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RESEARCH

Fusion of computed tomography data and optical 3D images of the dentition for streak artefact correction in the simulation of orthognathic surgery

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Objective: To determine the limits of accuracy of fusion of optical three-dimensional (3D) imaging and computed tomography (CT) with and without metal artefacts in an experimental setting and to show the application of this hybrid system in 3D orthognathic surgery simulation.
Methods: Ten plaster casts of dental arches were subjected to a CT scan and optical 3D surface imaging. Subsequently, the first molars in the plaster casts were supplied with metal restorations, bilaterally, and new CT scans and optical surface images were assessed. The registration of the surface data of the two imaging modalities of the study models without and with metal restorations was carried out. The mean distance between the two data sets was calculated. From a patient a CT scan of the skull as well as optical 3D images of plaster casts of the dental arches were acquired. Again the two imaging modalities were registered and virtual orthognathic surgery simulation was carried out.
Results: The mean distance between the corresponding data points of CT and optical 3D surface images was 0.1262 ± 0.0301 mm and 0.2671 ± 0.0580 mm, respectively, for the plaster casts without and with metal restorations. The differences between these data were statistically significant ($P < 0.0005$). For the patient case a mean difference of 0.66 ± 0.49 mm and 0.56 ± 0.48 mm for mandible and maxilla, respectively, was calculated between CT and optical surface data.
Conclusion: The accuracy of the fusion of 3D CT surface data and optical 3D imaging is significantly reduced by metal artefacts. However, it seems appropriate for virtual orthognathic surgery simulation, as post-operative orthodontics are performed frequently.
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Keywords: computed tomography; image fusion; metal artefacts; optical 3D imaging; phase measuring triangulation

Introduction

Computed tomography (CT) is a widely used imaging modality in oral and maxillofacial surgery. It permits access to the internal morphology of soft tissues and skeletal structures.[1] In recent years CT has been adopted for three-dimensional (3D) virtual reality surgical planning and simulation of the post-operative outcome in orthognathic surgery.[2–6] These techniques have gained wide acceptance as they help the patient to understand more completely the changes his face will undergo as a consequence of surgery. The virtual determination of cutting planes and the simulation of skeletal movements can be used for teaching purposes during the training of oral and maxillofacial surgeons. The soft tissue response to different courses of osteotomy lines and different distances of jaw movements can be tested. Moreover, 3D planning of the post-operative outcome after orthognathic surgery is a part of quality assurance in medicine.[7]

The correct relative positioning of maxilla and mandible during orthognathic surgery is achieved by the

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adjustment of the required dental occlusion. A precise imaging of the occlusal surfaces of the teeth is a prerequisite for an adequate virtual planning. It is estimated that only 15% of the 18-year-old population exhibits a caries-free dentition.[8] The treatment of these lesions often involves metal restorations, which lead to streak artefacts on CT images. These artefacts cause serious problems during the virtual planning as they obscure the dental arches in the CT scan. The simulation of the post-operative dental occlusion is hindered, because the occlusal relief is not represented accurately. Optical sensors facilitate precise 3D imaging of the relief of teeth without artefacts.[9] These sensors are non-invasive and do not expose the patient to irradiation. However, their use is limited to the acquisition of surfaces of objects.

Considerable progress has been made in the fusion of images from different imaging modalities using software approaches. Two modalities are combined and mounted in a single coordinate system. It seems reasonable to combine CT with optical 3D imaging to correct for metallic artefacts allowing precise assessment of the tooth surface and accurate simulation of the post-operative dental occlusion. Therefore, it was the aim of the present study to determine the limits of accuracy of fusion of optical 3D imaging data and CT 3D data with and without artefacts in an experimental setting and to show the application of this hybrid system in 3D orthognathic surgery simulation.

Materials and methods

Experimental study

For the experimental study, ten impressions of complete dentitions (five mandibular arches, five maxillary arches) were taken with alginate (Blueprint™ Cremix; Dentsply DeTrey-DeDent, Konstanz, Germany) from randomly selected patients, who were treated for different reasons. The impressions were poured with plaster (Fuji Rock; GC Europe, Leuven, Belgium).

