Gwen R.J. Swennen
Editor

3D Virtual Treatment Planning of Orthognathic Surgery

A Step-by-Step Approach for Orthodontists and Surgeons

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Springer

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A Step-by-Step Approach for Orthodontists and Surgeons

With Contributions by Martin Gaboury

Springer

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ISBN 978-3-662-47388-7 ISBN 978-3-662-47389-4 (eBook)
DOI 10.1007/978-3-662-47389-4

Library of Congress Control Number: 2016957321

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer-Verlag GmbH Berlin Heidelberg

First of all, I want to dedicate this book to my lovely wife Valérie and my sons Joaquin and Cédrique.

I also want to dedicate this colour atlas and manual to my former chairman, colleague and above all personal good friend, Professor Calix De Clercq.

Gwen R. J. Swennen

Foreword I

In the first half of the previous century, radiographic cephalometry moved the focus of orthodontists from malocclusions towards underlying skeletal disharmonies. Linear and angular measurements were not only used to study the dento-alveolar structures in relation to the jaws but also the jaws in relation to the rest of the cranio-facial complex. Data collected from longitudinal growth studies were used to better understand complex facial changes and establish reference values for "normality". For many decades, these cephalometric values and proportions were the bases for a better diagnosis of cranio-facial malformations, the planning of orthognathic surgery and the long-term evaluation of treatment outcome. However, cephalometric analyses are limited to 2 dimensions.

With the introduction of the cone-beam CT, reduction of the costs for the hardware and reduction of the radiation dose, 3D imaging became available for a growing group of clinicians and a standard tool for diagnosis and treatment planning in several disciplines. Colour maps generated after registration of 2 consecutive CBCTs on stable structures in the anterior cranial base give us new tools to assess in detail hard and soft tissue changes over time. This is a revolution for future research to study growth modifications induced by dento-facial orthopaedic appliances, treatment outcome and long-term stability after orthognathic surgery. The correction of cranio-facial malformations and asymmetries by surgical repositioning of both jaws, and complex rotations in 3 planes, can now virtually be simulated with high accuracy. Intermediate wafers made by CAD/CAM or 3D printing are the link between the virtual simulation and the surgeon in the operating room.

Gwen Swennen has written a masterpiece helping us to better explore all new potentials of 3D imaging for the planning of orthognathic surgery. With splendid illustrations and step-by-step procedures, this is the perfect guide for all clinicians, young and old, to improve their skills in extracting and implementing all these data for further improvement of the quality of patient care. This atlas and manual is the result of many years of enthusiastic research by the author. His input for the development of adapted software makes this technology available to all of us. We are grateful to the author willing to share his expertise with us.

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August 2016

Foreword II

I first met Gwen Swennen in May 2009, at the Spanish Association of Oral and Maxillofacial Surgery meeting in Bilbao. At that moment, I was still conventionally planning my surgeries with good results and was deeply convinced that computers would just unnecessarily complicate my routine work, besides being eventually time consuming. It was in that precise occasion that I had the opportunity to attend Gwen's lecture on 3D virtual planning which was utterly enlightening. The speaker's clear and rigorous demonstration of the concept's sequence, the high quality of the images proposed, and the compelling logic of the processes forced me to a critical revision of my own everyday activities. That young and clever surgeon had literally enchanted me, thanks to his technical knowledge and his passionate application of 3D virtual planning of orthognathic surgery.

We became good friends and, since then, we have been taking advantage of congresses and meetings around the world to meet, to reinforce our mutual consideration and respect, while sharing professional and private experiences with a touch of irony and *joie de vivre*. All occasions were perfect to spend some spare time with Gwen and Valérie, his precious wife, in Bruges or in Knokke.

It was in 2011 that, after passionately devouring all Gwen Swennen's articles and publications, I finally decided to convert to 3D virtual planning. I attended one of his courses in Bruges which definitely convinced me, and from that moment I dived into 3D virtual planning. I was helped by two valid surgeons and friends in this quest: Prof. Dr. Federico Hernandez Alfaro and, above all, Dr. Simonas Gribauskas. Moreover, I witnessed Dr. Bill Arnett, to whom I have tremendous respect, also making the same change. My personal shift to 3D virtual planning happened, and today, after 3 years of its routine clinical application, I have become absolutely convinced.

Anyway, after this personal digression, let us focus on Gwen Swennen's book. It was in Melbourne, last October, during the ICOMS 2015 congress that I assisted to the first presentation of his "integrated" work. Once more, Gwen surprised me with the lucidity and clarity with which he systematized his pioneering work.

First, it is an atlas, a manual notwithstanding its impressive dimension. The author's experience is so deep that the manuscript focuses on all aspects of 3D virtual planning of orthognathic surgery. The division in thematic chapters is prone to a rapid consultation on specific topics. All subjects are exemplified with illustrations and easily understandable to a general public. Diagnosis, transition from clinical practice to digital representation, orthodontical and surgical planning, and risk evaluation are clearly analyzed. Moreover, tricks but also potential pitfalls, risks, mistakes, and their prevention are included in the treatise. Finally, a great variety of cases are shown as examples in Chap. 6.

In short, all clinical relevant topics are critically analyzed by the author, who has been rationally applying his knowledge to his everyday clinical routine practice, going from first intuitions to actual simplification and moreover evaluation of potential future applications. Prof. Gwen Swennen with his well-known and recognized generosity is offering the reader his fatigue, his knowledge, and his vast clinical experience toward this subject. I am definitely suggesting his book to anyone who approaches 3D virtual planning in orthognathic surgery, ensuring that he will find in this work a theological "summa" on the subject.

Moreover, even those surgeons who still rely on conventional planning technique are advised to read Gwen Swennen's book since they may find in these pages, that sort of flash of inspiration which leads to a substantial change, besides benefiting from practical information to improve their own clinical practice in maxillofacial deformity surgery.

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August 2016

Preface

… Existing paradigms are held by a scientific community. They explain observations, are the basis for communication and guide future research …
… Observations that don't fit the paradigm are ignored, or are explained in ways that fit the paradigm …
… A crisis occurs when the existing paradigms no longer explains the observations and new theories arise. A revolution occurs and new paradigms are accepted …
… Once a paradigm shift has occurred, a veritable explosion of new ideas and information leads to rapid advances in the field …

Thomas S. Kuhn:
The Structure of Scientific Revolutions. The University of Chicago Press. 1996

When I reflect on this new project, I realise that I was already playing with the idea and preliminary outline of this book in my mind since 2009. This would definitely have been too early, and the book would most probably have been outdated already. The idea of our "Colour Atlas and Manual on Three-Dimensional Cephalometry (2005)" was an attempt to bridge conventional cephalometry with the 3D virtual approach and 3D cephalometry. It is amazing that after more than 10 years the concept of this latter atlas is currently more than actual for both orthodontists and surgeons.

With this new book, I hope to offer a comprehensive, systematic, standardised and above all individualised approach towards 3D virtual planning of orthognathic surgery in the daily clinical routine. This book is based on my personal experience having being involved in more than 2700 clinical cases on virtual planning since almost 20 years. Moreover, I was fortunate to be continuously triggered over all these years by my colleagues, residents, fellows, surgeons and orthodontists all over the world during scientific meetings, courses and workshops.

The concept towards "step-by-step" individualised and integrated 3D virtual treatment planning of orthognathic surgery outlined in this book aims to make once again the bridge between conventional and 3D virtual treatment planning:

1. ($3D\text{-}VPS_1$) "3D Cephalometry of the Patient's Hard Tissues and Teeth (Sect. 2.2.2)" can be compared to conventional cephalometric tracing.
2. ($3D\text{-}VPS_2$) "3D Cephalometry of the Patient's Soft Tissues (Sect. 2.2.3)"can be compared with direct or indirect anthropometric assessment of the patient.
3. ($3D\text{-}VPS_3$) "3D Virtual Osteotomies (Sect. 3.2)" can be compared to some extent with conventional "orthognathic model surgery".
4. ($3D\text{-}VPS_4$) "3D Virtual Occlusal Definition (Sect. 3.3)" can be compared with conventional occlusal definition on plaster dental models.
5. ($3D\text{-}VPS_5$) "10 Step-by-Step Individualised 3D Virtual Treatment Planning (Sect. 3.5)" finally attempts to provide the clinician a manner to integrate 3D virtual planning in daily clinical routine based on the concepts of conventional treatment planning.

The underlying philosophy of this colour atlas and manual is not to dogmatise but to push forward "the paradigm shift" that truly occurred in treatment planning of orthognathic surgery and especially stimulate further development and innovation in "3D Virtual Treatment Planning of Orthognathic and Orthofacial Surgery" to further improve patient care.

Professor Gwen R.J. Swennen, MD, DMD, PhD, MSc, FEBOMFS
Bruges, Belgium
August 2016

Acknowledgements

I especially wish to thank my teachers and mentors Professor Jarg-Erich Hausamen (former chair, Department of OMF and Plastic Surgery, Hannover Medical University, Hannover), Professor Henning Schliephake (Department of OMF and Plastic Surgery, Georg-August University, Göttingen), Professor Albert De Mey (former chair, Deparment of Plastic Surgery, University Hospital Brugmann and Queen Fabiola Children's University Hospital, Brussels) and Professor Chantal Malevez (former chair, Department of OMF Surgery, Queen Fabiola Children's University Hospital, Brussels) who taught me the importance of working hard to try to become not only an excellent surgeon and clinician but also a good researcher. I am also very grateful to Peter Brachvogel (former staff member, Department of OMF and Plastic Surgery, Hannover Medical University, Hannover) and Hannes Berten (former staff member, Department of Orthodontics, Hannover Medical University, Hannover) for teaching and sharing their clinical and scientific knowledge on orthognathic surgery with me during my training.

I want to thank my associate colleagues Professor Calix De Clercq, Johan Abeloos, Philippe Lamoral, Nathalie Neyt, Krisztian Nagy, Joke De Ceulaer, all our residents, international fellows and Professor Jan Casselman (chair, Department of Radiology and Medical Imaging, GH Hospital St-Jan Bruges) and his team for their continuous support. I am also very grateful to Bill Arnett (Santa Barbara, USA) and Mirco Raffaini (Florence, Italy) for sharing with me their knowledge and for all the stimulating discussions that we had together all over the world.

From all the fellows who have visited our department over the last 10 years since I have been in Bruges, I particularly want to thank Raquel Guijarro Martinez (Barcelona, Spain) and Martin Gaboury (Quebec, Canada). I am very proud that I had the opportunity to be together with my personal friend, Professor Federico-Hernandez Alfaro (Barcelona, Spain), director of the first Spanish OMF European PhD thesis conducted by Raquel on "Cone-beam computerized tomography evaluation of the upper airway in the context of orthognathic surgery". Moreover I am very grateful to Martin Gaboury for his critical reviewing of this project; his contribution to Chaps. 1, 2 and 4; and his collaboration in the videos, which are of major importance to the clinical reader of this book and would otherwise have never been realised without his help and efforts. I wish to thank all my referring orthodontists and colleagues for having been working together so nicely for the last 10 years in Bruges, and I look forward to close collaboration in the future.

