Department of Engineering Design and Production

Medical applications of additive manufacturing in surgery and dental care

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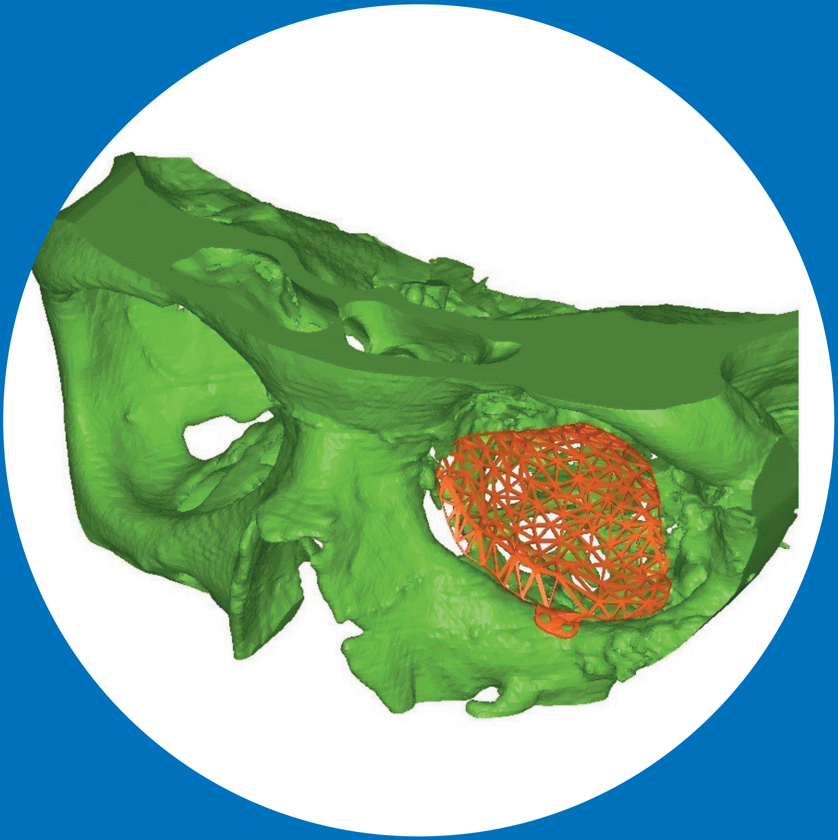
Mika Salmi



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Medical applications of additive manufacturing in surgery and dental care

Mika Salmi

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Abstract

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Abstract

At present handcrafting is still common in surgery and dentistry. The majority of patient specific implants are handmade during surgery and oral appliances are handmade by a dental technician in a dental laboratory. Surgical procedures are usually designed according to medical imaging, but during the surgery, plans are often changed due to issues that were not detectable from the two dimensional images. By using the modern digital technology it is possible to reduce or completely avoid manual work phases, and thus achieve remarkable advantages related to accuracy and speed.

Additive manufacturing is a material adding fabrication process, which suits for manufacturing objects with complex geometric shapes for either one piece or small series production. The parts are produced automatically according to a digital 3D model. By digitalizing the medical processes of additive manufacturing can be easily and rapidly performed. Therefore, it is a suitable manufacturing method in both surgery and dentistry.

This research concentrated on medical models and patient specific implants made by additive manufacturing, as well as oral appliances used in dentistry. The subjects included (1) medical 3D modeling and design, (2) applying various additive manufacturing technologies and (3) estimating the usability and dimensional accuracy of these processes. As a result a patient specific orbital floor implant and different oral appliances were produced using additive manufacturing and digital design. In addition the effects of different additive manufacturing methods for accuracy of medical models were studied. The results showed that additive manufacturing can be effectively utilized in surgery and dentistry, and patients' treatment results may improve when using the above methods.

Keywords 3D printing, rapid prototyping, rapid tooling, implants, medical models, occlusal splint, oral appliances

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Tiivistelmä

Kirurgiassa ja hammaslääketieteessä pääasiallinen työskentelytapa on käsityö, eikä digitaalisuuden kaikkia mahdollisuuksia vielä hyödynnetä. Kehittyneempiä tekniikoita kuten leikkausnavigointia, leikkausrobotteja ja digitaalista kuvantamista kyllä käytetään, mutta esimerkiksi potilaskohtaiset implantit kirurgi yleensä muotoilee käsin leikkauksen aikana tai käyttää valmiita implantteja, joista potilaalle valitaan sopivimman kokoinen ja muotoinen. Myös hammaslääketieteessä käytetyt suukojeet valmistetaan tavallisesti hammasteknikon toimesta käsityönä hammaslaboratoriossa. Leikkaukset suunnitellaan yleensä kuvantamistutkimusten perusteella, mutta leikkauksen aikana tulee usein esiin asioita, joita kaksiulotteisista kuvista ei pystytä havaitsemaan, ja näin ollen leikkaussuunnitelma voi muuttua leikkauksen aikana. Käyttämällä hyväksi digitaalisuuden tuomia mahdollisuuksia voidaan tuottaa 3D-malleja ja fyysisiä malleja potilaan anatomiasta, sekä vähentää tai poistaa kokonaan käsityövaiheita. Tämä nopeuttaa leikkausta ja parantaa tarkkuutta.

Materiaalia lisäävä valmistus on valmistusmenetelmä, joka soveltuu erityisesti monimutkaisten kappaleiden yksittäis- tai piensarjatuotantoon. Kappaleet tuotetaan automaattisesti digitaalisen 3D-mallin perusteella. Digitalisoimalla lääketieteen prosesseja voidaan materiaalia lisäävää valmistusta nopeasti hyödyntää. Se on myös erityisen sopiva valmistusmenetelmä lääketieteeseen, koska potilaiden tarpeet ovat erilaisia eivätkä samanlaiset ratkaisut sovellu kaikille.

