Digital three-dimensional image fusion processes for planning and evaluating orthodontics and orthognathic surgery. A systematic review


Abstract. The three important tissue groups in orthognathic surgery (facial soft tissues, facial skeleton and dentition) can be referred to as a triad. This triad plays a decisive role in planning orthognathic surgery. Technological developments have led to the development of different three-dimensional (3D) technologies such as multiplanar CT and MRI scanning, 3D photography modalities and surface scanning. An objective method to predict surgical and orthodontic outcome should be established based on the integration of structural (soft tissue envelope, facial skeleton and dentition) and photographic 3D images. None of the craniofacial imaging techniques can capture the complete triad with optimal quality. This can only be achieved by ‘image fusion’ of different imaging techniques to create a 3D virtual head that can display all triad elements. A systematic search of current literature on image fusion in the craniofacial area was performed. 15 articles were found describing 3D digital image fusion models of two or more different imaging techniques for orthodontics and orthognathic surgery. From these articles it is concluded, that image fusion and especially the 3D virtual head are accurate and realistic tools for documentation, analysis, treatment planning and long term follow up. This may provide an accurate and realistic prediction model.

Keywords: computer-assisted three-dimensional imaging; image fusion; orthodontics; maxillofacial surgery; surface-soft-tissue; facial skeleton; dentition; review.

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Facial soft tissue (skin, connective tissues, fat and muscles), facial skeleton (bone and cartilage) and dentition are the three important tissue groups in orthodontics and orthognathic surgery, which can be referred to as a triad9. Together with other structures such as the superficial musculoaponeurotic system, the skeleton and dentition support the facial soft tissue surfaces. The triad plays a decisive role in planning orthodontic therapy and orthognathic surgery. Patients with a dysgnathic deformity need careful assessment of the facial soft tissues surface, the underlying maxillofacial skeleton and the
dento-alveolar position and their interdependency.

Imaging and fusion techniques to analyse the facial profile, the facial skeleton and dentition for planning orthodontic therapy and orthognathic surgery have been available for over a century and can be described as analogue and digital techniques and image fusion models.

**Analogue techniques.** 10 years after the first orthognathic surgery for a congenital deformity was carried out, Babcock (1897) introduced the use of plaster casts for model surgery. This method of preoperatively performing the planned osteotomy on a dental plaster cast is still known as the ‘gold standard’ for planning postoperative occlusion. One decade later orthodontists start using anthropometry, clinical photographs, dental and facial plaster casts and early fusion models (1915–1926) for treatment planning. The development of these early fusion models was almost entirely abandoned in 1931 when Broadbent claims that cephalograms are more accurate for treatment planning, because they display the dentition in relation to the facial skeleton. Cephalograms were soon accepted as ‘the gold standard’ for planning orthodontic treatment and orthognathic surgery. In this way, clinicians started to concentrate on two of the three structures of the triad (facial skeleton and dentition), despite the fact, that the overlying soft tissues define the facial outline.

The disproportional focus on facial skeleton and dentition is evident in the treatment outcome of the patient, as this approach sometimes results in a good functional but poor aesthetic result. The use of cephalograms shows clinicians that some profile-related problems cannot be solved by creating a perfect dental arch with normal occlusion and that sometimes surgical displacement of the mandible and/or maxilla is required.

In the 1970s and 1980s, there was growing awareness that the aesthetic outcome is of equal importance to the patient as the rearrangement of the occlusion. Methods of studying the facial profile and or for planning surgical treatment, with for example Obwegeser’s ‘Wunschprofil’ or methods of analysing the facial soft tissue surfaces were reintroduced, including facial plaster casts, anthropometry, and analogue photography.

**Digital techniques.** Digital photography was introduced to evaluate facial harmony. It allows clinicians to establish a more proportional focus on all three structures of the triad, to assess the patient’s deformity. An accurate and objective assessment of a facial deformity or a preoperative prediction of the surgical outcome in two dimensions, especially regarding asymmetry, will always be deficient since it does not address the volumetric changes of all the facial portions that determine neuromuscular balance and facial harmony. As a consequence, with a computer graphic two-dimensional (2D) representation of facial appearance, it is not possible to achieve a realistic and acceptable result. From the 1980s, the shortcomings of these techniques induced an increase in the use of three-dimensional (3D) imaging techniques, such as facial surface laser scanning, 3D stereophotogrammetry (3D photography) and 3D video-imaging to render the soft facial tissue surface. Reconstructions of digital imaging and communications in medicine (DICOM) files from multislice CT (MSCT), cone-beam CT (CBCT) imaging or MRI slices to display the skeletal structures and digital dental models to display the dentition were also investigated (Table 1).

With CT data, it becomes feasible to produce a life-sized 3D milled model of a two stage resin model or a stereolithic model of a patient. Various methods have been developed to integrate plaster casts into such models. These skeletal models allow the surgeon to analyse the patient’s deformity and plan orthognathic surgery in three dimensions. In such a 3D (augmented) model, model surgery can be performed only once and the soft tissue changes cannot be simulated. So although the third dimension is introduced, one of the structures of the triad (the facial soft tissues surface) is underestimated.