I want to thank in particular S.O.R.G. (Strasbourg Osteosynthesis Research Group) and especially Professor Paul Stoelinga (former chair, Department of OMF Surgery, Radboud University, Nijmegen, and former chair, S.O.R.G. Orthognathic Section), Oliver Scheunemann and all my co-members of both the orthognathic and cranio-facial section of S.O.R.G for the excellent and stimulating collaboration over the years. I would also like to express my special thanks to Filip Schutyser, Wouter Mollemans and their engineering team for their invaluable support over almost 20 years. Finally, I wish to thank Christian Leibinger for his belief in me and the opportunity as a clinician to develop IPS CaseDesigner, which I truly believe is the next level of 3D virtual planning software.

Last but not least, I need to thank Springer for their trust, boundless patience and collaboration in publishing this new project.

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Bruges, Belgium
August 2016

Introduction

"3D Virtual Treatment Planning of Orthognathic Surgery" offers a "step-by-step" guide towards three-dimensional (3D) diagnosis, treatment planning and evaluation of maxillofacial deformity to orthodontists and orthognathic and orthofacial surgeons. Vertical cone-beam CT imaging has definitely revolutionised the treatment planning of orthognathic surgery. Moreover, it allows unprecedented evaluation of treatment outcome in patients with maxillofacial deformity. This colour atlas and manual attempts to provide clinicians a comprehensive, systematic, standardised and above all individualised "step-by-step" approach towards 3D virtual diagnosis, treatment planning and outcome assessment of orthognathic surgery. In Chap. 1, the 3D imaging workflow is explained along with how it can be integrated in the daily clinical routine. Systematic CBCT virtual diagnosis of the patient's deformity, anatomy and pathology (including 3D airway and TMJ) is described in a comprehensive way in Chap. 2. Moreover, 3D cephalometric analysis of the patient's soft and hard tissues and teeth and the potential of 3D mirroring and colour distance maps for enhanced patient diagnostics are elaborated. Chapter 3 focuses on the "Virtual Natural Head Position (*v*-NHP) and Planning Head Position (PHP)"; "3D Virtual Osteotomies and 3D Virtual Occlusal Definition"; "the Principles of 'Roll', 'Yaw' and 'Pitch' in the 3D Virtual Scene"; and finally "10-Step-by-Step Individualised 3D Virtual Treatment Planning". In Chap. 4, the transfer of the 3D virtual treatment plan towards the patient in the operation theatre is explained. Chapter 5 shows the unprecedented potential towards 3D virtual evaluation of treatment outcome of orthognathic surgery. Finally, after having provided this essential background information to the reader, Chap. 6 illustrates the application of the 3D virtual approach in different types of maxillofacial deformity. Based on almost 20 years of personal experience, the author discusses and shares with the reader the clinical relevant potential but also the current limits and actual pitfalls of 3D virtual diagnosis, treatment planning and evaluation of treatment outcome of orthognathic surgery throughout this book.

List of Videos

Video N° 1: 3D-VPS$_{1\text{-}2}$: Chapter 2
Video N° 2: NHP-PHP: Chapter 3
Video N° 3: 3D-VPS$_3$: Chapter 3
Video N° 4: 3D-VPS$_4$: Chapter 3
Video N° 5: 3D-VPS$_5$: Chapter 3

Videos can be found in the electronic supplementary material in the online version of the book.

On http://springerlink.com enter the DOI number given on the bottom of the chapter opening page. Scroll down to the Supplementary material tab and click on the respective videos link.

In addition, all videos to this book can be downloaded from http://extras.springer.com. Enter the ISBN number and download all videos.

Contents

Abbreviations

AM	Additive manufacturing
AUM	Augmented model
CAD/CAM	Computer-aided design/computer-aided manufacturing
CBCT	Cone-beam computed tomography
CCW	Counterclockwise
CR	Centric relation
CW	Clockwise
DICOM	Digital imaging and communications in medicine
FOV	Field of view
ICP	Iterative closest point
IO-CBCT	Intra-operative cone-beam computed tomography
IO-MSCT	Intra-operative multi-slice computed tomography
MSCT	Multi-slice computed tomography
NHP	Natural head position
c-NHP	Clinical natural head position
v-NHP	Virtual natural head position
PACS	Picture archiving and communication system
PHP	Planning head position
PSI	Patient-specific implant
RPT	Rapid prototyping technology
STI	Surface to image
STL	Standard tessellation language
VOI	Volume of interest
VOXEL	Volumetric pixel
VPS	Virtual planning step

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Imaging Workflow for 3D Virtual Treatment Planning of Orthognathic Surgery

Gwen R.J. Swennen and Martin Gaboury

G.R.J. Swennen (ed.), *3D Virtual Treatment Planning of Orthognathic Surgery*,
DOI 10.1007/978-3-662-47389-4_1

1.1 Image Acquisition for 3D Virtual Treatment Planning of Orthognathic Surgery

1.1.1 Image Acquisition and Virtual Rendering of the Patient's Head

For proper orthognathic and orthofacial surgery planning, the patient's head needs to be scanned without deformation of the facial soft tissue mask, with the mandible in "centric relation (CR)" and ideally in its individual "natural head position (NHP)":

1. "Without deformation of the facial soft tissue mask" implements that the patient is scanned in a vertical seated or standing position, without distortion of the facial mask especially lip morphology and posture. With the advent of "cone-beam CT imaging (CBCT)" in a seated or standing position, this has become feasible. Multi-slice CT (MSCT) scanning, which is performed in a horizontal position and also CBCT apparatus that scan the patient in a supine position, inherently falsify the 3D facial soft tissue mask of the patient due to the effects of gravity. On the other hand, careful attention should be paid that wax-bite wafers or registration devices do not disturb lip position neither lip morphology (◘ Figs. 1.1 and 1.2).
2. To ensure that the patient is scanned with the mandible "in CR", the patient needs to be scanned with a wax-bite wafer. This wax-bite wafer is not different than the one used in conventional orthognathic surgery planning. It is, however, important that this wax-bite wafer is meticulously trimmed in order to avoid deformation of the facial soft tissue mask by interference with the cheeks or lips (◘ Fig. 1.3). A CBCT scout view is made prior to scanning of the patient to assure that the wax-bite wafer is adequately in place and that the patient's mandible is in CR (◘ Fig. 1.4).
3. Based on the author's personal experience, the patient's head position during image acquisition never corresponds to its true clinical "NHP". Therefore, a "step-by-step" approach is described to virtually modify the patient's head position towards its individual clinical NHP (► see also Sect. 3.1), prior to start 3D virtual treatment planning.

> Accurate "3D virtual treatment planning of orthognathic surgery" starts with proper image acquisition.

Image Acquisition and Virtual Rendering of the Patient's Head

To illustrate the workflow towards (1) image acquisition of the patient's head, (2) additional image acquisition of the patient's dentition and occlusion and finally (3) additional image acquisition of the texture of the patient's head, volunteer M.G. will be used throughout this chapter.

On the other hand, the routine clinical imaging workflow for 3D virtual treatment planning of orthognathic surgery will be demonstrated on *Case 1* (Patient V.E.W.) which will be used throughout this book (▶ Chaps. 2, 3, 4, 5 and 6).

Fig. 1.1 Full face CBCT scanning of the patient, with a wax-bite wafer in CR, needs to be performed in a vertical position (seated or standing) without distortion of the facial soft tissue mask. To avoid movement artefacts, it is crucial that the patient is stabilised by a headrest in the back and a frontal headband. Note that although attempted to scan volunteer M.G. is its individual NHP, in a seated position with the use of laser lines, the shoulders were still distorted which caused a small "Yaw" rotation (▶ see also Sect. 3.4) to the left (i-CAT, Imaging Sciences International Inc., volunteer M.G.)

> Stabilisation of the patient's head is crucial during CBCT scanning.
> Do not use chin supports neither frontal bands that cover the forehead.

Image Acquisition and Virtual Rendering of the Patient's Head

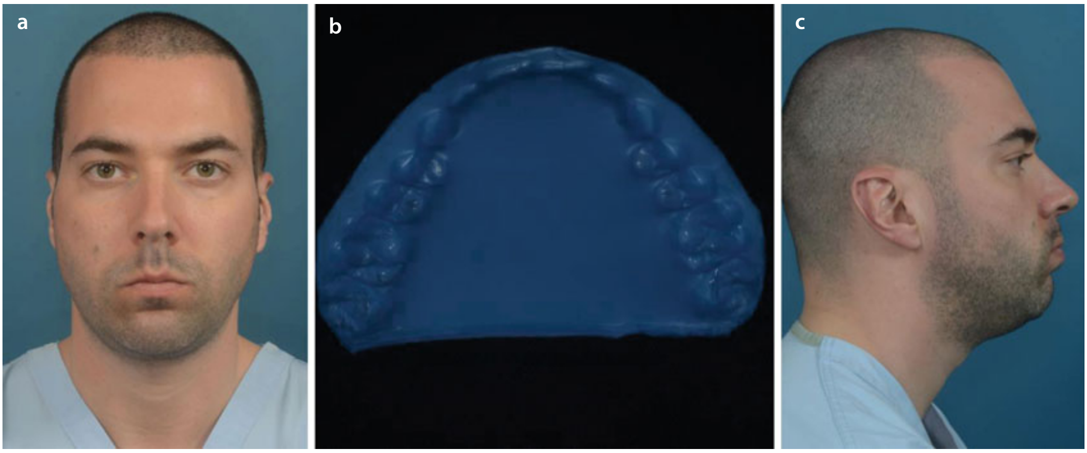


Fig. 1.2 A wax-bite wafer (Delar Corp., Lake Oswego, USA) was taken in CR as in conventional treatment planning to ensure adequate CR during CBCT scanning (**b**). Note the significant distortion of the lips and the cheeks when the wax-bite wafer is not trimmed (**a**, **c**) (volunteer M.G.)

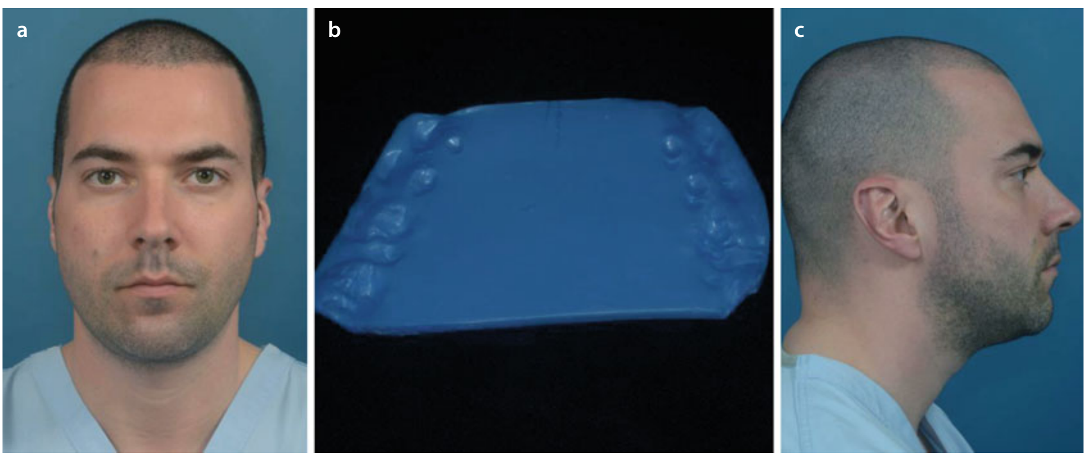


Fig. 1.3 A wax-bite wafer (Delar Corp., Lake Oswego, USA) was taken in CR as in conventional treatment planning to ensure adequate CR during CBCT scanning. The wax-bite wafer was meticulously trimmed to remove all parts that could interfere with the lips and cheeks during CBCT scanning (**b**). Note that there is no distortion of the lips neither of the cheeks (**a**, **c**) (► see also Sect. 1.1.3) (volunteer M.G.)