The ten plaster casts were submitted to a 16-slice spiral CT (Somatom Sensation 16; Siemens, Erlangen, Germany). The gantry of the CT scanner was tilted in a way that the axial plane was positioned parallel to the occlusal plane of the specimens. CT data acquisition was performed using the following protocol: 1 mm of slice thickness, 0.75 mm interval of reconstruction in 16 slices by 0.5 s time, using 120 kV and 200 mAs, standard matrix, with field of view (FOV) 80 mm and standard filter for bone tissue.

The volumetric data sets were post-processed with the Amira™ software (TGS Europe, Merignac Cedex, France) to perform volume rendering and the creation of isosurfaces. 250 Hounsfield units (HU) were chosen as limit for the extraction of the isosurfaces. The surface data were saved in the stl-format.

With an optical 3D sensor (SCAN^{3D}; 3D-Shape GmbH, Erlangen, Germany) 3D surface data of the plaster casts were acquired. A multi-axis robot is used for rotating and tilting the measured object in the measurement field to obtain different perspectives of the plaster casts. The sensor acquires a series of 3D measurements from different directions automatically. It is suitable for measuring objects up to $50\,mm \times 50\,mm \times 30\,mm$ in size. The time required for the data acquisition of plaster casts is 2 min. The optical 3D surface data of the plaster casts were saved in the stl-format.

After the assessment of optical surface data and a CT study, each of the ten plaster casts received occlusal amalgam restorations (Amalcap Plus Regular; Ivoclar Vivadent GmbH, Ellwangen, Germany) with a volume of 0.3 mm^3 in the first molars, bilaterally. Subsequently, new sets of CT and optical surface data were acquired from the plaster casts (Figure 1).

The optical and CT data were reduced to the clinical crowns of the dentition. The registration procedure was carried out with specialized software (SLIM^{3D}, 3D-Shape). First, the coarse registration was performed. In a second step the fine registration was carried out using an iterative closest point (ICP) algorithm. Data points of CT and optical 3D images were defined as corresponding when they showed a distance not greater than 1 mm.

For the plaster casts with metal artefacts the registration procedure was modified. Obvious streak artefacts were removed from the CT scan data, manually. After the regular coarse registration, the fine registration was divided into a two-step procedure. In a first step, data points of the two different imaging modalities were defined as corresponding if the distance between them did not exceed 5 mm. In a second step, a maximum distance of 1 mm was defined for corresponding points (Figure 1).

After completion of the registration the number of corresponding points was counted and the mean distance between the data points of CT scan and optical scan was calculated for the assessment of the registration error. All measurements were performed by one examiner.

The Mann–Whitney U-test was used for the statistical analysis of differences between the registration error between the plaster casts with and without artefacts. All calculations were performed using SPSS Version 11 for Windows (SPSS Inc., Chicago, IL).

Case study

A 39-year-old female patient, who gave her informed consent, suffering from an open bite and a mandibular prognathism was examined by a Somatom Sensation 16 CT scanner (Figure 2). The CT scan was performed at 120 kV and 80 mA with a slice thickness of 1 mm. The axial plane was parallel to the occlusal plane of the patient. A displayed FOV of 30 cm was chosen. From the raw data the axial CT images were calculated. With the Amira™ software the further preparation of the data was carried out. Bone and soft tissue were segmented and a 3D model of the patient's anatomy was reconstructed. Impressions of the maxilla and mandible were taken and plaster casts were produced. Optical surface data of the plaster casts were acquired. The registration of the CT data and the optical 3D surface data of the dental arches of mandible and maxilla was carried out with Amira™ (Figure 3). The relative positioning of maxilla and mandible for the adjustment of the occlusion was performed by direct transformation