3D virtual planning software programs with a virtual operating room (VOR) were introduced at the end of the 1980s. The IT revolution (2000s) has enabled significant improvements of these software modules. The reconstruction of DICOM files in a VOR enables the clinician to document, analyse and plan orthognathic surgery on a facial skeleton model as often and in as many different ways as required. Programs to analyse the facial soft tissue surface and dental models were also introduced. For the first time, these programs gave the clinician a true insight into all three structures of the triad, albeit separately and routinely on a 2D computer screen.

Since most of the 3D imaging techniques only display one of the three structures with optimal quality, it is evident that these imaging techniques are more powerful when they are used together. This emphasises the importance of image fusion of 3D image modalities to document and analyse the triad of a patient’s face accurately. This has enhanced a search for an ‘all in one’ assessment of the face. Such an assessment should be performed using one holistic digital data set as the result of an image fusion process, including the facial soft tissue surface, the facial skeleton and dentition: the 3D virtual head. This results in a realistic and accurate 3D fusion model, with the true rational relationships between the facial soft tissue surface, the facial skeleton and the dentition.

**Image fusion models.** An image fusion model is defined as a composition of at least two different imaging techniques. The principle of image fusion is based on the creation of a single data set that contains all three structures of the triad. With segmentation by thresholding it is possible to reconstruct a volumetric facial skeleton with and an untextured 3D facial soft tissue surface. For example, a reconstruction of a (CB)CT contains the facial soft tissue surface representing the soft tissue, the bone volume representing the facial skeleton and the dentition, but the (CB)CT skin is untextured and the dental structures may contain streak artifacts caused by (in)direct restorations and/or orthodontic fixed appliances. To improve the quality of the virtual face and dentition, it is necessary to superimpose a textured facial soft tissue surface (e.g. acquired with a stereophotogrammetrical camera setup) and to upgrade or replace the dental images (e.g. with digital dental casts).

3D data can be fused using three different methods: point based matching with or without the use of a reference frame; surface based matching; and voxel based matching. The matching process of the first method is based on corresponding points, while the other two use congruent surface points or voxels (volumetric picture elements) of a manually selected region. Based on the triad, four possible 3D fusion models can be distinguished: image fusion of the facial skeleton and the dentition; image fusion of the facial soft tissue surface and the facial skeleton; image fusion of the facial soft tissue surface and the dentition; and image fusion of the facial soft tissue surface, the facial skeleton and the dentition.

Three methods are used to display the facial skeleton and the dentition: the life-sized stereolithographic (STL)
milled\textsuperscript{51,63} models augmented with dental casts; digital dental casts integrated in cephalograms\textsuperscript{121,122}; and a 3D reconstruction of the (CB)CT with integrated digital dental casts\textsuperscript{29,82}. The first two are outdated. The third method virtually displays the facial soft tissue surface and the facial skeleton in 3D. The integration of digital dental casts into the CBCT reconstruction establishes an augmentation with improved visualisation of the dentition.

Apart from matching conventional\textsuperscript{26} or digital photographs with a lateral cephalogram, which is purely a 2D technique, three methods are used to fuse the facial soft tissue surface and the facial skeleton: matching a 3D photograph with a lateral and anteroposterior cephalogram\textsuperscript{5}; mapping 2D photographs onto CBCT or MSCT data\textsuperscript{75}; and fusing a 3D photograph or a 3D surface laser scan with the reconstruction of MSCT or CBCT data\textsuperscript{36,59}.

Table 1. Imaging techniques for the facial soft tissue surface, the facial skeleton and the dentition.

<table>
<thead>
<tr>
<th>Technique/hardware</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>3D digital</th>
<th>3D virtual head</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facial soft tissue surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D photography</td>
<td>Accurate</td>
<td>Not 3D Volumetric (CB)CT data necessary to match textured surface</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>MRI</td>
<td>See below</td>
<td>See below Time-consuming</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3D ultrasonography</td>
<td>Low costs</td>
<td>No textured surface Deformation of soft tissue due to contact between probe and skin</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3D laser surface scanning</td>
<td>Accurate data</td>
<td>Harmful to eyes Long acquisition time Multiple scanners necessary for textured surface high costs Sensitive to light and metal objects</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3D photography/3D stereophotogrammetry</td>
<td>No radiation Accurate and metrically correct data Short acquisition time (2 ms) Textured surface soft tissue</td>
<td>Poor accuracy eye lenses Poor accuracy of subnasal and submental area</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Facial skeleton</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSCT data</td>
<td>High quality images</td>
<td>Horizontal scanning position high dose ionizing radiation High amount of streak artifacts high costs Out of office imaging</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(CB)CT reconstruction</td>
<td>Upright scanning position Reduced ionizing radiation In office scanning</td>
<td>Relatively more noise in data No Hounsfield unit calibration</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MRI</td>
<td>Acquisition time of 40 s or less</td>
<td>High costs Horizontal scanning position No textured surface data Long acquisition time</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Dentition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digitized plaster cast</td>
<td>Reduction of streak artifacts</td>
<td>Plaster casts mandatory</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(CB)CT reconstruction</td>
<td>See above</td>
<td>See above Impression is mandatory</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>CT/laser scanned impression</td>
<td>Plaster casts not needed Correct occlusion with wax bite Possibility to produce a plaster casts remains</td>
<td>Spray on dentition</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Digital impression by intraoral scanning device</td>
<td>No impression needed Acquisition time 30 s Easy to use Patient friendly</td>
<td></td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