Image Acquisition and Virtual Rendering of the Patient's Head

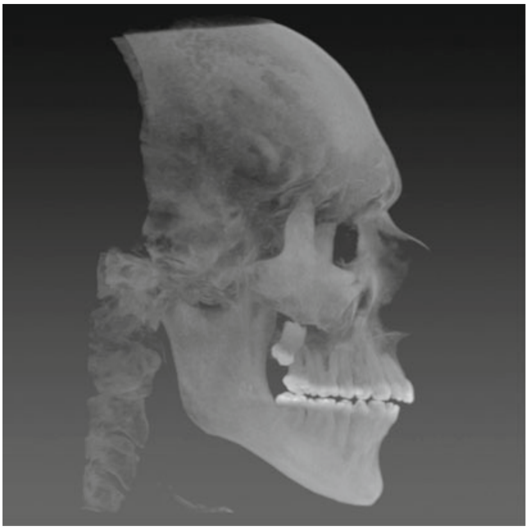


Fig. 1.4 CBCT profile scout view, to ensure that the wax-bite wafer is adequately in place and that the patient's mandible is in CR prior to CBCT scanning (i-CAT, Imaging Sciences International Inc., volunteer M.G.)

Always
Take a scout view prior to CBCT scanning of the patient to verify:
1. Adequate CR
2. Adequate positioning of the wax-bite wafer

Virtual Rendering of the Patient's Head in a "3D Virtual Scene Approach"

An appropriate "3D virtual visualisation paradigm" (Swennen and Schutyser 2007) is needed to visualise the DICOM CBCT data, but also additional image data (► see also Sects. 1.1.2. and 1.1.3) that can be acquired from other 3D imaging sources.

A "3D Virtual Scene Approach" is therefore adopted in which the "3D virtual space" is considered as a "3D virtual scene" with "medical image data" as "actors" (Schutyser 2005). This "3D virtual scene" is viewed with a virtual camera and the resulting views are shown on the computer screen. The virtual camera can be moved around in the "3D virtual scene" to image and inspect the structures of interest from various angles and positions.

Besides visualising the patient's image data with the virtual camera, the "3D virtual visualisation paradigm" and the "3D Virtual Scene Approach" allow other actions and interactions in the "3D virtual scene" such as indicating 3D cephalometric landmarks of the patient's hard tissues and teeth (3D-VPS_1) (► see also Sect. 2.2.2), indicating 3D cephalometric landmarks of the patient's soft tissues (3D-VPS_2) (► see also Sect. 2.2.3), performing 3D virtual osteotomies (3D-VPS_3) (► see also Sect. 3.2), indicating 3D virtual occlusal definition (3D-VPS_4) (► see also Sect. 3.3) and moving bone fragments with additional soft tissue simulation, towards the "step-by-step" individualised 3D virtual treatment planning (3D-VPS_5) of orthognathic surgery (► see also Sect. 3.5).

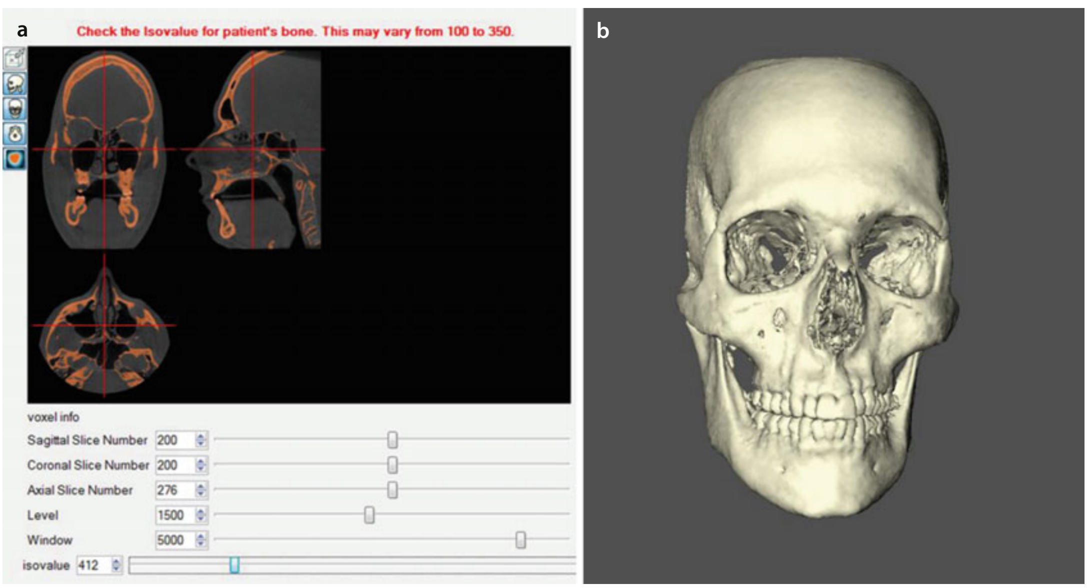
After proper image acquisition of the patient's head, CBCT imaging results in a 3D volume of DICOM (Digital Imaging and Communications in Medicine) data, consisting of a collection of "cube-like blocks" called "voxels". Each voxel has a certain height, width and depth. A typical voxel size of a CBCT scan of the patient's head is $[v_x, v_y, v_z]$ = [0.4 mm, 0.4 mm, 0.4 mm].

Virtual Rendering of the Patient's Head

The CBCT DICOM data can be "rendered" to generate a 3D virtual image of the patient's head by (1) "surface rendering" or (2) "volume rendering".

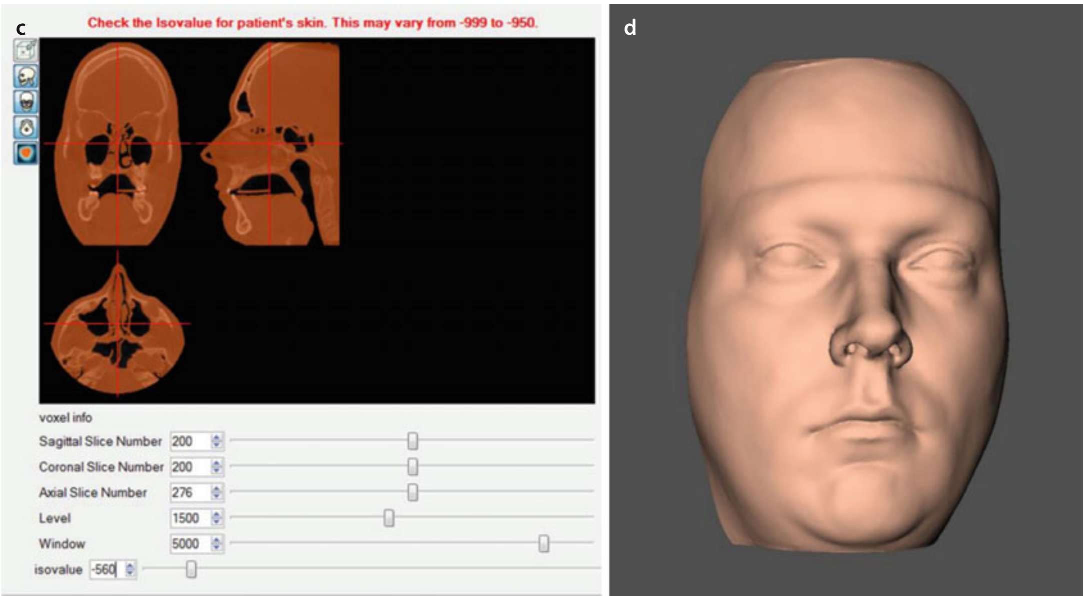
1. **"Surface rendering"** is an indirect way for reconstruction of 3D structures by segmentation (▣ Figs. 1.5 and 1.6) based on the grayscales of the image data towards surfaces that are drawn on the computer screen given a viewing direction of the virtual camera (▣ Fig. 1.7). "Surface rendering" has the advantage that it allows additional actions and interactions in the "3D virtual scene" such as indicating 3D cephalometric landmarks, performing 3D virtual osteotomies, 3D virtual occlusal definition, moving bone fragments with additional soft tissue simulation and 3D superimposition of datasets. Moreover, axial, coronal, sagittal and multiplanar reslices can be calculated and added to the "3D virtual scene". Finally, "surface rendering" allows to integrate the results from surface scanning hardware for additional image acquisition of the patient's dentition and occlusion (► see also Sect. 1.1.2) or texture of the patient's head (► see also Sect. 1.1.3) in a straightforward way.
2. **"Volume rendering"** is a more direct way for reconstruction of 3D structures by rendering a volume of voxels. Towards each voxel, a colour and opacity is assigned based on shading algorithms. According to the viewing direction of the virtual camera in the "3D virtual scene", a projection image is computed and presented on the computer screen. Compared to "surface rendering", "volume rendering" has the advantage that the transitions between several tissues (e.g. teeth and bone) are smooth which results in more detailed anatomy of the teeth and interdental spaces (▣ Figs. 1.8 and 1.9). It however does not allow actions and interactions such as indicating 3D cephalometric landmarks, performing 3D virtual osteotomies, 3D virtual occlusal definition, moving bone fragments with additional soft tissue simulation and 3D superimposition of datasets.

For optimal 3D virtual treatment planning of orthognathic surgery, both "surface rendering" and "volume rendering" are combined.



▣ **Fig. 1.5** "Surface rendering" (Maxilim v. 2.3.0.3) of the hard (**a**, **b**) and soft (**c**, **d**) tissues of the head of volunteer M.G. after CBCT image acquisition. For the hard tissue rendering, the isovalue was set at 412, while for soft tissue rendering, it was set at -560 (i-CAT™, Imaging Sciences International, Inc., Hatfield, USA, "extended field" modus; FOV, 17 cm diameter – 22 cm height; scan time 2 × 20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (volunteer M.G.)

Virtual Rendering of the Patient's Head



■ **Fig. 1.5** (continued)

During the "surface rendering" process, the "threshold" is adjusted to optimise the visualisation of the 3D hard (■ Fig. 1.5a and 1.6) and soft tissue (■ Fig. 1.5c) surface representations of the patient's head.

"Thresholding" is the process of creating a "black-and-white image" out of a "grayscale image" consisting of setting exactly those pixels to white whose value is above a given threshold while setting the other pixels to black. Finally, a colour can be assigned to the reconstructed 3D hard (■ Figs. 1.5b, 1.6 and 1.7) and soft tissue (■ Figs. 1.5d and 1.7) surface representations.