Tässä tutkimuksessa keskityttiin materiaalia lisäävillä valmistustekniikoilla toteutettuihin lääketieteellisiin malleihin ja potilaskohtaisiin implantteihin sekä hammaslääketieteessä käytettyihin suukojeisiin. Tutkittuja aiheita olivat lääketieteellisten 3D-mallien muodostus, lääketieteellinen 3D-mallintaminen, eri valmistusmenetelmien soveltaminen ja prosessien käyttökelpoisuuden ja mittatarkkuuden arviointi. Työn tuloksena saatiin valmistettua ainetta lisäämällä toimiva yksilöllinen silmänpohjaimplantti, sekä erilaisia suukojeita. Tutkimuksessa selvitettiin myös eri materiaalia lisäävien valmistusmenetelmien tarkkuutta lääketieteellisten mallien valmistamiseen. Tulokset osoittivat, että tutkitut menetelmät tuovat uusia mahdollisuuksia potilaiden hoitamiseen ja mahdollistavat näin parempia hoitotuloksia.

Avainsanat 3D tulostus, pikavalmistus, implantit, lääketieteelliset mallit, purentakisko, suukojeet

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Preface

This study was carried out at the BIT Research Centre, Department of Industrial Engineering and Management, School of Science, Aalto University during the years 2009-2013. It was financed by the Finnish Funding Agency for Technology and Innovation (Tekes), DeskArtes Oy, EOS Finland Oy, Vektor Claims Administration, Planmeca Oy, Inion Oy and LM-Instruments Oy. I would like to express my sincere appreciation to all of these parties for financing and supporting this research.

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I wish to express my gratitude to the preliminary examiners Dr. Richard Bibb and Professor Paulo Bártolo for their valuable input in improving this thesis, and to Professor Antti Salminen for being the opponent. I thank Docent Vesa Saikko and Piritta Niemi for language checking as well as for their comments on the thesis.

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Finally, I thank my family and friends, who have always been there to support me and helped me keep my working life and private life in a balance. My parents, Katja, Harri, Piritta and Leo are all especially thanked.

Contents

List of original publications

This doctoral thesis is based on the following publications:

I Salmi M, Tuomi J, Paloheimo KS, Björkstrand R, Paloheimo M, Salo J, Kontio R, Mesimäki K, Mäkitie AA: Patient specific reconstruction with 3D modeling and DMLS additive manufacturing. Rapid Prototyping Journal 18:209-214, 2012.

II Salmi M, Tuomi J, Sirkkanen R, Ingman T, Mäkitie A: Rapid Tooling Method for Soft Customized Removable Oral Appliances. The Open Dentistry Journal, 6:85-89, 2012.

III Salmi M, Paloheimo KS, Tuomi J, Wolff J, Mäkitie A: Accuracy of medical models made by additive manufacturing (rapid manufacturing). Journal of Cranio-Maxillofacial Surgery, 41:603-609, 2013.

IV Salmi M, Paloheimo KS, Tuomi J, Ingman T, Mäkitie A: A digital process for additive manufacturing of occlusal splints: a clinical pilot study. Journal of the Royal Society Interface 10:20130203, 2013.

The publications are referred to in the text by their roman numerals.

Author´s contribution to the appended joint publications:

I-IV The design of the research plan was carried out by Mika Salmi in collaboration with the co-authors. Mika Salmi performed the experimental work and was responsible for investigating the patient data capturing, creating 3D models from the data, medical 3D modeling and selecting suitable AM technology and materials. He carried out the measuring method development as well as geometry evaluation with the help of co-authors. The results were interpreted together by the co-authors. Mika Salmi was the principal author and corresponding author of all the manuscripts.

Abbreviations

3D	Three dimensional
3DP	Three dimensional printing
AM	Additive manufacturing
CAD	Computer aided design
CAM	Computer aided manufacturing
CBCT	Cone beam computed tomography
CMM	Coordinate measuring machine
CT	Computed tomography
DICOM	Digital imaging and communications in medicine
DMLS	Direct metal laser sintering
EBM	Electron beam melting
ELI	Extra low interstitial
FDM	Fused deposition modeling
MRI	Magnetic resonance imaging
MSCT	Multi slice computed tomography
PEEK	Polyether ether ketone
PMMA	Poly(methyl methacrylate)
RP	Rapid prototyping
SL	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
STL-file	Stereolithography-file
Ti64 ELI	Titanium alloy Ti6Al4V with particularly low level of impurities
UV	Ultraviolet

1 Introduction

Traditionally medical devices are designed according to “an average person” because customized devices need to be specially handmade and are therefore costly. Currently, the majority of patient specific implants are handmade during surgery and oral appliances are handmade by a dental technician in a dental laboratory. The development of medical imaging, especially imaging software and digital three-dimensional (3D) scanning has made it possible to create various 3D models from medical images. These 3D models can be directly manufactured into physical objects using additive manufacturing (AM) or the 3D models can be used as a design template for personalized medical and dental devices. This obviates the handicraft and may result in more accurate and economical devices. Combining known techniques and novel design and manufacturing methods offers medical professionals new means to treat patients and to enhance their quality of life.

The increase of welfare in Western countries sets higher expectations for a better quality of life. But on the contrary, the ageing of the population sets its own challenges. The lifestyle of our Western society has dramatically reduced physical exercise and increased the amount of sedentary work. As a consequence, the physical condition of people is deteriorating causing various health issues, such as problems with back and joints, among many others. These challenges require new and improved medical devices and advanced manufacturing technologies. It is estimated that in the European Union the old-age dependency ratio will grow from 25 % in 2010 to 50% by 2050 (Eurostat 2013). Furthermore, in the US, China and India the old-age dependency is estimated to double during the next 40 years (United Nations 2012). Based on these figures, there is great potential for new technologies, such as AM.

Several terms are used for AM, for example rapid prototyping, layer manufacturing, freeform fabrication and rapid manufacturing. Since the inventing of first AM equipment in 1986, the development has been fast. In the field, there are at least 21 different technologies for AM such as stereolithography (SL), three dimensional printing (3DP), fused deposition modeling (FDM), PolyJet, electron beam melting (EBM), direct metal laser sintering (DMLS) among others and at least 36 systems manufacturers with different types of systems commercially available (Wohlers 2011). Accuracy of the AM processes and properties of material have significantly improved over the last 20 years, and due to these improvements, some materials in AM technologies nowadays meet the strict requirements set for material in medical devices. AM is superior in one-off production, since there is no need for tooling and objects are manufactured automatically. Thus AM has huge potential for the production of patient-specific medical devices. The newest, specific materials are biocompatible and some materials can be used for implantation purposes. However, most doctors and dentists are not even aware of this technology and the use of implants and devices produced with AM is not yet a standard clinical procedure.