FSTS, facial soft tissue surface; FS, facial skeleton; DT, dentition; (CB)CT, cone-beam computer tomography; MSCT, multislice CT; MRI, magnetic resonance imaging; DICOM, digital imaging and communications in medicine.
Several methods were developed about 80 years ago to display both the facial soft tissue surface and the dentition, which have all been abandoned. Nowadays, it is possible to fuse 3D data of the facial soft tissue surface with a digital dental model.

The integral fusion model consists of a (CB)CT reconstructed bony volume, in which the dental structures are replaced by a digital dental model and the textured facial soft tissue surface is superimposed upon the untextured facial soft tissue surface of the (CB)CT. This model visualises the textured facial surface, as well as the 3D skeletal structures and the dentition without artifacts.

Despite progress in surgical outcome (functionality, aesthetics and stability), orthodontists and oral and maxillofacial surgeons have not been able to develop an objective method to evaluate the soft tissue changes caused by orthognathic surgery, nor to predict the surgical outcome. Four subqueries were defined, categorising the fusion processes, the head, 3D and the medical field of interest. The subqueries were combined for the overall systematic search in PubMed and OVID, which resulted in the following query:

\[(\text{generic OR image OR fusion OR fusion* OR registration OR registrated OR dataset OR augmented OR model OR superimposition OR 'composite model' OR simulation}) \text{ AND (head OR skull OR face OR facial OR maxillofacial OR craniofacial OR cranio-maxillofacial OR orofacial OR dentofacial OR hard tissue OR 'hard tissue' OR bone OR bony OR soft tissue OR 'soft tissue' OR virtual head OR 'virtual head' AND (3D OR 3-D OR 'three dimensional' OR three-dimensional OR three-dimensional imaging) AND (orthodontic* OR oral surgical procedures OR orthognathic* OR dysgnathic*)].\]

Methods and materials

Search strategy
The PubMed databases (Medline database, free open access of PubMed central, out of range articles, articles marked as ‘epub ahead of print’ and free full text articles) (1950 to 11 June 2009), and the OVID databases (Embase, 1980 to June 2009 and the Cochrane databases (the Database of Abstracts of Reviews of Effects and the Central Register of Controlled Trials)) (4 June 2009) were searched. No language limit was applied.

Inclusion and exclusion criteria
As the first step, articles concerning image fusion models of the head were included. The following exclusion criteria were applied: studies concerning implantology or head and neck oncology, to limit the review to the field of imaging in orthognathic surgery; and studies describing integration of dental models into a stereolithographical 3D model, even though the resulting real model can be manipulated, the digital data cannot be manipulated.

As the second step, all articles discussing a fusion of at least two different 3D imaging techniques were included. Exclusion criteria were: measurements made on linked anteroposterior and lateral cephalograms, often referred to as 3D cephalometry (this form of cephalometry is not performed on a 3D image so models using it to register a digital dental cast or a 3D photograph were excluded); articles concerning navigation; and studies on prediction/simulation models, since these focused on marker registration or simulation algorithms, respectively, and did not discuss the image fusion processes itself.

The reference lists of each selected publication were hand-searched to c-
### Table 2. Overview of fifteen articles discussing a 3D fusion model, including a complete overview of the integral fusion model.