Virtual Rendering of the Patient’s Head

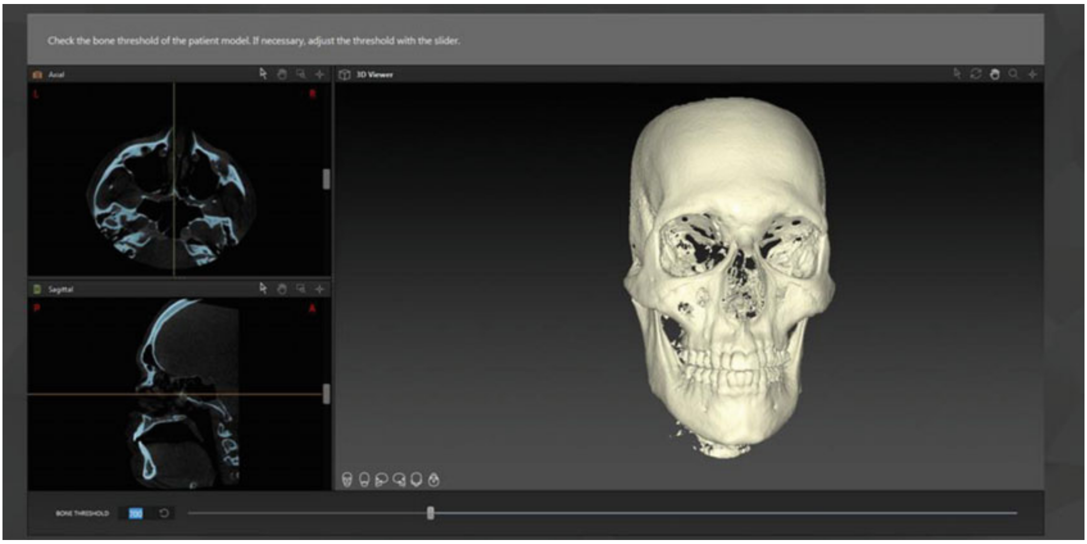


Fig. 1.6 “Surface rendering” (IPS CaseDesigner ALPHA version) of the hard tissues of the head of volunteer M.G. after CBCT image acquisition. The threshold is adjusted to optimise the visualisation of the hard tissues (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA, “extended field” modus; FOV, 17 cm diameter – 22 cm height; scan time 2×20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (volunteer M.G.)

Virtual Rendering of the Patient's Head

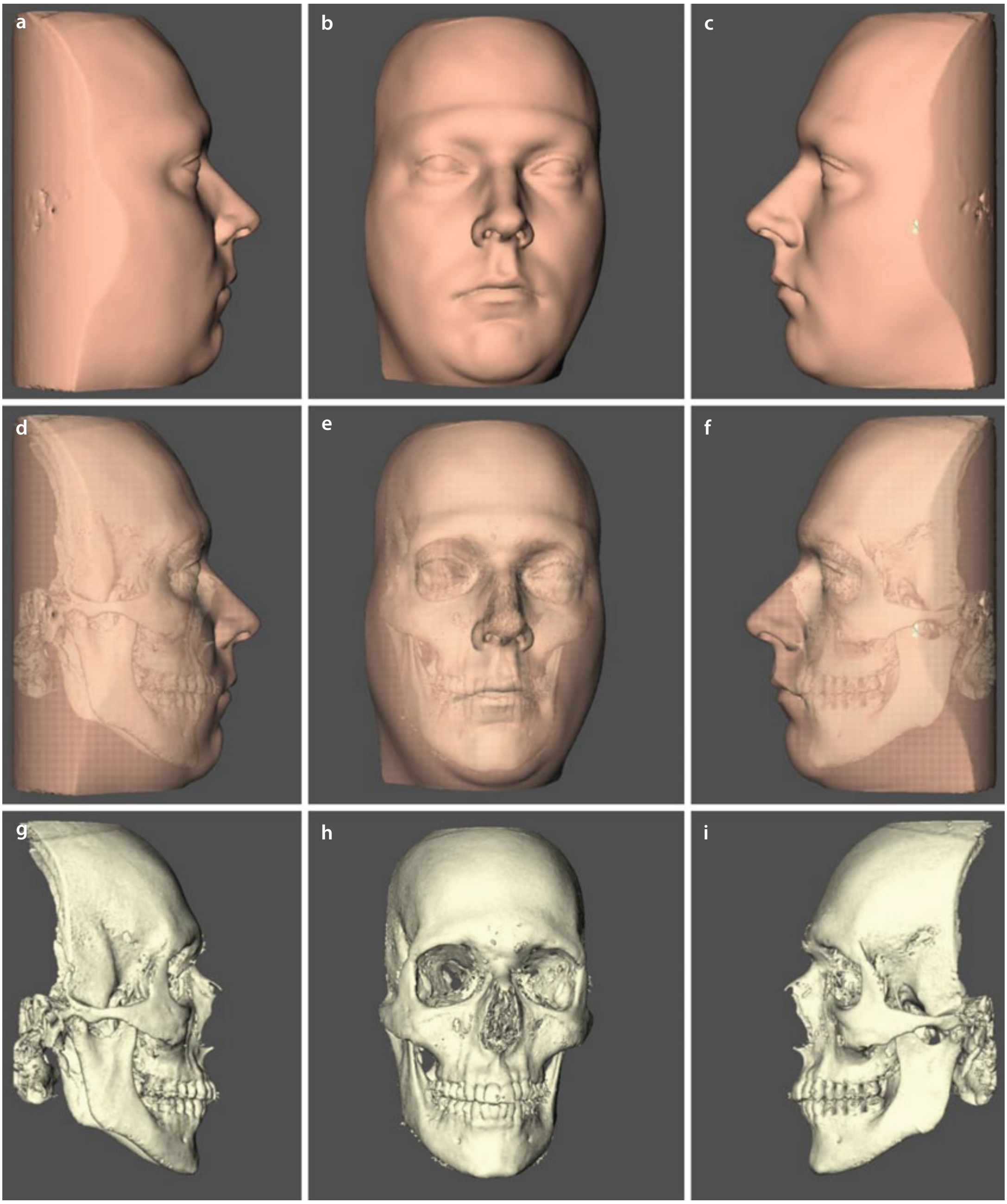


Fig. 1.7 3D "surface-rendered" (Maxilim v. 2.3.0.3) soft and hard tissues representations of the head of volunteer M.G., as acquired during CBCT image acquisition (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA). Volunteer M.G. was vertically scanned with a wax-bite wafer in place in a natural seated position using a standardised CBCT scanning protocol ("extended field" modus; FOV, 17 cm diameter – 22 cm height; scan time 2 × 20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (volunteer M.G.). Right profile (**a**, **d**, **g**), frontal (**b**, **e**, **h**) and left profile (**c**, **f**, **i**) views. Note the incorrect position and orientation of the head ("Yaw" rotation to the left, ► see also Sects. 3.1 and 3.4) although it was attempted to scan volunteer M.G. in his correct NHP. Also note the presence of artefacts at the dentition level although volunteer M.G. does not have orthodontic brackets neither dental reconstitution materials

Virtual Rendering of the Patient's Head

During the "volume rendering" process, a colour and opacity are assigned towards each voxel (Figs. 1.8 and 1.9) based on shading algorithms.

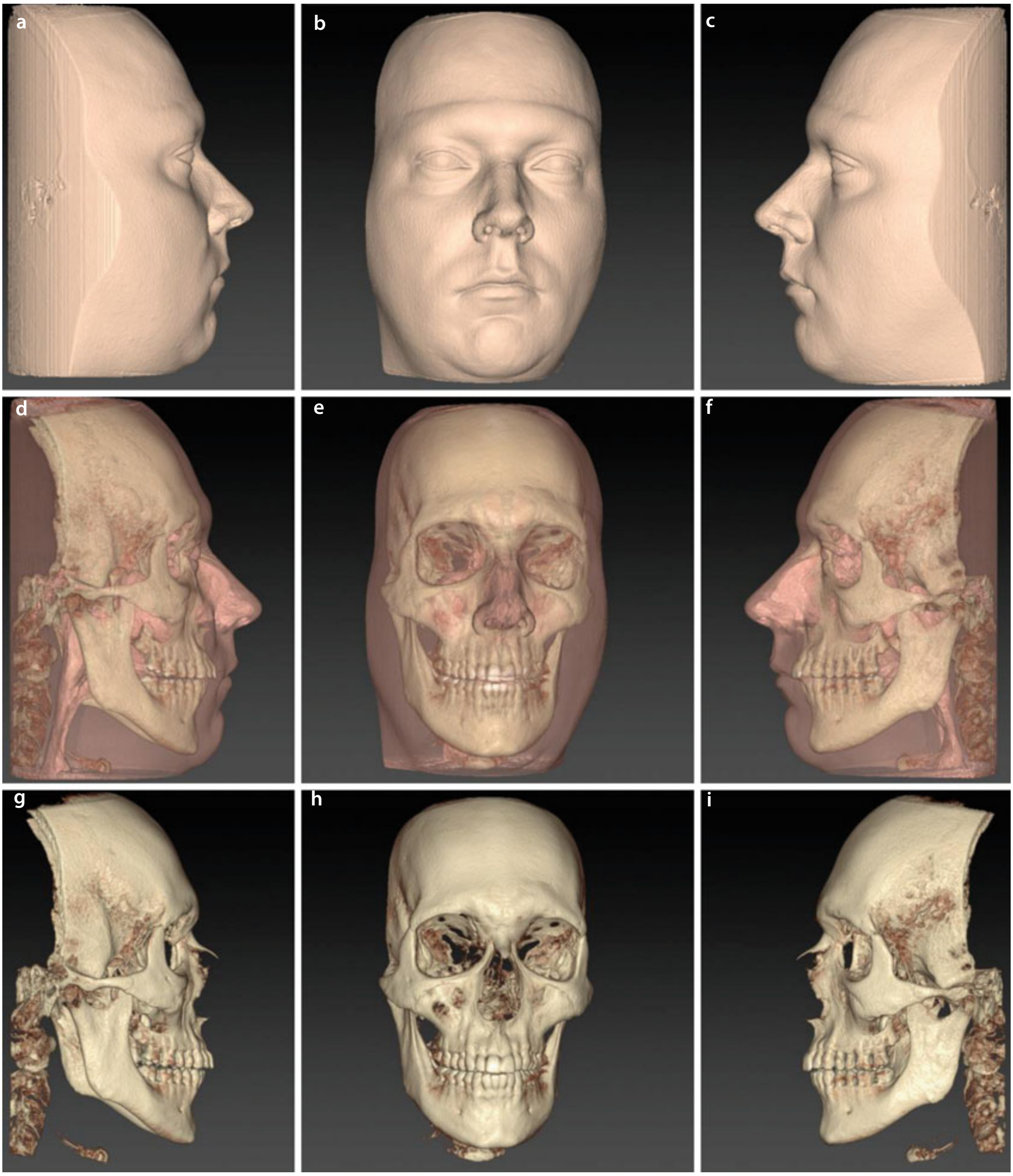


Fig. 1.8 3D "volume-rendered" (IPS CaseDesigner ALPHA version) soft and hard tissues representations of the head of volunteer M.G., as acquired during CBCT image acquisition (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA). Volunteer M.G. was vertically scanned with a wax-bite wafer in place in a natural seated position using a standardised CBCT scanning protocol ("extended field" modus; FOV, 17 cm diameter – 22 cm height; scan time 2 × 20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (volunteer M.G.). Right profile (**a**, **d**, **g**), frontal (**b**, **e**, **h**) and left profile (**c**, **f**, **i**) views. Note that "volume rendering" produces less artefacts at the dentition level

Virtual Rendering of the Patient's Head

Attention

Towards 3D virtual diagnosis, 3D virtual treatment planning and 3D outcome evaluation, both "surface rendering" and "volume rendering" are necessary and need to be combined.