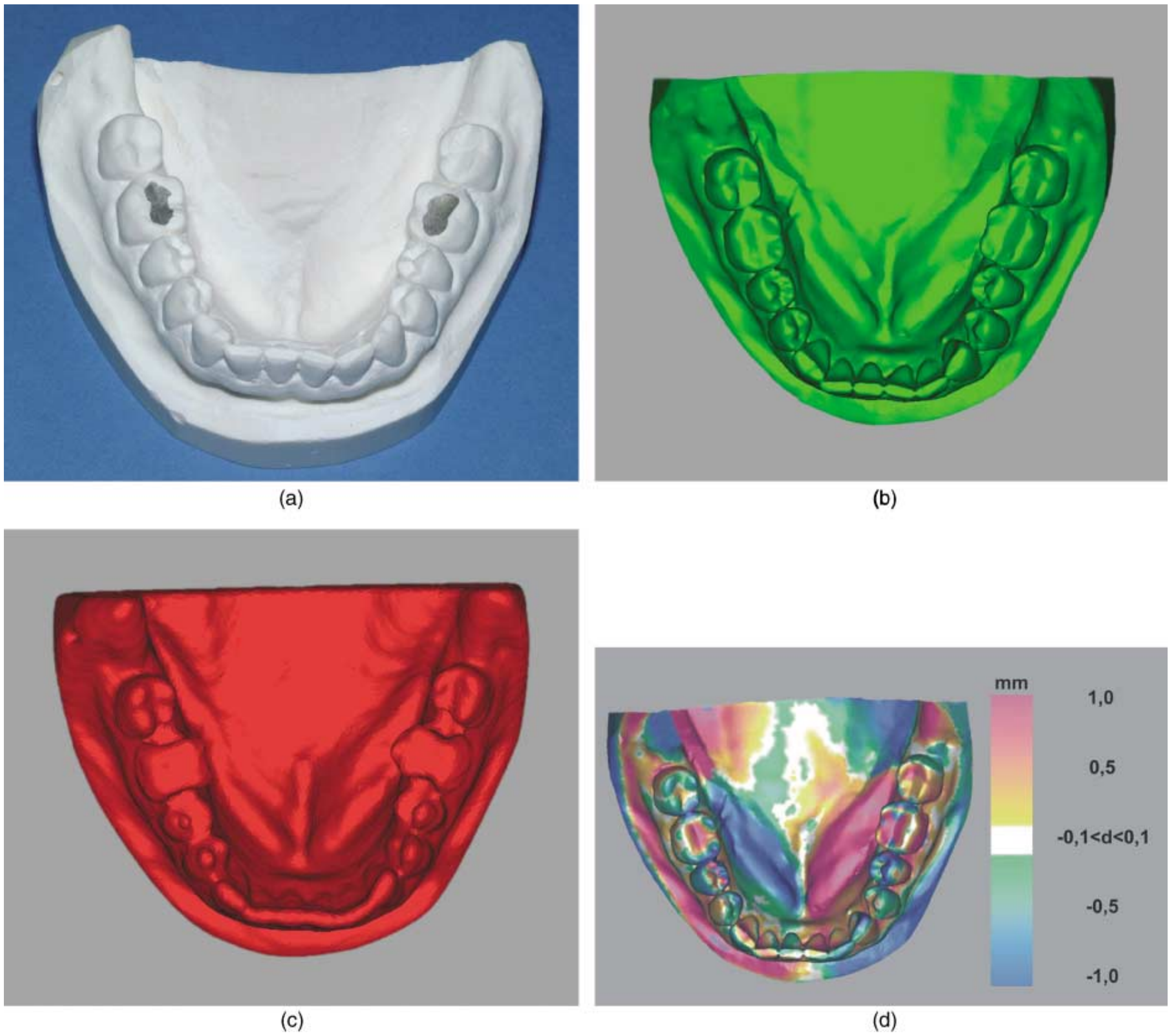


Figure 1 (a) Plaster cast with occlusal metal restorations in the first molars, bilaterally. (b) Optical surface data of the plaster cast. (c) Isosurface generated from the CT scan of the plaster cast after streak artefact correction. (d) Colour-coded visualization of the differences between CT and optical data after the registration procedure

under collision control of the dentition (Figure 4). Subsequently, the virtual osteotomy lines for bimaxillary surgery were defined and osteotomies as well as relocation of the mandibular and maxillary segments were simulated.

