be operated on by 1 or more surgeons working from different geographic locations.

In addition, the further development and implementation of 3D ultrasound holography and MRI in fetal diagnosis, along with emerging developments in intrauterine surgery, might offer new opportunities for the treatment of patients with maxillofacial disorders during the midgestational fetal stage of life, probably resulting in more satisfactory results and less need for surgical and medical interventions for these patients later in life.

## CONCLUSIONS

Up until the present, it has been impossible to find a totally satisfactory method of 3D imaging for practical application in the everyday clinical practice. However, laser scanning along with stereolithographic biomodeling, in its most developed form, seem to be techniques that when combined offer a promising way toward optimum 3D imaging. On the other hand, there is still plenty of room for improvement, and constant efforts should be made in the direction of developing and enhancing the existing techniques as well as in the development and implementation of more modern methods based on other sound scientific and technology principles.

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