Fig. 1.9 3D "volume-rendered" (IPS CaseDesigner ALPHA version) hard tissue representations of the head of volunteer M.G., as acquired during CBCT image acquisition (i-CAT™, Imaging Sciences International, Inc., Hatfield, USA). Volunteer M.G. was vertically scanned with a wax-bite wafer in place in a natural seated position using a standardised CBCT scanning protocol ("extended field" modus; FOV, 17 cm diameter – 22 cm height; scan time 2 × 20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (volunteer M.G.). Frontal (**a**), right profile (**b**) and left (**c**) views. Note that "volume rendering" produces less artefacts and gives more detailed information towards the roots of the teeth and interdental space

1.1.2 Additional Image Acquisition of the Patient's Dentition and Occlusion

For proper "3D virtual treatment planning of orthognathic surgery", additional image acquisition of the patient's dentition is necessary, since isolated CBCT scanning of the patient's head (▶ see Sect. 1.1.1) does not provide accurate occlusal and intercuspidation data, necessary for 3D virtual occlusal definition (▶ see also Sect. 3.3) and 3D CAD/CAM splint manufacturing (▶ see also Sect. 4.1.1).

Additional image acquisition of the patient's dentition in order to obtain accurate occlusal and intercuspidation data can be performed by:

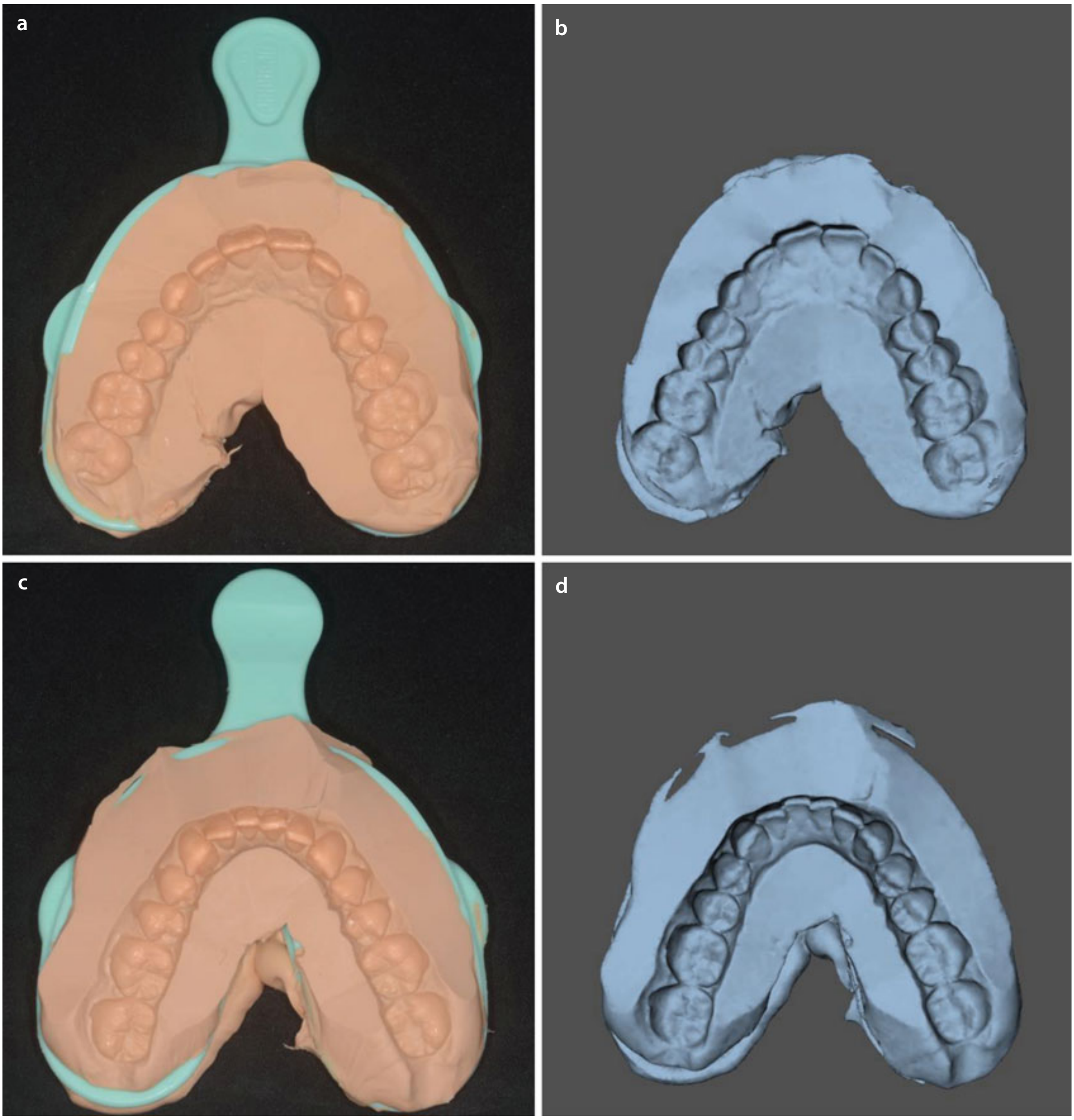
1. Direct scanning of the impressions of the patient's dental arches
2. Indirect scanning of the plaster dental models of the patient
3. Intra-oral scanning of the patient's dentition

> "Single CBCT scanning of the patient's head" does not provide accurate occlusal and intercuspidation data which are mandatory for proper 3D virtual orthognathic surgery planning.

1. Direct scanning of the impressions of the patient's dental arches

Direct scanning of the impression(s) of the patient's dental arches can be performed with the same CBCT apparatus that is used for scanning of the patient's head. Either an "all-in-one" impression or separate impressions of the upper and lower dental arches can be CBCT scanned. Laser surface scanning is not recommended for scanning of impressions since undercuts are not imaged correctly due to the fact that the laser light is following a straight path.

Direct CBCT scanning of the impression(s) of the patient's dental arches provides additional accurate occlusal and intercuspidation data data (◘ Figs. 1.10 and 1.11).



◘ **Fig. 1.10** Clinical photographs of the "all-in-one" impression of the upper and lower dental arches (**a**, **c**, **e**) and 3D "surface-rendered" representations (**b**, **d**, **f**). The Triple Tray® AlgiNot^{TM} impression (▶ see also Sect. 1.2.2) was scanned using a high-resolution standardised CBCT scanning protocol (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA, "high-resolution" modus; FOV, 17 cm diameter – 6 cm height; scan time 40 s; voxel size 0.2 mm, at 120 kV according to DICOM field, 0018,0060 KVP, and 47 mA according to DICOM field, 0018,1151 XRayTubeCurrent) (Maxilim v. 2.3.0.3., volunteer M.G.). Note that the plastic Triple Tray® is no longer visible on the 3D surface representations because of its radiolucent nature

Direct Scanning of the Impressions of the Patient's Dental Arches

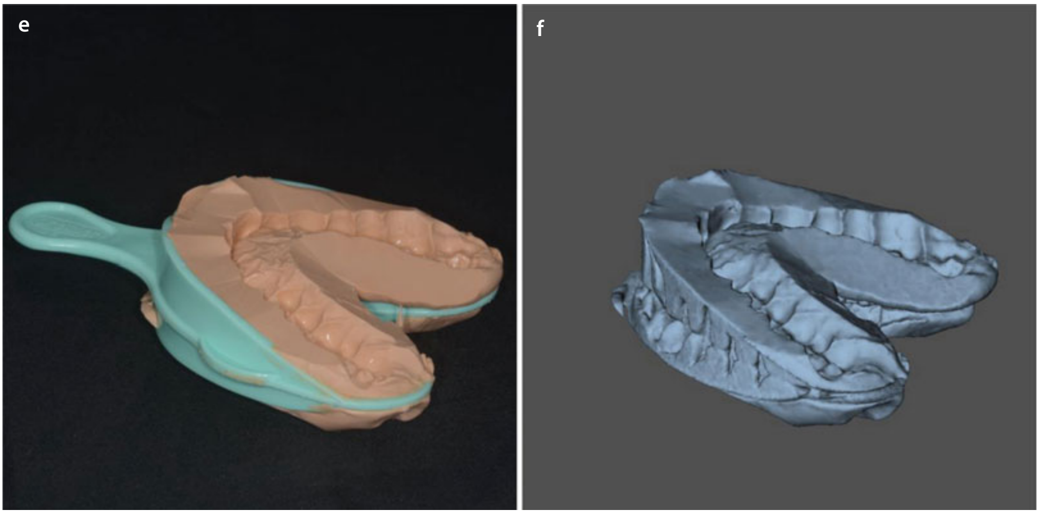


Fig. 1.10 (continued)

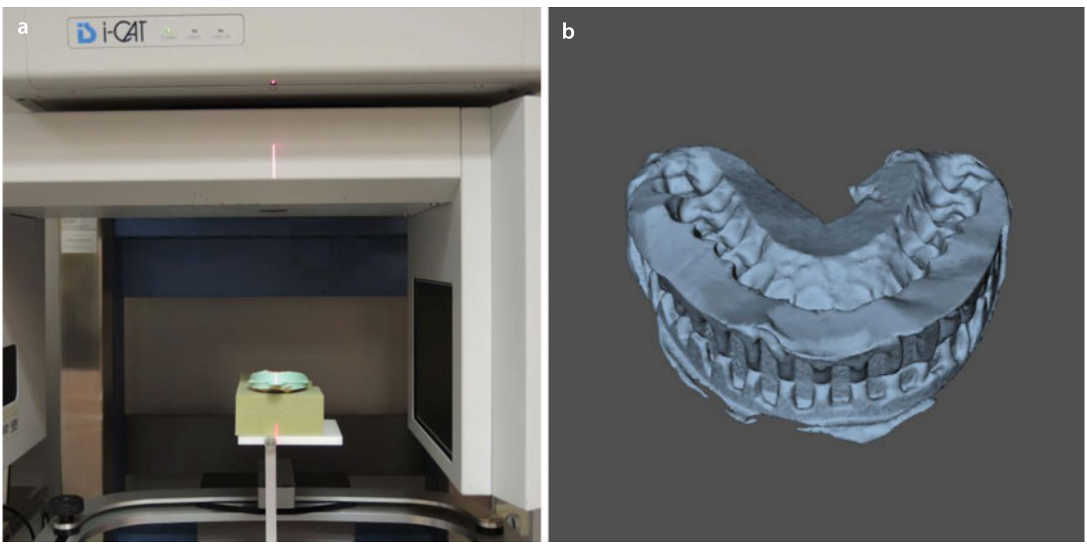
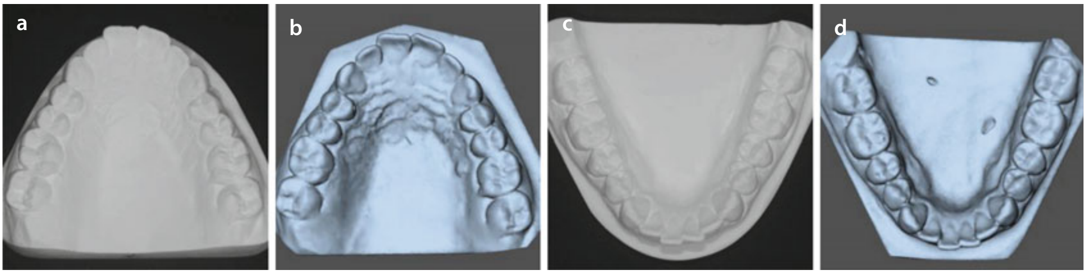