Results

For the surface registration the number of corresponding data points that were used ranged from 4416 to 9110 for the plaster casts without metal restorations (6494.2 ± 1621.6). After completion of the registration procedure the mean distance between all sets of corresponding points was 0.1262 ± 0.0301 mm (min. 0.095 mm, max. 0.168 mm).

From the plaster casts with metal restorations 6676.4 ± 1417.9 sets of corresponding data points were used for the registration procedure (min. 3932, max. 9241). After the registration procedure the mean distance between all sets of corresponding data points was 0.2671 ± 0.0580 mm. The data ranged from 0.205 mm to 0.376 mm (Figure 1).

The number of corresponding data points that were used for the registration procedure did not differ statistically significantly for the plaster casts without and with metal restorations ($P = 0.605$). The mean distance between the corresponding data points increased statistically significantly for plaster casts with metal restorations compared with the plaster casts without artefacts ($P < 0.0005$) (Table 1).

For the study of the patient case, again fusion of CT and optical data of the maxilla and the mandible was performed. The digitized plaster cast of the maxilla, consisting of 12878 data points, was aligned with the corresponding maxillary surface region reconstructed from CT data. The optical 3D data of the plaster cast of the mandible with 15433 data points were registered with the corresponding CT data of the mandibular dentition. For the mandible a mean error of 0.66 ± 0.49 mm was found

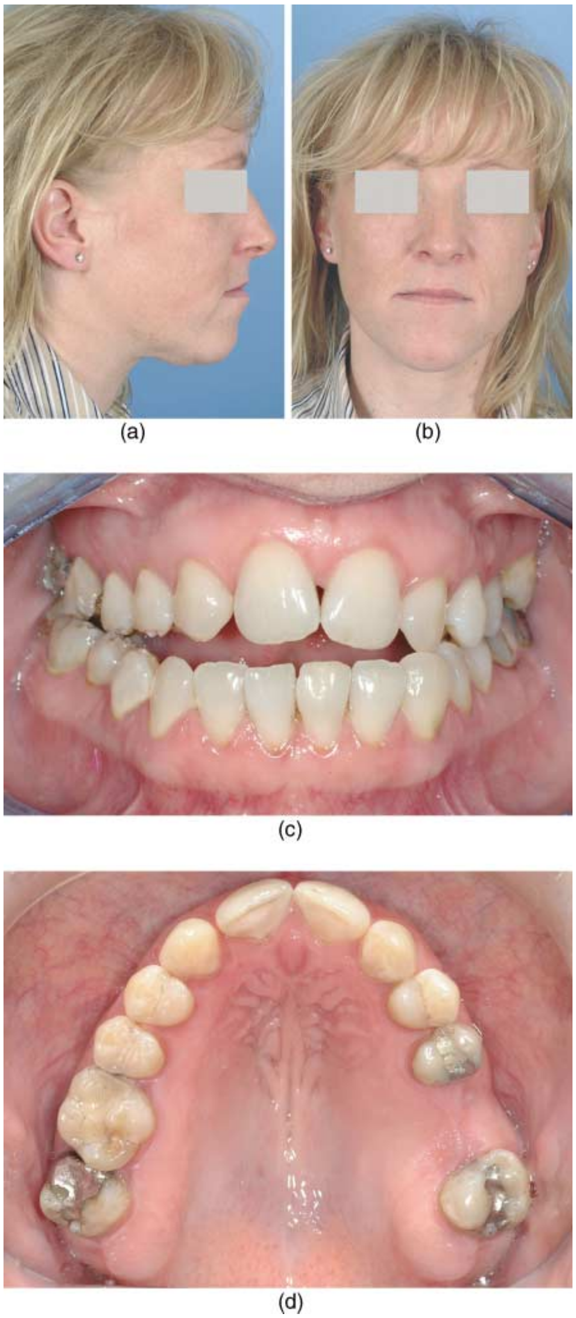


Figure 2 (a) Profile photograph of the patient. (b) Frontal view of the patient. (c) Open bite. (d) Dental arch of the maxilla with metal restorations

with 44% of the point deviations below 0.5 mm. The registration of the maxilla lead to a mean error of 0.56 ± 0.48 mm with 54% of the point deviations below 0.5 mm (Figures 3 and 4).