<table>
<thead>
<tr>
<th>Author</th>
<th>Facial soft tissue surface</th>
<th>Facial skeleton</th>
<th>Dentition</th>
<th>Data set for reconstruction</th>
<th>Registration</th>
<th>Bite registration</th>
<th>In vivo/in vitro</th>
<th>Patients (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image fusion of the facial soft tissue surface and the facial skeleton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AYOUB⁶</td>
<td>3D photography</td>
<td>MSCT</td>
<td>–</td>
<td>DICOM</td>
<td>Surface based</td>
<td>–</td>
<td>In vivo (dentofacial deformities)</td>
<td>6</td>
</tr>
<tr>
<td>GROEVE³⁶</td>
<td>3D photography</td>
<td>MSCT</td>
<td>–</td>
<td>DICOM</td>
<td>Surface based</td>
<td>–</td>
<td>In vivo (facial asymmetry)</td>
<td>1</td>
</tr>
<tr>
<td>KHAMBAY⁵⁹</td>
<td>3D photography</td>
<td>MSCT</td>
<td>–</td>
<td>DICOM</td>
<td>Surface based</td>
<td>–</td>
<td>In vivo</td>
<td>1</td>
</tr>
<tr>
<td>MAAL⁶⁸</td>
<td>3D photography</td>
<td>CBCT</td>
<td>–</td>
<td>DICOM</td>
<td>Surface based</td>
<td>–</td>
<td>In vivo, dysgnathic patients</td>
<td>15</td>
</tr>
<tr>
<td><strong>Image fusion of the facial skeleton and the dentition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GATENO²⁰</td>
<td>–</td>
<td>CT</td>
<td>Laser scanned impression</td>
<td>DICOM</td>
<td>Fudicial markers</td>
<td>Triple tray</td>
<td>In vitro dry skull</td>
<td>1</td>
</tr>
<tr>
<td>GATENO³¹</td>
<td>–</td>
<td>CT</td>
<td>Laser/CT scanned dental cast</td>
<td>DICOM</td>
<td>Fudicial markers</td>
<td>Bite jig with fiducial markers</td>
<td>In vivo (craniofacial deformities)</td>
<td>5</td>
</tr>
<tr>
<td>NKENKE⁸²</td>
<td>–</td>
<td>MSCT</td>
<td>MSCT Scanned dental cast</td>
<td>DICOM</td>
<td>Fudicial markers</td>
<td>Acrylic wafer</td>
<td>In vivo</td>
<td>1</td>
</tr>
<tr>
<td>SCHUTYSER¹⁰²</td>
<td>–</td>
<td>CT</td>
<td>CT scanned dental cast</td>
<td>DICOM</td>
<td>Point based</td>
<td>Splint with gutta percha markers</td>
<td>In vitro (dry skulls)</td>
<td>10</td>
</tr>
<tr>
<td>SWENENNEN¹¹⁰</td>
<td>–</td>
<td>CBCT</td>
<td>CBCT of triple tray impression</td>
<td>DICOM</td>
<td>Voxel based</td>
<td>Wax bite</td>
<td>In vivo (dysgnathic)</td>
<td>10</td>
</tr>
<tr>
<td>SWENENNEN²⁰²,¹⁰⁹</td>
<td>–</td>
<td>MSCT</td>
<td>MSCT scanned dental cast</td>
<td>DICOM</td>
<td>Point based</td>
<td>Acrylic wafer</td>
<td>In vitro (dry cadavers)</td>
<td>10</td>
</tr>
<tr>
<td>SWENENNEN¹¹²</td>
<td>–</td>
<td>MSCT</td>
<td>MSCT scanned dental impressions</td>
<td>DICOM</td>
<td>Point based</td>
<td>Wax bite</td>
<td>In vivo</td>
<td>10</td>
</tr>
<tr>
<td>SWENENNEN¹¹³</td>
<td>–</td>
<td>CBCT</td>
<td>CBCT scanned alginate impressions</td>
<td>DICOM</td>
<td>Surface based</td>
<td>Modified wax bite wafer</td>
<td>In vivo</td>
<td>10</td>
</tr>
<tr>
<td>UECHI¹²²</td>
<td>–</td>
<td>MSCT</td>
<td>Laser scanned dental cast</td>
<td>DICOM</td>
<td>Fudicial markers</td>
<td>Splint with fiducial markers</td>
<td>In vivo (dysgnathic patients)</td>
<td>2</td>
</tr>
</tbody>
</table>

Image fusion of the facial soft tissue and the dentition

RANGEL⁹⁶        | 3D photography            | –              | CT scanned impressions | –         | Surface based | –                | In vivo | 1            |

Image fusion of the facial soft tissue surface, the facial skeleton and the dentition

OLSZEWSKIE⁸³    | MRI                        | MSCT            | Laser scanned dental cast | DICOM | Voxel and surface based | Alginot impression | In vivo | 1            |

3D FIRG model⁴  | 3D photography            | CBCT            | Alginot triple scan | DICOM | Voxel and surface based | Alginot impression | In vivo | 1            |

CBCT, cone-beam CT; MSCT, multislice CT; MRI, magnetic resonance imaging; DICOM, digital imaging and communications in medicine.

*Integral fusion model preferred by the authors (unpublished).*
The five imaging techniques most used for image fusion of hard and soft tissues are: 2D photography, MRI, 3D ultrasonography, 3D surface laser scanning, and 3D photography/sterophotogrammetry. With 2D photography, 2–6 2D photographs can be added to the,untextured skin surface of a (CB)CT scan. Although the technique is fundamentally not based on 3D data and a 3D surface of CT or CBCT is mandatory in the background, it is an easy, accurate and low priced technique for image fusion of hard and soft tissues.