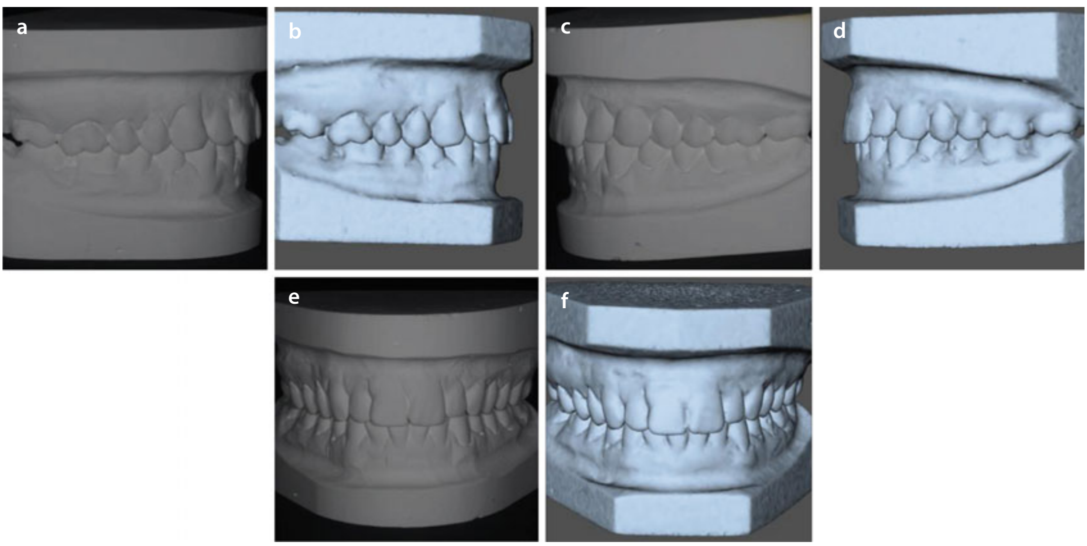
Fig. 1.11 To scan the Triple Tray® AlgiNot™ impression, it was put on a commercially available sponge (**a**) to avoid segmentation problems with the CBCT apparatus table. The Triple Tray® AlgiNot™ impression was scanned using a high-resolution standardised CBCT scanning protocol (i-CAT™, Imaging Sciences International, Inc., Hatfield, USA, "high-resolution" modus; FOV, 17 cm diameter – 6 cm height; scan time 40 s; voxel size 0.2 mm, at 120 kV according to DICOM field, 0018,0060 KVP, and 47 mA according to DICOM field, 0018,1151 XRayTubeCurrent). 3D "surface-rendered" representation (**b**) (Maxilim v. 2.3.0.3.) (volunteer M.G.)

2. Indirect scanning of the plaster dental models of the patient

Additional accurate occlusal and intercuspidation data can also be obtained "indirectly" by scanning of the plaster dental models of the patient. This can be performed with the same CBCT apparatus (◘ Fig. 1.12) that is used for scanning of the patient's head or by laser surface scanning. Moreover, the actual occlusion of the patient can be scanned (◘ Fig. 1.13).



◘ **Fig. 1.12** Additional image acquisition of the dentition by indirect high-resolution standardised CBCT scanning of the upper and lower plaster dental models (**a**, **c**) (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA, "high-resolution" modus; FOV, 17 cm diameter – 6 cm height; scan time 40 s; voxel size 0.2 mm, at 120 kV according to DICOM field, 0018,0060 KVP, and 47 mA according to DICOM field, 0018,1151 XRayTubeCurrent) and their 3D "surface-rendered" representations (**b**, **d**) (Maxilim v. 2.3.0.3.) (volunteer M.G.)



◘ **Fig. 1.13** Additional image acquisition of the occlusion by indirect high-resolution standardised CBCT scanning of the upper and lower plaster dental models, in final occlusion (**a**, **c**, **e**) (i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA, "high-resolution" modus; FOV, 17 cm diameter – 8 cm height; scan time 40 s; voxel size 0.2 mm, at 120 kV according to DICOM field, 0018,0060 KVP, and 47 mA according to DICOM field, 0018,1151 XRayTubeCurrent) and their 3D "surface-rendered" representations (**b**, **d**, **f**) (Maxilim v. 2.3.0.3.) (volunteer M.G.)

3. Intra-oral scanning of the patient's dentition

Intra-oral scanning allows scanning of the patient's upper and lower dental arches with an accuracy of a few microns (▶ Fig. 1.14a, c). The scanning process is currently still rather slow compared to direct scanning of impressions or indirect scanning of plaster dental models. More-

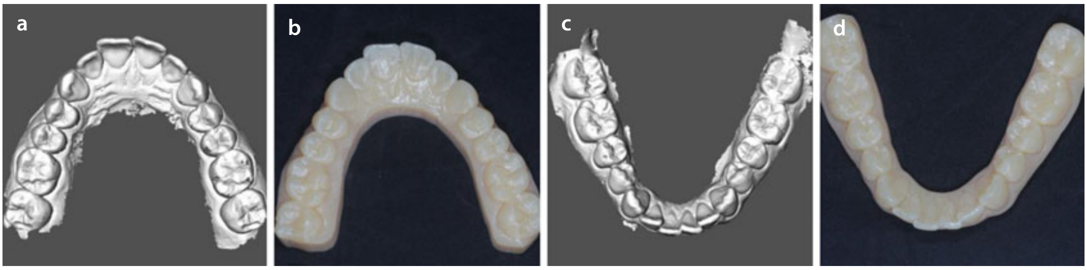


Fig. 1.14 Additional image acquisition of the patient's dentition with direct intra-oral optical scanning (3M^{TM} Lava^{TM} Chair-side Oral Scanner) of the upper and lower dental arches. 3D "surface-rendered" representations of the upper (**a**) and (**c**) lower arches (Maxilim v. 2.3.0.3.). The STL files were 3D printed (**b**, **d**) for educational purposes (volunteer M.G.)

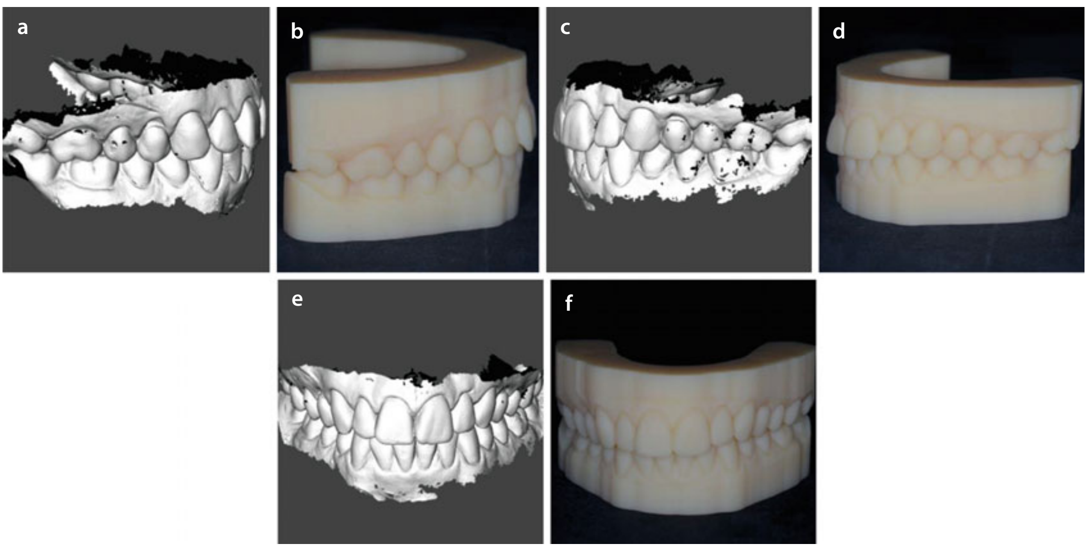


Fig. 1.15 Additional image acquisition of the occlusion with direct intra-oral optical scanning (3M^{TM} Lava^{TM} Chair-side Oral Scanner). 3D "surface-rendered" representations (**a**, **c**, **e**) (Maxilim v. 2.3.0.3.). The STL files were 3D printed (**b**, **d**, **f**) for educational purposes (volunteer M.G.)

over, the actual occlusion of the patient can be scanned (► Fig. 1.15a, c, e).

1.1.3 Additional Image Acquisition of the Texture of the Patient's Head

For proper "3D virtual treatment planning of orthognathic surgery", additional image acquisition of the texture of the patient's head in order to augment (► see also Sect. 1.2) the CBCT 3D facial soft tissue mask of the patient with texture and colour is not essential and currently still error prone.

Additional image acquisition of the texture of the patient's head can be performed by:

1. Standardised clinical 2D photographs of the patient's head in rest in NHP (► Fig. 1.16a, b, c, g, h, i, m)
2. 3D photographs made by 3D surface imaging systems based on active stereo photogrammetry (► Fig. 1.16d, e, f, j, k, l, n)

Towards 3D virtual evaluation of orthognathic surgery, 3D photographs offer an important clinical relevant potential and benefit towards longitudinal non-ionising treatment outcome analysis (► see also Sect. 5.2.2).

Additional dynamic 4D image acquisition of the texture of the patient's head and the underlying 3D facial soft tissue mask is promising. From a computational point of view, it is currently too time consuming to implement in the clinical daily routine and therefore actually dedicated for research purposes.

Attention
Additional image acquisition of the texture of the patient's head in order to augment the 3D facial soft tissue mask is not essential for proper 3D virtual treatment planning, however, certainly of interest in "Step 9" of 3D-VPS$_5$ "Patient Communication of the Individualised 3D Virtual Treatment Plan".