Discussion

Virtual orthognathic planning methods are normally based on CT scans. Severe drawbacks in the imaging of the dentition because of metal artefacts are encountered that prevent simulation of the dental occlusion with a sufficient accuracy. However, the importance of precise planning of the occlusion for a stable long-term result of orthognathic surgery has been recognized previously.[10] As an early approach to the solution of the problem, the integration of plaster casts in stereolithographic models has been described.[11] This technique is expensive and time consuming. It is not suited for every day use. In another experimental study the combination of a CT scan with a laser scan of the dentition has been reported for the case of a single dry skull.[12] However, the problem of metal artefacts was not considered.

Therefore, it has been the aim of the study to introduce a new technique for the generation of hybrid virtual dental models based on CT scans and optical 3D surface data with improved imaging quality of the dentition. The limits of accuracy of fusion of optical and CT 3D data with and without artefacts arising from metal restorations were assessed in an experimental setting and the application of this hybrid system in a patient case of 3D orthognathic surgery simulation is shown.

Streak artefacts in CT are caused by the attenuation characteristics of metal within the FOV. Because of the higher atomic number, metals attenuate X-rays in the diagnostic energy range much more than soft tissue and bone. The most severe effect of metals is missing data. The X-ray beam is attenuated so strongly that almost no photons reach the detectors. The resultant effects show up in the CT images as pronounced dark and bright streaks, non-linear edge gradients, and sampling errors arising from the surface of a restoration.[13,14] Streak artefacts are removed by interpolating raw data in the shadows of the metal object with adjacent raw data that does not contain the source of the artefact. The removed metal object is significantly scaled down in CT density and added back into the image.[1] However, the results achieved with metal artefact reduction are still not satisfying as far as the precise imaging of the occlusal relief of a tooth is concerned.

The use of optical 3D sensors for precise 3D surface imaging in oral and maxillofacial surgery and especially in the field of orthognathic surgery is well established.[9,15,16] With short measurement times, they offer a non-contact, non-invasive technique without irradiation that permits the data acquisition of complete facial surfaces or dental arches. The image is immediately available and can be viewed from varying directions using the appropriate shading. It is possible to store the image and retrieve it for superimposition. Although the equipment is specialized, it is of low cost compared with previously described devices like the laser scanner. A 3D workstation is not required. The expenses during the use of the sensor are minimal.

Recently, a computerized composite skull model has been introduced to orthognathic surgery.[12] It is said to eliminate the need for plaster casts. For the creation of the digital dental models only impressions of the dentition have to be taken that are subsequently scanned by a laser surface scanner. Plaster casts do not have to be produced from the impressions. Thus it appears that a source of error that reduces the accuracy of the complete system is removed. However, specialized radiolucent dental