MRI uses a powerful magnetic field disturbed by radiofrequency fields causing the hydrogen nuclei to create a detectable rotating magnetic field to produce multiple 2D axial images, which can be reconstructed into 3D models. The main advantages of MRI are the absence of ionizing radiation and information about the inner soft tissue layers. Disadvantages are high costs, the horizontal scanning position of the patient, no textured surface, a long acquisition time and hence the risk of facial movement during scanning. These make MRI imaging unsuitable for image fusion.

3D ultrasonography uses a special probe in contact with the skin through an interface of gel to scan the facial soft tissue surface. The costs of this technique are low and there is no use of radiation. It is time-consuming, there is no textured surface and the mild compression on the surface, which differs per investigator, leads to small changes of the soft tissues. Overall, this technique has too many disadvantages to be used.

A laser beam reflected by facial features contains more noise and the grey value representation of textured facial soft tissue is used to capture 3D skin information for 3D surface laser scanning. The reflection is registered by digital cameras. The laser beam is harmful to the eyes, the relatively long acquisition time (8–30 s) increases the risk of movement artifacts and scanning of the coloured texture of the facial surface can only be done with multiple laser beams, resulting in high costs. The system is very sensitive to light and metal objects, which requires careful control of the environment. Consequently, laser surface scanning is not the optimal method for capturing the facial soft tissue surface.

With 3D photography it is possible to capture 3D textured surfaces of the face that are metrically accurate and photorealistic in appearance. Two to six cameras in a stereo setting acquire in only 2 ms a set of images out of which a digital 3D image is reconstructed in 10–20 s. This reconstructed image is then rendered. As a result, a polygonal mesh with true colour textured information is obtained. Further advantages are lack of ionizing radiation as well as movement artifacts, accurate representation of textured facial soft tissue surface and reduced costs in comparison to, for example laser surface scanning. Disadvantages of certain stereophotogrammetrical camera setups are the necessity of daily calibration, poor precision of shiny surfaces, such as eye lenses and teeth, and difficulties with hair, glasses and undercut areas, such as the subnasal and the submental area.

Owing to the severity of certain disadvantages, 3D ultrasonography (distortion of the surface), MRI (horizontal scanning position) and laser surface scanning (harmful to the eyes) are not suitable for 3D image fusion. 2D and especially 3D photography do provide high quality images without harm to the patient and are suitable for 3D image fusion.

There are three 3D imaging techniques used to capture data for the reconstruction of the facial skeleton: MSCT data, CBCT data, and MRI slices. A MSCT scanner uses a fan shaped X-ray to collect multiple thin slices of a patient’s face on multiple 2D detectors. A high radiation dose is needed, which results in high quality images but increases the amount of streak artifacts. Data are collected in a horizontal position, as a result of which the facial soft tissues are not captured in their natural shape. Further disadvantages are the high costs and out of office imaging.

In contrast to the MSCT scanner, the CBCT scanner uses a cone shaped X-ray beam and one large 2D detector to capture the cone shaped beam. The 2D detector is able to record a large (e.g. 16 cm x 22 cm) area of the face in one or two rotations (20–40 s), thus reducing the effective radiation dose as compared to MSCT scanning. Artifacts at the level of the occlusion and their extension into the soft tissue are reduced, which increases the accuracy of the registration. The patient can be positioned upright with a natural head position and the facial soft tissues are captured in their natural shape. Office-based imaging increases access for the routine dentofacial patient, while avoiding waiting lists and reducing costs. In comparison to a MSCT scanner, a CBCT has several disadvantages: owing to the lower radiation dose, the image contains more noise and the grey value of a structure in the field of view is dependent of the scanning volume and the scanning position. There is no Hounsfield unit calibration. The cone shaped X-ray beam causes the Hounsfield units to vary within the same type of tissue, necessitating improved cone beam reconstruction algorithms. It is expected that an enlargement of the field of view of the CBCT scanners and shortening of the acquisition time will reduce the risk of movement artifacts improving the quality of the images.

MRI slices can also be used to capture the facial skeleton. Hypothetically, MRI is preferred over (CB)CT, because it does not expose the patient to radiation. Besides the disadvantages mentioned earlier, the quality of the skeletal data is currently not acceptable for planning orthodontic therapy and orthognathic surgery.

Overall, a CBCT scan with a horizontal scanning position is preferred to a MSCT scan and MRI scan for imaging the facial skeleton when planning orthodontic therapy or orthognathic surgery.
Four imaging methods are available to digitise the patient’s dentition for the virtual head: digitisation of the plaster cast, with a (CB)CT scanner102, laser scanner51,62, or Moiré topography58; a digital data set reconstructed from (CB)CT data102, a CT or laser scanned impression56; and a digital impression obtained by direct intraoral 3D scanning.

Digitisation of a plaster cast can be done with a (CB)CT scanner102, a digitiser (laser scanner)14, a non-destructive laser59 or Moiré topography58. After pouring the impression and scanning the dental cast, the digital dental cast is easily stored on any storage device as a small file (<1 Mb) and is simultaneously viewable at multiple locations (peer-view communication). Each of these imaging techniques for rendering the dental model significantly reduces the streak artifacts, which improves the quality of the digital dental cast52, but it is mandatory to pour the cast.