In the present work an attempt is made to better understand the multidisciplinary process, which is needed to develop and evaluate digital manufacturing of medical and dental devices. It is a proof of concept that these processes and procedures are functioning on real patients with advantages compared to the standard processes used by hospitals and dentists. With more awareness and case studies this can be a major technical step in medical field development.

This research was carried out in Aalto University in two projects funded by Tekes (the Finnish Funding Agency for Technology). The projects Bioman II (2007–2010) and MedAMan (2010–2012) were carried out in cooperation with industry and hospitals, and the objective was to find new business opportunities for the Finnish industry and to solve problems arising from the clinical side. Papers I and II are based on the results of the Bioman II project and papers III and IV are based on the MedAMan project.

1.1 General aims of the study

The general aim of this Doctoral Thesis was to investigate the use of digital 3D modeling technology and AM to improve surgery and dental care processes. The processes were studied including all the phases from the beginning to the end. The use of AM technology can be divided into several steps, which were all investigated to obtain knowledge of the process:

i. Suitable software and hardware for digital imaging and data capturing were investigated to obtain data for patient-specific geometry. Communication with radiologists was essential to obtain high quality in imaging.
ii. Patient-specific data was transformed into a 3D model for the modeling phase. Suitable software and parameters were selected for each case.
iii. Medical 3D modeling was performed by utilizing a 3D model of a patient as a reference. Suitable software for each purpose is required. The 3D models were produced for AM without triangulating errors.
iv. The most suitable AM process and material were selected for each application.

1.2 Specific aims

The specific aims of this Doctoral Thesis can be divided in to the following sub-aims:

1. To develop a process to produce patient-specific implants using AM and data from computed tomography (CT) images. The process was tested from the beginning to the end with a patient in order to reduce manual work phases during surgery and operation time compared to the currently used methods to prepare patient-specific implants. Previously, cranial implants have been made using such a process (Poukens et al. 2008), but in this research the focus was in orbital implants requiring more accuracy. The geometry and macrostructure of the implant were optimized. The geometry included both the boundary surface to the bone and the functional form.

2. To study the accuracy of different AM methods in medical model production in order to understand the variations in different models, and to develop a suitable measuring method by taking into account special characteristics of AM. The accuracy has been previously investigated, but often using manual measuring equipment and repeatability has not been estimated (El-Katatny et al. 2010, Ibrahim et al. 2009, Silva et al. 2008). Therefore, the aim was to develop an automatic measuring method with high repeatability.

3. To investigate the use of a rapid tooling technique in order to produce soft orthodontic appliances utilizing a plaster model from a patient's teeth as a starting geometry and silicone as a material for the appliance. Hard aligners made by rapid tooling (Joffe 2003) are commercially available. Soft material may allow using fewer aligners and therefore reducing costs. And they have not been previously produced using rapid tooling. Therefore, the aim was to prove the concept for making soft aligners by rapid tooling.

4. To study the use of AM as a direct fabrication method for an occlusal splint by capturing data from a patient's plaster model, and to find a suitable material for the application. Computer-assisted method for design and milling of splints has been presented earlier (Lauren et al. 2008). Using AM for occlusal splint manufacturing has not been reported or studied. The aim was to reduce manual work phases for a more accurate and efficient production of occlusal splints.

1.3 Scientific contribution

This work showed that it is possible to utilize AM in surgery and dental care. Aa patient-specific orbital implant was produced using digital design and AM. There are some studies, which report the manufacturing of implants using AM, but that is still rare and the implant prepared in this study was one of the first orbital implants. The automatically generated and adjustable macrostructure of the implant was designed to allow cells and tissues to grow through the implant. The accuracy of three different AM technologies for medical model production was measured with the method developed as a part of this study. The previous accuracy studies did not discuss the repeatability of the measurements (El-Katatny et al. 2010, Ibrahim et al. 2009, Silva et al. 2008). The repeatability of the measuring method, which was developed in this study, was excellent with only minor variations in the repeated measurements.

Hard occlusion splints made by rapid tooling are commercially available, but it has not been used to manufacture soft occlusion splints. Individualized soft occlusion splints have not been published earlier. In this study a functional occlusion splint was made by AM and clinically tested on a patient with promising results. This was one of the first occlusion splints directly produced using AM and tested on a patient for a period of six months. No tooth wear, significant splint wear or other problems were detected during the test period. At the follow-up visits less grinding was needed compared to standard splints. Multidisciplinary cooperation with surgeons and dentists was established.

The author’s scientific contribution during this research was to investigate the patient data capturing, to create 3D models from the patient data, to perform medical 3D modeling, to select the suitable AM technology and material for specific purposes and measure, and to evaluate geometry of the manufactured part.

2 Background

2.1 Classification of medical applications of additive manufacturing

During the recent years more and more medical applications of AM have been developed and reported. This research area is challenging because the development is always a multidisciplinary process and includes work related to medical imaging, 3D modeling, medical treatment and the actual AM technology. There is a number of requirements related to AM technology when applying it in the medical field. Therefore, an application-based classification system for medical applications is needed. Hopkinsson et al. (2006) categorized medical applications to: presurgery AM, orthodontics, drug delivery devices, limb prostheses and *in vivo* devices. Gibson et al. (2009) defined the categories as: surgical on diagnostic aids, prosthetics, manufacturing, tissue engineering and organ manufacturing. More and more new applications are emerging without belonging to these categories. Medical implants can be defined as devices placed either inside or on the surface of the body to accomplish a particular function, such as to replace, assist or enhance the functionality of some biological structures (Bartolo et al. 2012). These can be categorized to: external to body, temporally internal to body and permanently internal to body (Bartolo et al. 2012). One of the most recent attempts to classify the whole area of medical applications of AM uses the following five categories (Tuomi et al. 2010):

1. Medical models for preoperative planning, education and training.

   These models can be used for planning or simulating the surgery preoperatively. The models can be used for educating students as well as patients and families and for surgical training purposes. Depending on the application different qualities of the models such as anatomical accuracy, material characteristics and haptic response of the model are important.