Additional Image Acquisition of the Texture of the Patient's Head

Fig. 1.16 Additional image acquisition of the texture of the head. Standardised 2D clinical photographs (**a**, **b**, **c**, **g**, **h**, **i**, **m**) and 3D photographs of the head (**d**, **e**, **f**, **j**, **k**, **l**, **n**) (Planmeca ProMax® 3D Max, ProFace™, Planmeca Oy, Helsinki, Finland) (volunteer M.G.). Note that 2D clinical photographs still have a higher image quality than 3D photographs

Additional Image Acquisition of the Texture of the Patient's Head

Fig. 1.16 (continued)

1.2 Processing of Acquired Image Data Towards a 3D Virtual Augmented Model of the Patient's Head

1.2.1 Principles of Rigid Registration

Single CBCT image acquisition of the patient's head (▶ Sect. 1.1.1) does not provide a 3D virtual patient model appropriate for 3D virtual treatment planning of orthognathic surgery since it lacks sufficient accuracy at the occlusal and intercuspidation level.

Therefore, additional image acquisition of the patient's dentition (▶ Sect. 1.1.2) is necessary to provide accurate occlusal and intercuspidation data.

Moreover, additional image acquisition of the texture of the patient's head (▶ Sect. 1.1.3) can be performed but is not essential for proper 3D virtual planning of orthognathic surgery.

In order to process the acquired image data towards a "3D virtual augmented model (AUM)" of the patient's head appropriate for 3D virtual treatment planning of orthognathic surgery, accurate "rigid registration" is necessary.

Registration techniques are based on similarity measures between two (e.g. pre- and post-treatment) or more (e.g. pretreatment, 3D virtual treatment plan and post-treatment) datasets (Swennen and Schutyser 2007).

With "rigid registration", a rotation and translation is searched which aligns both or more datasets and therefore increases the similarity of both or more datasets.

Traditionally, different types of "rigid registration" exist: (1) point-based, (2) surface-based and (3) voxel-based rigid registration.

1. **"Point-based rigid registration"** only uses corresponding points to compute the rotation and translation between datasets. The residual distance between the point pairs after registration is minimised.
2. **"Surface-based rigid registration"** uses surface information of two datasets to compute the rotation and translation between datasets. Corresponding points and shapes are searched and the distance after rotation and translation is minimised.
3. **"Voxel-based rigid registration"** uses the grey value information of two datasets to compute the rotation and translation between datasets by maximising the mutual information between both datasets.

A new and innovative rigid registration algorithm, "surface to image registration (STI)" (Nobel Biocare c/o Medicim NV, Mechelen, Belgium) also called "CBCT to image registration" or "smart fusion", was evaluated and validated in 2013 by Swennen and colleagues to obtain a 3D virtual AUM of the patient's head appropriate for orthognathic surgery planning (▶ see also Sects. 1.2.2 and 1.2.3).

"Surface to image registration (STI)" uses a combined surface to voxel approach and registers the image intensities of the surfaces "gradient based" to the corresponding voxels.

To integrate accurate occlusal and intercuspidation data into the 3D patient model, "rigid registration" with or without markers, based on points, surfaces, voxels or a combination, currently still *needs to be performed* of:

1. The CBCT imaging acquisition data of the patient's head (▶ Sect. 1.1.1)
2. Additional image acquisition data of the patient's dentition and occlusal surfaces (▶ Sect. 1.1.2)
   (a) Without the use of plaster dental models
   (b) With the use of plaster dental models

Although different attempts have been reported by different research groups, only few methods have been properly validated and consequently applied in sufficient consecutive clinical patient series in order to provide evidence-based data. Moreover, all existing protocols at the moment still have their limitations and drawbacks towards the daily clinical application.

1.2.2 Without the Use of Plaster Dental Models

In 2009, Swennen and colleagues introduced and validated the "Triple CBCT Scan Protocol" in order to obtain an AUM of the patient appropriate for 3D virtual orthognathic surgery planning without the use of plaster dental models.

1. "CBCT scan N°1": Full face scan of the patient in a vertical natural seated position in CR with a wax-bite in place without deformation of the facial soft tissue mask (▶ see also Sect. 1.1.1) (◘ Fig. 1.17)
2. "CBCT scan N°2": Limited low-dose scan of the patient with a Triple Tray® AlgiNot™ all-in-one impression in place (◘ Fig. 1.18)
3. "CBCT scan N°3": High-resolution scan of the Triple Tray® AlgiNot™ all-in-one impression (◘ Fig. 1.19)

Following sequential semi-automatical triple "voxel-based rigid registration", the patient's head is augmented with accurate occlusal and intercuspidation data (◘ Fig. 1.20). The "Triple CBCT Scan Protocol" has meanwhile been used in daily clinical routine in the author's department in more than 2250 cases. Although accurate, it requires an important learning curve towards the imaging workflow for both image acquisitions as processing of the acquired image data towards a 3D virtual AUM of the patient. Moreover, the protocol requires two CBCT scans of the patient, which inherently increases the amount of radiation.

In 2013, Swennen and colleagues evaluated and validated "CBCT to image registration (also called Smart Fusion)" in order to obtain an AUM of the patient appropriate for 3D virtual orthognathic surgery planning without the use of plaster dental models.

Following "surface to image registration (STI)", the patient's head is augmented with accurate occlusal and intercuspidation data. Although the "CBCT to image registration protocol" has been validated on 30 orthognathic patients without the use of plaster dental models, it still needs to be integrated in the daily clinical workflow. Compared to the "Triple CBCT Scan Protocol", the imaging workflow for both image acquisitions as processing of the acquired image data towards a 3D virtual AUM of the patient is less time consuming and more user-friendly. Moreover, it requires only one CBCT patient scan in CR without deformation of the patient's facial soft tissue mask (▶ see also Sect. 1.1.1).

In 2013, Hernandez-Alfaro and Guijarro-Martinez evaluated intra-oral scanning of the patient's dentition to augment the patient's head with accurate occlusal and intercuspidation data in an in vitro ($n = 3$) and in vivo study ($n = 6$) based on "surface-based rigid registration". Intra-oral scanning of the dental arches of the patient in order to create an AUM is promising but still needs further validation towards accuracy in large prospective and consecutive patient series.

3D Virtual Augmented Model (AUM) of the Patient's Head "without the Use of Plaster Dental Models"

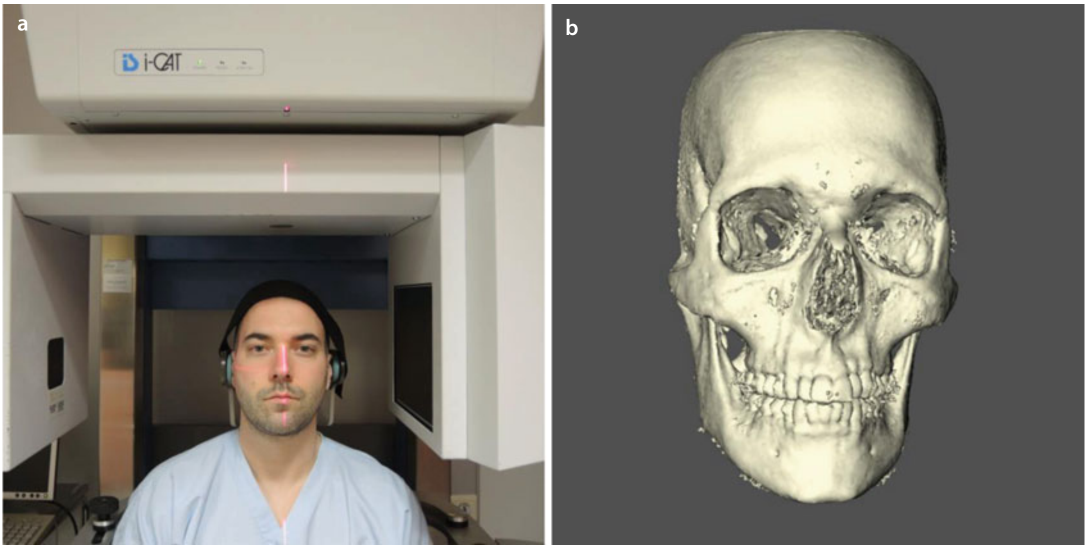


Fig. 1.17 CBCT scan N°1 in CR of the "Triple CBCT Scan Protocol". Volunteer M.G. was vertically scanned with a wax-bite wafer in place in a natural seated position (**a**) using a standardised CBCT scanning protocol ("i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA: extended field" modus; FOV, 17 cm diameter – 22 cm height; scan time 2 × 20 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent). 3D "surface-rendered" (Maxilim v. 2.3.0.3) hard tissues surface representation (**b**) (volunteer M.G.). Note that there is no distortion of the lips neither of the cheeks

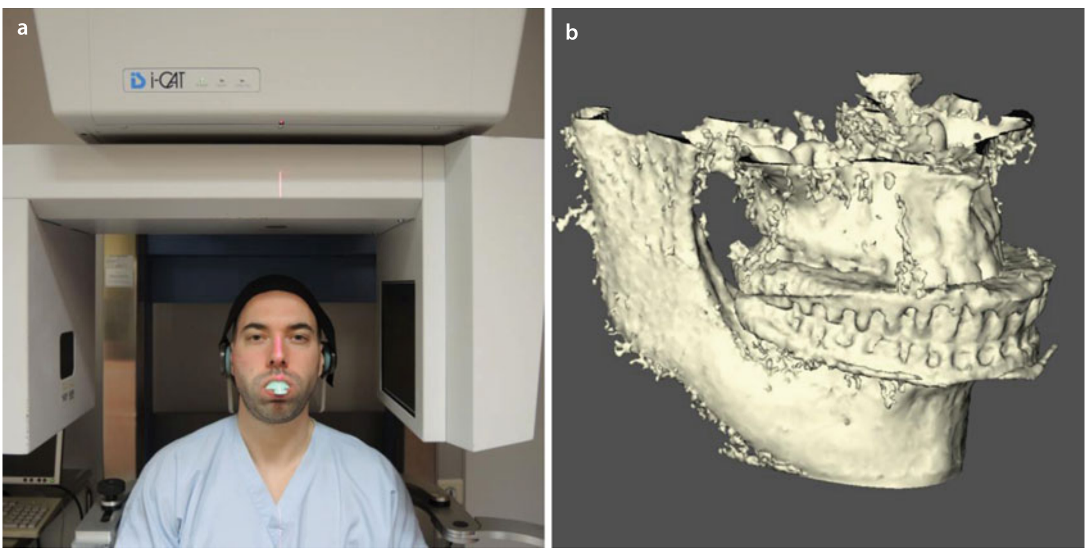


Fig. 1.18 "Low-dose" CBCT scan N°2 of the "Triple CBCT Scan Protocol". Volunteer M.G. was vertically scanned in a seated position with the Triple Tray® AlgiNot^{TM} impression in place (**a**) using a standardised CBCT scanning protocol ("i-CAT^{TM}, Imaging Sciences International, Inc., Hatfield, USA: FOV, 17 cm diameter – 8 cm height; scan time 1 × 10 s; voxel size 0.4 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent). 3D "surface-rendered" (Maxilim v. 2.3.0.3) hard tissues surface representation (**b**) (volunteer M.G.). Note the significant distortion of both the lips and the cheeks