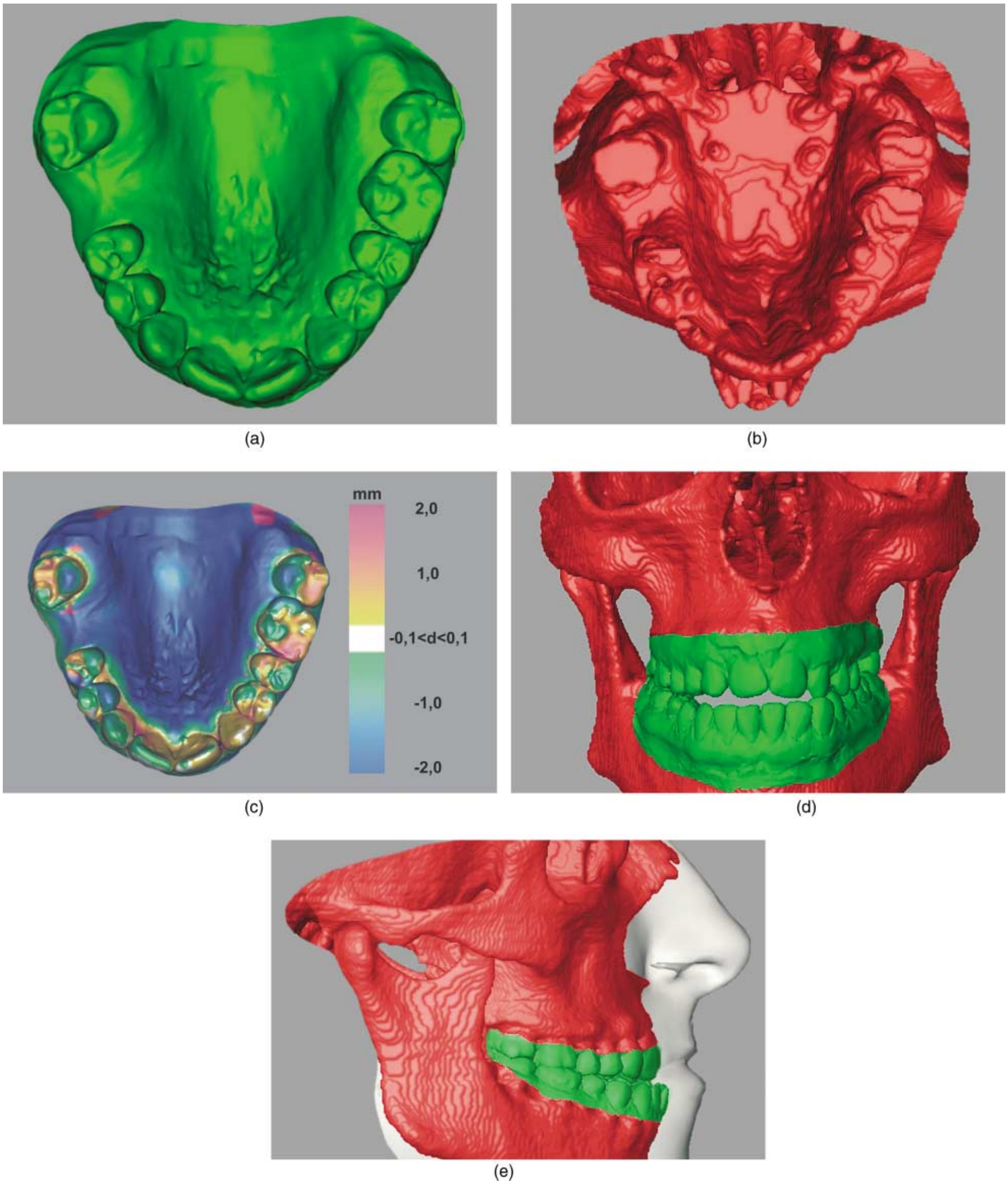
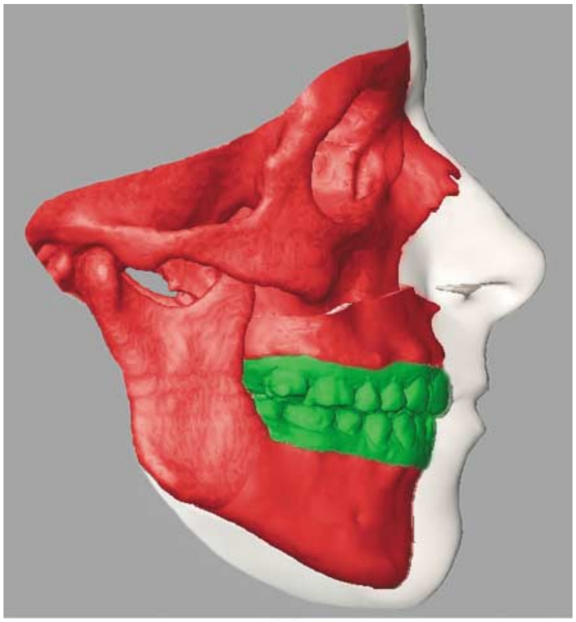
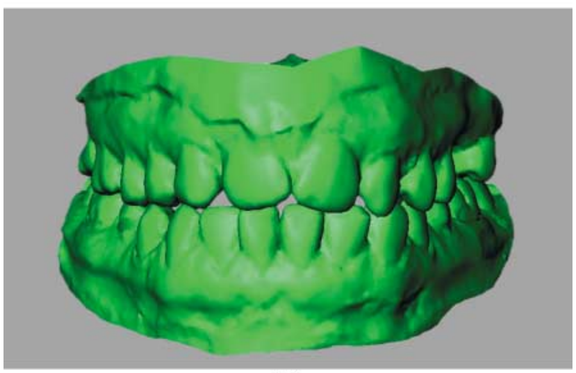