2. Tools, instruments and medical device parts

   AM is used to create tools and hardware for medical applications. Drilling, sawing and cutting jigs belong to this class. Manufacturing of operation or patient-specific instruments or preforms are included in this category (Kontio et al. 2012). Parts in this class can be invasive but not implantable.

3. Medical aids, supportive guides, splints and prostheses
   AM technologies are utilized for anatomic personalization of a device or corresponding element. For example prosthetic sockets, appliances for dental malocclusion and patient-specific external ankle support (Björkstrand et al. 2010) belong to this category. Drill-guiding microtables belong to this class and devices in this class are external to body and non-invasive.

4. Inert implants
   Implants in this group are usually made of an inert metal or alloys, such as titanium or cobalt-chrome alloy. The implants may be created based on medical imaging and 3D modeling. Inert implants can be manufactured directly or indirectly by manufacturing a mold with AM. This class includes dental crowns and bridges.

5. Biomanufacturing
   Biomanufacturing combines AM and tissue engineering to produce biologically active implants, tissues and organs. This group includes biologically compatible parts such as tissues and reactive implants. In addition, biocompatible scaffolds and culture media used for tissue growth belong to this class. Fox example, AM can be used to produce scaffolds from polylactic acid or polycaprolactone (Mäkitie et al. 2013). Tissues can be externally grown or they can be the patient’s own. Contrary to the inert implants, reactive implants react with the body, such as by dissolving over time or by releasing drug in a controlled manner. Scaffolds can be used as a skeleton, providing support for cell growth, protection from external physical forces and as an optimal medium for 3D culture of cells (Yan et al. 2003). Culture media with a desired shape or form can be manufactured with AM technologies. Research in the field of direct AM of tissues is rapidly increasing (Hutmacher et al. 2004; Wang et al. 2006; Xu et al. 2007). The development of an innovative biomedical system can be a major breakthrough in the healthcare industry (Mitsuishi et al. 2013).

Categories 1, 3 and 4 are discussed in more detail in the following chapters, as the model of the patient orbital (Paper I) and skull models (Paper III) belong to class 1, directly and undirectly manufactured oral applications (Paper II & IV) belong to class 3, and orbital implant (Paper I) belongs to class 4.

2.2 Medical models

Medical models are physical objects that can be cut or sawn. It is possible to draw on the model with pencil to visualize section plans. Medical scan data from CT, magnetic resonance imaging (MRI), ultrasound, optical or laser scanner can be transformed to 3D surface model using segmentation, and after that used to produce physical models with AM techniques for use in surgery or prosthetic rehabilitation (Bibb 2006). Medical models made by AM can be used to help planning or simulating difficult phases of surgical operations (McDonald et al. 2001). Because of this preoperative planning, the use of these medical models can significantly reduce the operating time (D'Urso et al. 1999). In cosmetic surgery, harmonious facial contour can be achieved by planning cutting lines of jawbone preoperatively (Jiang et al. 2012). The medical models can be used as a template for pre-bending reconstruction plates (Lethaus et al. 2012) or custom implant manufacturing by taking a silicone mold from it for casting (Eppley 2002). It is possible to preoperatively pre-shape a titanium mesh for orbital wall reconstruction over a medical model (Kozakiewicz 2009 & 2011). Customized reconstruction plates can be manufactured according to a medical model by forming a wax over it and applying a casting technique using a metal alloy (Klammert et al. 2009). Medical models can be used for communication with students, patients, and families in procedures such as a temporal bone dissection (Mäkitie et al. 2008). AM can improve students' understanding of human anatomy by bringing the anatomical variations from the clinics into preclinical studies (Rengier et al. 2010). Different properties of the models such as anatomical accuracy, material characteristics or haptic response depend on the application. A haptic response similar to a bone is especially desirable in surgical training models (Mäkitie et al. 2008).

The process of making medical models involves various steps, each of which can be a source of errors. The imaging, segmentation and manufacturing phases can all contribute to the errors. In each phase the size or the shape can go wrong. Medical skull models can vary markedly depending on the DICOM to STL conversion software and the parameters used (Huotilainen et al. 2013). Significant errors can arise from CT data import, CT gantry tilt distortion, model stair-step artefact, irregular surface from support structures and mathematical modeling, metal and movement artefacts as well as image threshold (Winder & Bibb 2005). Communication between surgeons, radiologists and engineers is crucial. For example, images are taken using a thin slice thickness, but when archived, only half of the slices are saved to save storage capacity (Huotilainen et al. 2013). Choi et al. (2002) measured the skull in three phases: dry cadaver skull, 3D model from CT images and SL model, and found that errors between the dry skull and the 3D model was greater than between the SL model and the dry skull. This means that the errors in the middle of the process are larger than in the end, which can be explained by that the errors in different phases are compensating each other's. Errors of several millimeters were found when using cadaver skulls with soft tissues (Chang et al. 2003). El-Katatny et al. (2010) used digital calibers to measure the margin between a 3D model of a skull and a mandible compared to physical models made using FDM. Errors were some tenths of millimeters. Substantially less accuracy was found when comparing a dry cadaver bone to a replica made by AM (Ibrahim et al. 2009; Silva et al. 2008). Nizam et al. (2006) found small differences but with high standard deviation when measuring distances between different anatomical landmarks from a dry cadaver skull and a SL model. Some studies state that such a high accuracy is not needed for AM because the data from the 3D imaging is less accurate (Gibson et al. 2006), but the fast development of imaging has changed this.