The second method consists of capturing a (CB)CT scan of the patient and using the DICOM images to render a 3D volume of the dentition102,115. Dental imaging derived from CT data have important disadvantages: (in)direct metal restorations and brackets generate streak artifacts and acrylic resin fillings show a grey value similar to the grey value of the soft tissues, which imply that this method is not suitable for capturing the dentition for planning orthodontic therapy and orthognathic surgery.

The third method is to scan the dental impression of the dental arches with a (CB)CT scanner96. Without the need for a plaster cast, a digital dental model with the correct relationship between the upper and lower arch is reconstructed from the (CB)CT data.

The fourth method is a digital impression taken with chairside intra-oral scanning devices. With this technology, the 3D data of the dentition are directly captured without the need for impression material or the fabrication of a plaster cast. The technique is rapidly developing, but its use in a clinical setting is still limited.

At present both dental cast models (either (CB)CT or laser scanned) and digitally scanned impressions can be used in fusion models for dental imaging. In the future digital impressions may be used as well.

**Critical evaluation of 3D image fusion models**

Three methods are used to display the facial skeleton in combination with the dentition: life-sized STL71 or milled51,63 models augmented with dental casts; digital dental casts integrated in cephalograms121,122; and 3D reconstruction of the (CB)CT with integrated digital dental casts30,31,82,102,109,110,112,113,122.

The first method was developed shortly after the introduction of life-sized STL or milled 3D models. Researchers invented methods to integrate a plaster cast into such a model, which have been used for planning and simulating orthognathic surgery51,62,71. One of the advantages of these augmented models is the elimination of streak artifacts51,62. Osteosynthesis plates or devices can be present on these models. The radiation dose, costs, inaccuracy and difficulty of the procedure do not counter-vail against the ability of performing model surgery only once.

Fusion of cephalograms and digital dental casts121,122 was developed to reduce radiation exposure or to overcome the unavailability of MSCT or CBCT hardware. Specific landmarks on the cephalograms and dental cast are identified, digitised and integrated with each other to create a semi-3D outline of the facial skeleton and the dentition. In comparison to the use of MSCT data, there is a reduction in radiation exposure and cost. The non-adjustable digitised cephalometric landmarks create a computerised outline of the patient, without a true volumetric representation of the facial skeleton. This reduces the value of these models for volumetric prediction and simulation models.

The third method (nine hits)30,31,82,102,109,110,112,113,122 is to augment the (CB)CT reconstruction by the integration of digital dental casts, eliminates the problems of the previous methods and enhances the quality of the dental structures31,102,110,113. The visualisation of the interocclusal relationship is accurate and results in precise dental morphology of the surfaces and cusps. The disadvantages, such as the significant computing time required for the fusion process and the exposure to radiation are outweighed by the advantages of the 3D virtual planning and simulation. The developmental progress of this fusion model resulted in a method that enables accurate planning and simulation of orthodontic therapy and orthognathic surgery.

Three methods can be used to determine the exact localisation of a digital dental model in a (CB)CT data set: point based registration with a splint with markers (seven hits)30,31,102,109,112,113,122; surface based registration (one hit)62 and voxel based registration with an impression based bite registration (one hit)110. For the first registration method, dental casts and a specially designed splint have to be fabricated. Next, a double scan procedure is used to acquire a data set of the patient while wearing the splint and a data set of the dental cast with the splint between the upper and lower cast model. Markers on the splint are necessary for point based iterative closest point (ICP) registration10,36 of the scan of the patient with splint and the scan of the dental cast with splint. This registration method is accurate but the position of the integrated digital dental model may vary because only a few points of the available volume are used for registration. This method is too time consuming for daily practice especially since the dental models of the upper and lower arch are integrated separately110.

For the second registration method a surface laser scanner is used to digitise the dental model. The digital dental model is surface based registered with the dental surface of the reconstruction of the CT scan data30.

In the third method, voxel based registration is used to augment the facial skeleton110. An impression based bite registration (Alginaf50 Kerr USA, Orange, CA, USA), made with a triple tray (Premier, Plymouth Meeting, PA, USA) is scanned to capture an accurate digital model of the dentition. Two low radiation dose scans capture the patient once with and once without the impression. Specific comparable volumetric regions are used to register these three data sets, which reduces matching errors compared with point based registration techniques. The patient is exposed to more radiation.

The (CB)CT image of the facial skeleton augmented with a digital dental model is currently the most accurate fusion model to display the facial skeleton and the dentition, especially when it is voxel based. This model increases the preoperative insight into the occlusal and skeletal anatomy of the patient, but it does not represent skin texture. Consequently, an upgrade with a textured facial soft tissue surface is mandatory.