Figure 3 (a) Optical surface data of the patient's maxilla. (b) Isosurface of the maxilla generated from the CT scan after streak artefact correction. (c) Colour-coded visualization of the differences between CT and optical data of the maxilla after the registration procedure. (d) *En face* situation of the registered, pre-operative CT (red) and optical data (green). (e) Profile situation of the registered, pre-operative CT (red) and optical data (green), with overlying soft tissue

impression trays with fiducial markers are needed to allow for the registration of the dental arches assessed by CT and laser scans. This technique causes new sources of error, because several additional steps accompany the data acquisition and the registration procedure. Therefore, the authors have chosen a simpler approach to the registration of the CT scans and the optical surface images. The experimental superimposition of the plaster casts



(a)



(b)

Figure 4 (a) Simulation of the post-operative occlusion. (b) Simulation of the post-operative profile situation after bimaxillary surgery (CT data red; optical data green)

without artefacts showed the high precision of the procedure with distances of corresponding points of CT and optical surface images of only 0.1262 ± 0.0301 mm. Unfortunately, a comparison with the study on the computerized composite skull model is not possible as the required data have not been calculated in this case.[12]

In the present study, the fusion of CT scans with metal artefacts with another imaging modality has been carried out the first time. The distances between corresponding points were significantly larger than the distances assessed for plaster casts without metal restorations. While the accuracy of the optical data remains unchanged, the limiting factor is the CT. Although the mean distance was 0.2671 ± 0.0580 mm, the accuracy of the composite skull models seems to be sufficient for reasonable virtual planning of the post-operative dental occlusion, for training purposes, for the simulation of a real patient cases and the fabrication of surgical splints based on the digital dental models.[17] As post-operative orthodontic treatment has to be performed frequently in the majority of the patient cases, the accuracy of the hybrid dental models in the submillimetre range seems to be acceptable.

The fusion of CT and optical 3D surface data improves the imaging of the dental arches for virtual orthognathic surgery simulation. This technique helps to reduce the problem of metal artefacts in CT scans. However, the precision of the registration of CT scans with metal artefacts is still reduced compared with cases without artefacts. It seems that further development of CT scanners with higher resolution will not eliminate the problem of metal artefacts. Therefore, the image fusion technique should be established as a standard procedure in orthognathic surgery simulation.

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Table 1 Results of the registration procedure of CT and optical data of the plaster casts

	Plaster casts without artefacts		*Plaster casts with artefacts*	
ID No. of plaster casts	*Number of corresponding data points between CT and optical data*	*Mean distance between the corresponding points after the registration procedure (mm)*	*Number of corresponding data points between CT and optical data*	*Mean distance between the corresponding points after the registration procedure (mm)*
1	9110	0.145	3932	0.324
2	6494	0.123	7812	0.221
3	6930	0.168	6236	0.230
4	4589	0.087	6676	0.297
5	6069	0.098	6489	0.224
6	5647	0.111	6840	0.293
7	4416	0.126	6194	0.206
8	7496	0.095	6359	0.267
9	8405	0.152	9241	0.324
10	5786	0.156	6985	0.376
Mean value (SD)	6494.2 (1621.6)	0.1262 (0.0301)	6676.4 (1417.9)	0.2671 (0.0580)
	$P = 0.605$		$P < 0.005$	

SD, standard deviation

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