The imaging method and parameters affect the quality of images and therefore the accuracy of the medical model. The accuracy of five cone beam computed tomography (CBCT) devices and one multislice computed tomography (MSCT) device have been compared for the imaging of anatomical structures (Liang et al. 2009a, 2009b). CBCT image quality was comparable to those obtained using MSCT technology, but there were some variations between the CBCT devices in delicate structures. The accuracy of MSCT device was better (mean deviation 0.137 mm) compared to the CBCT devices (mean deviation ranged from 0.165 mm to 0.386 mm). The partial volume effect related to the limited resolution occurs during the imaging and can make 3D model from facial structures unreliable and the thin walls of the cavities in the skull tend to disappear from the image (Lamecker et al. 2007). When measuring linear distances between anatomical landmarks from a dry skull and a 3D virtual model made using CBCT images, the measurement uncertainty was much higher for the 3D model (Periago et al. 2008). This may be explained by that it is difficult to select an exact point from the 3D model without a special software. The accuracy of combining helical CT and the 3DP method by changing the threshold value of the segmentation process produces a difference in the range of tenths of millimeters (Naitoh et al. 2006). The accuracy of a conversion from CT images to 3D reconstruction varies between conversion parameters (Mallepree and Bergers 2009).

2.3 Medical aids, supportive guides, splints, and prostheses

AM is utilized for anatomic personalization of a device or a corresponding element. Making prosthetic sockets has traditionally been labor intensive, taking two to three days per socket. By using computer aided manufacturing systems and AM technologies the time is reduced to less than 4 hours (Ng et al. 2002). Microtable drill guides made by AM were used in five cochlear implant surgeries and they reduced the operation time and overall costs (Labadie et al. 2008).

Wax patterns for facial prostheses produced by AM have been found to be more accurate than a conventional duplication (Sykes et al. 2004). An obturator prosthesis made from poly(methyl methacrylate) (PMMA) has been manufactured by using an AM model as a mock up (Lethaus et al. 2010). In addition, for facial prostheses laser surface digitizing with computer-aided design (CAD) and computer aided manufacturing (CAM) technologies has been successfully used (Cheah et al. 2003a&b). Facial prostheses can be fabricated more precisely using optical 3D imaging and CAD/CAM systems than conventional manual sculpturing techniques (Feng et al. 2010). Photography-based 3D imaging system has been found sufficiently accurate for clinical description of the mid-face structures and potentially useful for AM of facial prostheses (Kimoto et al. 2007). AM and 3D reconstruction from CT images have been used for fabricating dental splints for orthognathic surgery (Yanping et al. 2006). It has been considered that after CAD/CAM systems AM is the next revolution in dental device manufacturing (Van Noort 2012).

Occlusion splints and oral appliances are categorized in this group. The traditional protocol to fabricate oral appliances includes alginate impressions and wax registrations taken by a dentist and the appliance is made by a dental technician. 3D-CAD allows a greater use of industrially manufactured appliances while taking into account the biomechanics (Vassura et al. 2010). The prenatal development of the human temporomandibular joint has been monitored using computer-aided graphical 3D-reconstruction (Radlanski et al. 1999). Geometric copies of tooth roots have been manufactured using a combination of CT and AM (Lee et al. 2006). The first and the best known combination of CAD/CAM technologies in odontology is Cerec (Siemens, Germany) to produce ceramic inlays (Pallasen and Van Dijken 2000). Clear and hard tooth aligners can be digitally manufactured by first digitizing the teeth, then straightening them virtually by a computer, and further producing a mold by AM for pressure forming (Lin 2005). Lauren et al. (2008) digitalized the teeth from stone casts and virtually adjusted them by a computer. They used milling as the manufacturing method for these hard occlusal splints. AM can be used in a treatment of dental malocclusion by making a mold for a series of transparent and removable appliances (Miller et al. 2002). Hard appliances are made by the following method: digitalizing the tooth, virtually straightening the tooth, making a mold by AM, pressure forming and finishing the appliance (Joffe 2003). On the other hand, a soft appliance, which guides the eruption of the teeth, has been found an effective method to achieve normal occlusion for children and to eliminate the need for further orthodontic treatment (Keski-Nisula et al. 2008).

The accuracy of different CAM systems varies from the best mean value 58 μm to the worst ones 183 and 206 μm (Kohorst et al. 2009). The accuracy of a plaster model scanning and producing plaster replica by AM have been tested with four different digitizing systems and eight different combinations of AM technology with various materials, but since there is no reference models for non-standard shapes, an absolute accuracy value for the scanning process cannot be stated (Germani et al. 2010). CT imaging has been combined with an optic plaster model scanning to obtain a virtual model with accurate teeth and jaws for occlusion control. Jaws can be repositioned virtually and according new position a splint for orthognathic surgery can be manufactured with a 3D printer or subtractive manufacturing (Metzger et al. 2008).

2.4 Inert implants

One method for manufacturing patient-specific implants is a preoperative fabrication of a wax pattern on a skull model and using conventional dental replication methods (D'Urso et al. 2000a; Al-Sukhun et al. 2006) A silicone mold can be formed over a preoperative model and used for casting (Eppley, 2002). A digitally designed implant can be used as a positive part for silicone rubber mold, which in turn can be used for creating an implant by casting (Singare et al. 2005) or as a pattern in investment casting (Singare et al. 2009).

A reconstruction of a skull has been performed successfully using digital design and AM (Poukens et al. 2008, Rouse 2009). Cranial plates for direct implantation have been digitally designed and made using AM (Janssens & Poukens 2007). Traditional machining methods can be used in digitally designed patient-specific implants manufacturing by using CT images as a design reference (Poukens et al. 2008). Implants can be manufactured directly from metal alloys using direct metal laser sintering (DMLS) or electron beam melting (EBM) (Lethaus et al. 2011, Ciocca et al. 2011). Machined polyether ether ketone (PEEK) plastic has been used in implants for humans (Lethaus et al. 2011) and laser sintered PEEK tested in pigs without complications (Von Wilmonsky et al. 2009). Customized porous scaffolds, in which bone tissues can grow, has been studied to be manufactured using selective laser melting (SLM) (Warnke et al. 2009).