Three methods are used to fuse the facial soft tissue surface and the facial skeleton: matching a 3D photograph with a lateral and anteroposterior cephalogram2; mapping 2D photographs onto CBCT or MSCT data52; and a 3D textured surface derived from a 3D photograph or a 3D surface laser scan with the reconstruction of MSCT, CBCT data or MRI slices30,31,59,68.

Matching a 3D photograph with a lateral and anteroposterior cephalogram2, was developed to avoid the use of a CT.
scan and limiting exposure to ionizing radiation. The disadvantages are comparable to the fusion model of cephalograms and digital dental casts and do not provide a complete 3D representation of the patient.

Mapping 2D photographs onto CBCT or MSCT data is relatively easy and cheap. Six digital photographs (frontal, left and right three quarter, left and right lateral and submental view) are fused into a reconstruction of the facial soft tissue surface of (CB)CT reconstructed data set using surface based registration. In this way, texture is added to the 3D data set. This method needs a specific algorithm and can only be realised with specific software with a virtual operating room.

Fusing a 3D textured surface derived from a 3D photograph or a 3D surface laser scan with the reconstruction of MSCT, CBCT data or MRI slices is currently the most applied technique. Until 4 years ago, 3D laser surface scanning was often applied to capture the facial soft tissue surface. Currently, 3D stereophotogrammetry imaging systems are more reliable and have become the gold standard: all publications discussing fusion models of the facial skeleton and the surface soft tissue use 3D stereophotogrammetry (four hits). CBCT is mentioned in only one publication. This is probably due to the recent availability of CBCT scanners with a large enough field of view to scan the complete face, which may change over the coming years. CBCT is preferred because of the upright scanning position, the limited exposure to ionizing radiation and the straightforward reconstruction of both soft, hard and dental structures from the DICOM files. The surface based registration procedures consist of several (semi) automatic steps. First, the data sets are approximately aligned with a Procrustes algorithm without scaling. The next step to align the data precisely is based on an ICP algorithm. The final registration step is performed with non-rigid registration, which allows translational, rotational and deformational movements of the data. This non-rigid registration is not preferred for image fusion because rough surfaces, differences in facial expression and acquisition artifacts along the eyes, nose and mouth, can cause an imperfect match. This means that non-rigid registration is still necessary to enable fusing the data.

Matching a 3D photograph with a 3D reconstruction of CBCT data has potential for future models of prediction and simulation of orthodontics and orthognathic surgery, especially if captured with an all-in-one imaging technique. It can provide additional information about facial harmony because the relationship between the facial skeleton and the facial soft tissue surface is preserved. When comparing pre- and postoperative data sets it enables objective evaluation and quantitative measurement of soft tissue changes induced by orthognathic surgery while creating a photographic 3D representation of changes in facial harmony. The remaining challenge is the transfer of the virtual planning into the surgical situation. For that purpose, accurate data of the dentition are mandatory and upgrading with a digital dental model is necessary.

Since the introduction of 3D imaging there has been a renewed interest in the fusion of facial soft tissue surface and dentition, because for most orthodontists the dentition and the facial outline are the most important structures for analysis, treatment planning and prediction. Only one article describes a technique to fuse the facial soft tissue with a digital dental cast. The 3D data of the facial soft tissue surface are rendered twice with a stereophotogammetric camera setup: after a picture with normal facial expression is taken a second photograph with cheek retractors is taken to visualise the tooth surfaces. With a double surface based registration procedure on selected regions such as the buccal surfaces of the teeth for the first and the forehead for the second registration, the digital dental model is fused with the 3D photograph. This fusion process results in anatomically correct positioned dentition within the facial surface. The main advantages are that it is a relatively cheap, easy and patient friendly fusion model, which does not harm the patient because there is no radiation exposure. The main disadvantage is the lack of information about the facial skeleton, which may be overcome by setting up a normative reference database. Potentially, this model can be of great importance, especially in growth studies.

Three different methods have been described for the integral fusion model, of which one model was included in the search: a mean 3D head based on conventional cephalograms adjusted with 3D facial and dental data; a 3D head based on MSCT and MRI data, and the 3D virtual head based on the augmented model (unpublished).

Nakasima et al. developed the first complete 3D model for prediction of orthognathic surgery based on a ‘standard Japanese model’, which can be adjusted to the patient’s head with digitised landmarks from conventional 2D cephalograms, 3D stereophotographs and dental casts. Noguchi et al. described a comparable image fusion technique using a conventional lateral and anteroposterior cephalogram (representing the axes of a Cartesian coordinate system) as a base to integrate a 3D laser scanned facial surface and a 3D laser scanned dental cast. In order to use the model for simulation of a bilateral sagittal split osteotomy, a generic MSCT model of a mandible is used, which is mathematically transformed (reshaped) before integrating it with the cephalograms and the dental casts. In these two Japanese models, the limitations of 2D imaging are preserved within these 3D models, because the 3D models are aligned to 2D representations of the patient’s outline. Using a ‘mean’ head, adjusted to the patient’s 2D data, does not guarantee an accurate preoperative representation of the patient’s head. Since the patient has not been exposed to high doses of ionizing radiation, the 3D model is not a realistic representation of the patient’s face and therefore, it is not suitable for a realistic prediction of orthognathic surgery. In the second and third methods, these problems are overcome by using volumetric data from the individual patient.