3D Virtual Augmented Model (AUM) of the Patient's Head "without the Use of Plaster Dental Models"

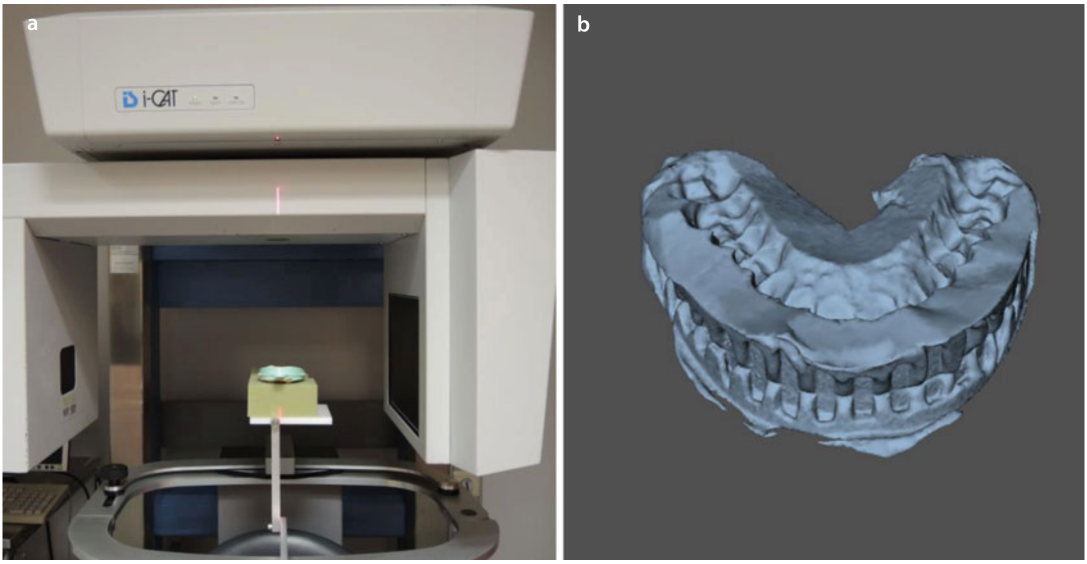


Fig. 1.19 "High-resolution" CBCT scan N°3 of the "Triple CBCT Scan Protocol". The Triple Tray® AlgiNot™ impression is scanned with the same CBCT apparatus (**a**) with high resolution using a standardised CBCT scanning protocol ("i-CAT™, Imaging Sciences International, Inc., Hatfield, USA: "high-resolution" modus; FOV, 17 cm diameter – 6 cm height; scan time 40 s; voxel size 0.2 mm at 120 kV according to DICOM field, 0018,0060 KVP, and 48 mA according to DICOM field, 0018,1151 XRayTubeCurrent). 3D "surface-rendered" (Maxilim v. 2.3.0.3) surface representation (**b**) (volunteer M.G.). Note that the impression is placed on a commercially available sponge instead of directly on the table of the CBCT apparatus to avoid segmentation problems

Rigid Registration
of the CBCT scan of the patient's head (▶ Sect. 1.1.1) and additional image acquisition of the patient's dentition (▶ Sect. 1.1.2) are mandatory for proper 3D virtual orthognathic surgery planning.

1

3D Virtual Augmented Model (AUM) of the Patient's Head "without the Use of Plaster Dental Models"

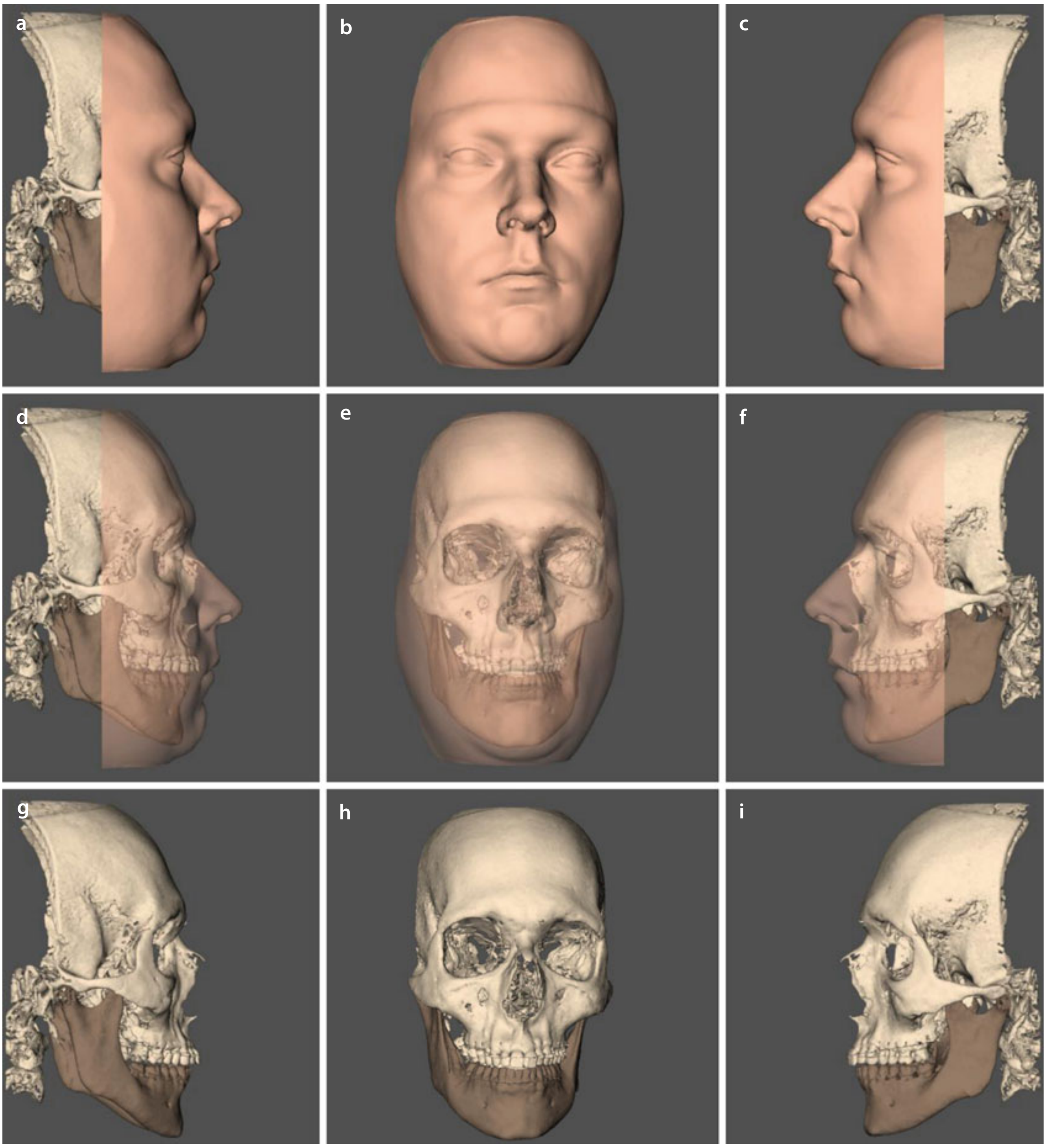


Fig. 1.20 Pre-surgical 3D "surface-rendered" AUM of the head following the "Triple Scan Protocol". Right profile (**a**, **d**, **g**), frontal (**b**, **e**, **h**) and left profile (**c**, **f**, **i**) views (i-CAT, Imaging Sciences International Inc., Maxilim v. 2.3.0.3., volunteer M.G.). Note the integration of accurate occlusal and intercuspidation data compared to Fig. 1.7. Also note the incorrect position and orientation of the patient's head although it was attempted to scan the patient in his correct NHP

3D Virtual Augmented Model (AUM) of the Patient's Head "without the Use of Plaster Dental Models"

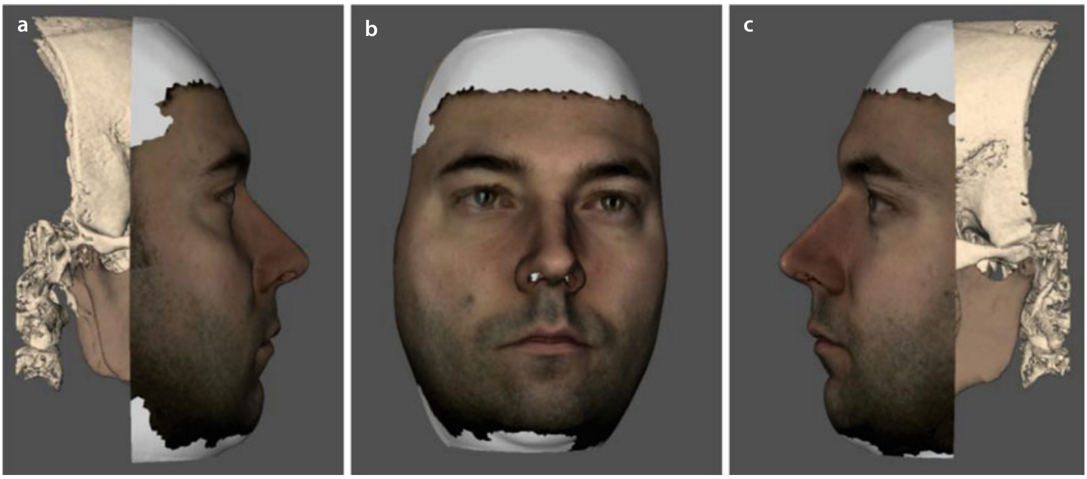


Fig. 1.21 Pre-surgical 3D "surface-rendered" AUM of the head following CBCT image acquisition (i-CAT, Imaging Sciences International Inc.) according to the "Triple Scan Protocol" with additional "surface-based rigid registration" of the 3D photograph (Planmeca ProMax® 3D Max, ProFace™, Planmeca Oy, Helsinki, Finland): right profile (**a**), frontal (**b**) and left profile (**c**) views (Maxilim v. 2.3.0.3., volunteer M.G.). Note the incorrect position and orientation of the head although it was attempted to scan volunteer M.G. in his correct NHP

Additional image acquisition (Sect. 1.1.3) and rigid registration of the texture of the patient's head is not essential for proper 3D virtual planning of orthognathic surgery (Fig. 1.21). Moreover, it is not recommended since it is still too error prone, too time consuming in the daily clinical routine and above can falsify the patient's 3D facial soft tissue mask.

It is therefore advised to use the CBCT 3D facial soft tissue mask for the following 3D virtual planning steps:

1. (3D-VPS_2) Definition of 3D cephalometric landmarks of the patient's soft tissues (► see also Sect. 2.2.3).
2. (3D-VPS_5) "Step-by-step" individualised 3D virtual treatment planning of orthognathic surgery (► see also Sect. 3.5).

However, additional image acquisition and rigid registration of the texture of the patient's head is certainly of interest in "Step 9 of 3D-VPS_5 – Patient Communication of the Individualised 3D Virtual Treatment Plan".