An orbital prosthesis has been produced using digital design and creating a wax model by AM to produce a physical pattern that could be used in the conventional prosthesis manufacturing process (Evans et al. 2004). Custom-made titanium orbital floor prosthesis has been manufactured with the help of SL. First a medical model of an orbital fracture is made by SL and repaired in the medical model using wax. Second silicone mold is taken from SL model and the mold is used to replicate the repaired orbital floor from plaster material. And finally plaster model is covered a layer of titanium using pressure flask and trimmed, polished as well as sterilized (Hughes et al. 2003). A flow chart of the different routes to produce personalized implants from polymers, metals or ceramics is shown in Figure 1.

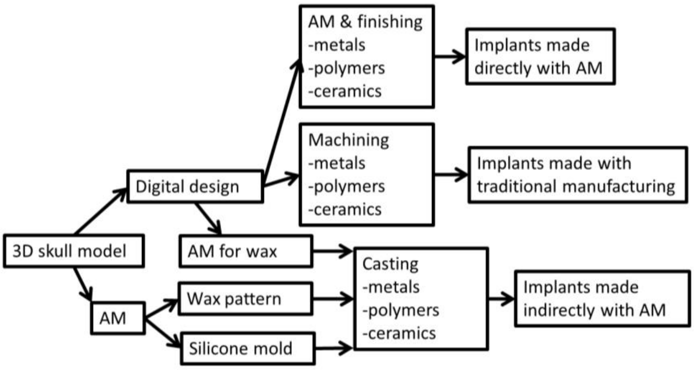

Figure 1 *Example of different routes to produce customized implants.*

2.5 Additive manufacturing

AM is a process, where parts are manufactured directly from a digital 3D model by adding material, usually on a layer by layer basis as opposed to subtractive manufacturing methods, such as traditional machining (ASTM 2012). According to ASTM, AM processes can be divided into the following categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization.

2.5.1 Binder jetting

In a binder jetting process a liquid bonding agent is selectively deposited to join powder materials (ASTM 2012). Additional support structures are not needed as the powder supports the part that is being built. Materials range from gypsum powder to metal powders. The process is not very costly, but material properties of the parts are not superior to other AM processes. Binder jetting is commercially used for example by Z Corporation and ExOne.

2.5.2 Directed energy deposition

In direct energy deposition process the focused thermal energy is used to fuse materials by melting as they are being deposited (ASTM 2012). Additional support structures are not needed because the building platform has four or five axial movement. Usually the produced parts need further processing, such as machining or polishing. Direct energy deposition is commonly used for repairing existing objects. Currently only metals are used as the materials. The process is expensive and the surface quality is low, but the material properties are excellent. Directed energy deposition is commercially used for example in Optomec's LENS process.

2.5.3 Material extrusion

In a material extrusion process the material is selectively dispensed through a nozzle (ASTM 2012). Additional support structures are needed for overhanging features. The produced objects need post-processing, at least the removal of the support structures. Thermoplastics are the most commonly materials. The process is not expensive but it is slow and the surface quality is low. On the other hand, the material properties are good. Material extrusion is commercially used for example in Stratasys's FDM process.

2.5.4 Material jetting

In the material jetting process droplets of build material are selectively deposited (ASTM 2012). If overhanging features are used, there is a need for support structures. The produced parts usually need post processing such as support removal or curing. Materials are commonly photopolymers or waxes. Process is moderate price and surface quality is good. Material properties are low. Commercially material jetting is used example Objet in Polyjet process.

2.5.5 Powder bed fusion

In powder bed fusion process thermal energy selectively fuses regions of a powder bed (ASTM 2012). For plastics there is no need for support structures since powder can support overhanging features, but metals need support structures because of thermal tensions. Metal parts need support removal and plastic parts can often use direct after cleaning from powder. Material ranges from technical plastis to metals. Process is expensive, but material properties of parts are excellent compared to other processes. Commercially powder bed fusion is used example in SLS and DMLS processes.

2.5.6 Sheet lamination

In sheet lamination sheets of material are bonded to form an object (ASTM 2012). There is no need for support structures but support removal may be troublesome. Material ranges from paper to plastic and to metal. Process is cheap, but material properties are poor in layer direction. Commercially sheet lamination is used example in Mcor paper printing process and in Fabrisonic metal printing process.

2.5.7 Vat photopolymerization

In vat photopolymerization liquid photopolymer in a vat is selectively cured by light-activated polymerization (ASTM 2012). There is need for support for overhanging features. Parts need post processing. Material ranges are photopolymers. Process is expensive, but very accurate. Material properties of parts are average compared to other processes. Commercially vat photopolymerization is used example 3D Systems SL equipments.

3 Materials and methods

3.1 Medical imaging and digital 3D scanning (Papers I-IV)

Medical imaging is used to noninvasively create images from the inside of a human body. The most commonly used imaging methods are ultrasound, X-ray, CT, MRI and nuclear medicine imaging. All these techniques produce digital imaging and communications in medicine (DICOM) images, which is a standard format in medical imaging. In implants, GE LightSpeed QX/I CT (General Electric Company, Fairfield, USA) was used with a slice thickness of 1.25 millimeters. Accuracy was studied with OsiriX DICOM sample Phenix image set (www.osirix-viewer.com/datasets/DATA/PHENIX.zip), with a slice thickness of 1.5 millimeters.

Digital 3D scanning is a method where the surface of an object is digitized. In medical or dental field this can be done directly or indirectly. Teeth can be scanned directly from the mouth using intraoral scanner or by taking a plaster model and scanning it. The used scanners, for dental models were GOM ATOS (GOM GmbH, Braunschweig, Germany) and 3Shape D710 Multi Die Scanning (3Shape A/S, Copenhagen, Denmark). GOM ATOS was used for geometry and accuracy verification of the occlusal splint and the oral appliance. The technologies used for geometry capturing are presented in Table 1. All of these methods produce triangulated 3D surface models, which contain triangulating errors.