The second method uses MRI slices for the volumetric soft tissues and MSCT data for the facial skeleton, both captured in a horizontal position, and laser scanned dental casts for the dentition. Although all the structures of the triad are included, the model misses a textured facial surface and the soft tissues are not captured in a natural head position so changing the facial soft tissue surface shape. It does include the volumes of the mimic muscles, which enables the study of musculovolumetric changes caused by orthognathic surgery.

The third method is based on the augmented model of Svendsen et al. (one hit). CBCT data are used as a data set for skeletal information but also as a volumetric base for the fusion processes. A 3D image and CBCT scanned impressions are added to augment the CBCT skeletal data set. A fusion model of the volumetric facial skeleton, the digital dental model and textured facial surface provides a realistic and accurate virtual model of the patient’s head. An impression based bite registration is scanned to capture an accurate digital model of the dentition. The patient is scanned with the impression, which unavoidably causes distortion of the facial surface. A second scan of the
patient is acquired to capture the undisturbed facial soft tissue surface. A voxel based matching procedure is used to fuse these three models, which is less sensitive to matching errors compared with a point based registration. Finally, a 3D photograph can be fused with the untextured facial surface to complete the 3D virtual head (surface based registration).\textsuperscript{115} Advantages of this model are the accurate 3D representation of the patient's face and the unlimited possibilities when importing it into a virtual scene to perform cephalometric analyses\textsuperscript{117}, virtual osteotomies, distraction osteogenesis as well as simulations and prediction of the surgical outcome.\textsuperscript{115} Relative disadvantages are the additional exposure to ionizing radiation, separated data gathering, the lack of fully automated fusion processes and the considerable computing time. The unique advantage is that this is the only fusion model providing a complete 3D virtual head, with all the three structures of the triad.

There are several problems related to the integral fusion model of the facial soft tissue surface, the facial skeleton and the dentition. 3D imaging and 3D image fusion processes are expensive and time consuming. A large amount of hardware and software is needed and it takes approximately 1 h to compute a 3D virtual head. This includes many semi-automated steps, which are prone to errors. A physician or engineer has to participate in the fusion process, which increases staffing costs. These are relatively important disadvantages: a simulation cannot replace the clinical assessment of the patient and may add questionable added value for simple cases. This, combined with a conservative attitude and a predilection towards traditional methods, tends to keep clinicians from implementing 3D virtual imaging into daily practice.

In time these steps will reduce computing time and costs as it provides a realistic model with detailed anatomy of the patient’s triad. It allows for the most accurate communication and shared decision making with patients and colleagues. 3D treatment planning is more meticulous compared with 2D treatment planning as it illustrates volume changes of the facial structures instead of projected midline changes. Multiple simulations of different osteotomies and skeletal movements can be made within the virtual operating room, aiding decision making regarding aesthetic and functional predictions\textsuperscript{81,117}. This fusion model replaces the need for model surgery, since the virtual head can also be used to design a surgical wafer. The latter, which can be used as a surgical guide, transfers the virtual planning to the operating theatre. Postoperative evaluation will give feedback on the performed procedure and can be used for teaching purposes. Long term follow up of various orthodontic deformities and procedures will deliver normative and reference data, which can be used to enhance the accuracy of prediction models\textsuperscript{8,55,119}. In time, these data will enable more individualized, rather than average, predictions of soft tissue changes induced by facial skeleton displacements, but also allow the computation of the necessary facial skeleton changes to achieve the desired soft tissue adjustments. It is reasonable to expect that the long-term outcome of orthognathic surgery will improve thanks to more systematic accurate planning and comparison of pre- and postoperative appearances when using the 3D virtual head\textsuperscript{8,55,59,40,52,55,89,89,117}. Ideally, the data should be acquired with an ‘all in one’ imaging technique, which would reduce the differences in facial expression at the moment of acquisition.

Overviewing the current literature, it is obvious that many clinicians agree that 3D imaging and 3D image fusion are of great importance for preoperative clinical assessment and postoperative follow up\textsuperscript{69,9,35,65,101,111,115,127}. When an image fusion model is used, the authors prefer the 3D virtual head based on the augmented 5. All currently available fusion models are expensive and need improvements before they meet the demands of improved prediction and simulation. If the fusion models are implemented in daily clinical practice, the authors expect that the financial and IT problems are solvable within the next 5 years.

Clinicians have striven for a 3D (virtual) fusion model, such as the 3D virtual head for more than a century to support decision making with patients and colleagues. The sponsors had no influence upon the study design, analysis or interpretation of the data, upon the writing of the manuscript and submitting the manuscript for publication.

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