Table 1 *The technologies used for geometry capturing.*

Technology / Source of data	Purpose
CT (slice thickness 1.25 mm) / patient	To determine patient's orbital geometry for reconstruction **(Paper I)**
CT (slice thickness 1.50 mm) / Phenix sample image set	To create a 3D skull model for accuracy measurements **(Paper III)**
GOM ATOS / plaster model from teeth	To capture tooth geometry to a mold for the manufacturing of a soft oral appliance **(Paper II)**
GOM ATOS / the soft oral appliance	To verify the geometry of the soft oral appliance **(Paper II)**
3Shape D710 Multi Die Scanning / plaster model from teeth	To capture tooth geometry to produce an occlusal splint **(Paper IV)**
GOM ATOS / the occlusal splint	To verify the geometry of the occlusal splint **(Paper IV)**

3.2 3D reconstruction and STL-file fixing (Papers I-IV)

DICOM images were reconstructed to 3D models in stereolithography format (STL format) using Osirix (open source, http://www.osirix-viewer.com) software. STL is a file format, where an unstructured, triangulated surface is described by the unit normal and vertices. 3D reconstruction was based on creating voxels (3D equivalent of a pixel) between image slices and using a selected value for the variation of density intensity. Each corner point of the voxels was examined. If the density of the voxel corner point was higher than the selected density intensity, the corner point was included in the 3D model, and vice versa. Based on the density of the corner points, surface triangles were created inside the voxel, and after all of the voxels were examined, the surface triangles covered the whole 3D model. In accuracy measurements and in the orbital reconstruction DICOM images were segmented to 3D models using 500 Hounsfield unit value.

3D models from medical imaging or digital scanning contain errors. These errors include gaps, flipped normals and triangulating errors. Before the 3D models can be manufactured using AM, errors must be repaired. These errors can be automatically or manually corrected using specified software. STL files were repaired using 3Data Expert

(DeskArtes Oy, Espoo, Finland) and Viscam RP 4.0 software (Marcam Engineering GmbH, Bremen, Germany).

3.3 Medical modeling (Papers I-IV)

Medical modeling includes creating and modifying geometry according to the data received from the 3D reconstruction. There is a need to perform different operations, such as surface modeling and Boolean operations, but so far no software includes all the needed features. Surface modeling is needed when a new geometry is created and Boolean operations are required for modifying this geometry to fit the patient. Minor editing of the triangulated surface is usually needed. There is a possibility to automatically transfer the surface to a volumetric net structure to allow tissue cells to grow through the structure. The software and purpose of the use are summarized in Table 2.

Table 2 *The used software for various purposes of medical modeling*

Software	Purpose of use
Rhinoceros 2.0 (McNeel Europe, Barcelone, Spain)	Surface modeling
3Data Expert beta version (DeskArtes Oy, Espoo, Finland)	STL-repair Convert surface to volumetric net Boolean operations Measurements
Pro Engineer Wildfire 4.0 (Parametric Technology Corp, Needham, USA)	Repositioning of teeth Placing the measurement balls
Viscam RP 4.0 (Marcam Engineering GmbH, Bremen, Germany)	STL-repair Cutting models, separating parts Smoothing, reduce triangles surface extruding Boolean operations Measurements

In accuracy measurements six measuring balls (Ø 10 mm) were attached to the 3D skull model, and the coordinates of the center points of these balls were determined. The distances between the balls were calculated from the coordinates. The locations of the balls are shown in Figure 2.

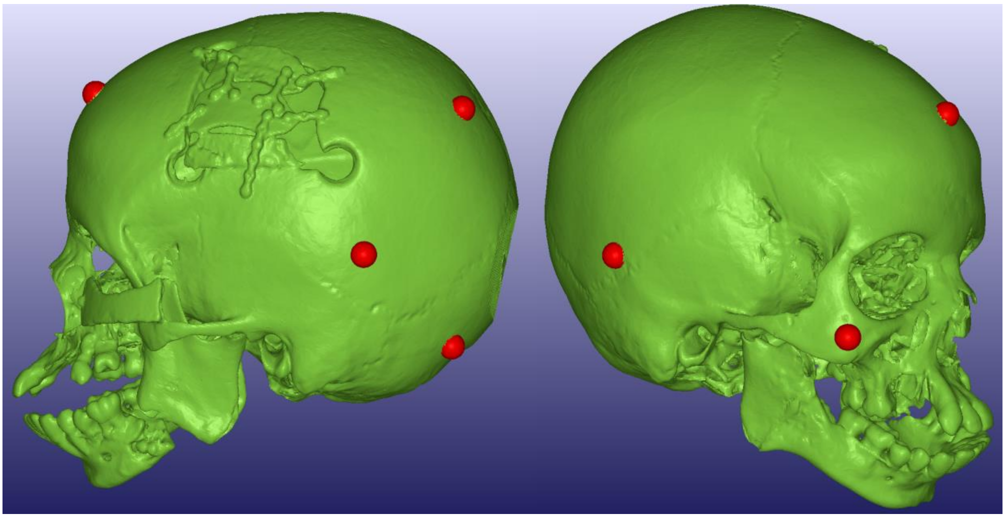

Figure 2 *The locations of measurement balls on a human 3D skull model (Paper III).*

Three versions of the 3D skull model were created for the accuracy experiments: “original”, “moderate” and “worse”. Moderate and worse models were created by reducing the accuracy of the original model by decreasing the tolerance of the STL model using Viscam RP 4.0 software (Marcam Engineering GmbH, Bremen, Germany). The tolerance is determined with the maximum distance and the angle between the new and the old triangle surface. For the moderate model, the tolerance was 3 millimeters, 10º and 50 steps and for the worse model millimeters, 15º and 50 steps. Angle deviation was dominating when decreasing tolerances.

3.4 Additive manufacturing (Papers I-IV)

AM technologies can be widely used in medical applications. In Table 3 the equipment, materials, technologies, purpose of use and parameters for AM used in the present study are shown.

Table 3 *The equipment, materials, technologies, purpose of use and parameters of AM technologies used in the present study.*

Equipment and material	Manufacturing technology	Purpose of use	Layer thickness (µm)
EOSINT M270 Ti and EOS Titanium Ti64 ELI (EOS GmbH - Electro Optical Systems, Krailling, Germany)	DMLS	Implant for orbital reconstruction **(Paper I)**	30
EOSINT P380 and SLS2200 (EOS GmbH - Electro Optical Systems, Krailling, Germany)	SLS	Preoperative medical model of the orbita **(Paper I)** SLS [models A & B] medical skull model for accuracy measurements **(Paper III)**	150
Objet Eden 350V and VeroWhite FullCure 830 (Objet Ltd, Rehovot, Israel)	PolyJet	Objet medical skull model for accuracy measurements **(Paper III)**	16
Zprinter 450 and ZP 150 (Z Corporation, Burlington, USA)	3DP	3DP (original, moderate, worse) three medical skull models for accuracy measurements **(Paper III)**	90
SLA 350 and Somos ProtoGen O-XT 18420 (3D Systems, Rock Hill, USA) and (DSM Functional Materials, Elgin, USA)	SL	Mold for soft oral appliance **(Paper II)**	50
SLA 350 and Somos WaterShed XC 11122 (3D Systems, Rock Hill, USA) and (DSM Functional Materials, Elgin, USA)	SL	Occlusal splint **(Paper IV)**	50

3.4.1 3D Printing (Paper III)

In 3DP an inkjet-like printing head moves over a powder bed and deposits a liquid binder material in the shape of the cross-section of the part being manufactured. After that a new layer of powder is spread over the previous one and new cross section printing starts. After manufacturing these parts need to be cleaned and post processed adding a hardener and drying in an oven. The systems used for medical skull models were Zprinter 450 (Z Corporation, Burlington, USA) with a layer thickness of 0.09 millimeters. ZP 150 powder (Z Corporation Burlington, USA) was used as the material. 3DP was selected to accuracy measurements since it is commonly used in medical models because of colors, no need for support structures and low cost as compared with other AM processes. 3DP does not have biocompatible material options.

3.4.2 Selective laser sintering (Papers I & III)

Selective laser sintering (SLS) uses a laser for sintering plastic powder layer by layer. At first, a layer of powder is spread on the building platform with a roller or a sweeper. In the next step, the laser sinters the powder to form the geometry of a specific layer. After these steps, the building platform is descended by one layer and the process starts over. The finished parts need to be cleaned from powder, but no other post-processing is needed.

The manufacturing system for preoperative orbita model and two medical skull models was EOSINT P380 (EOS GmbH - Electro Optical Systems, Krailling, Germany) and the material used was fine polyamide PA 2200 (EOS GmbH - Electro Optical Systems, Krailling, Germany). The layer thickness was 0.15 millimeters. SLS was selected for the preoperative orbita model because of the overhanging features in orbita bottom were thin. SLS is commonly used in medical models as it does not require post-processing or support structures, and therefore it was selected in accuracy measurements. There are biocompatible material options for SLS, such as PA 2200.

3.4.3 PolyJet (Paper III)

PolyJet is a method, which uses a jetting head to deposit UV light curable photopolymer at a desired place. After the layer has been deposited, the building platform is descended by one layer and a new layer can be deposited. UV light is used to cure the UV photopolymer. The parts need support structures and post processing.

The medical skull model was manufactured with Objet Eden 350V (Objet Ltd, Rehovot, Israel) from VeroWhite FullCure 830 (Objet Ltd, Rehovot, Israel). The layer thickness was 0.016 millimeters. Polyjet was selected because of its potential for greater accuracy with higher costs. Nowadays there are biocompatible material options such as MED610 (Objet Ltd, Rehovot, Israel).

3.4.3 Stereolithography (Papers II & IV)

SL is an AM technology, where parts are built layer by layer by curing a photopolymer with an UV laser. The shape of the cross-section is traced out on the surface of a liquid resin using a laser beam. After finishing the layer, the building platform is descended by one layer. A schematic figure of the SL process is shown in Figure 3. SL is one of the most accurate AM processes but more expensive than most others. The process requires support structures and post processing.

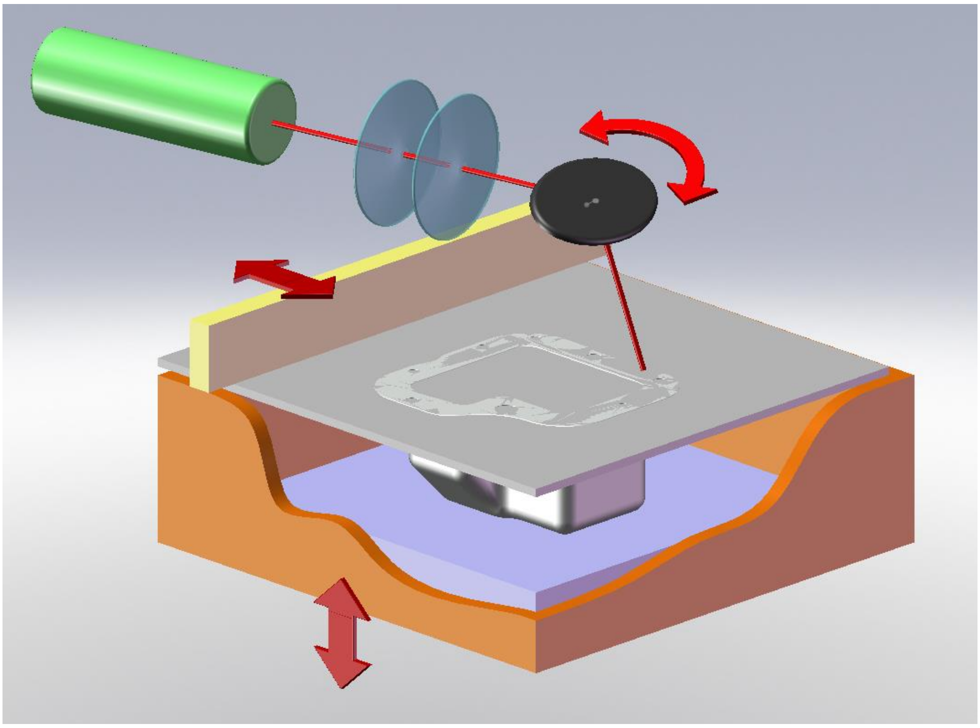

Figure 3 *A schematic presentation of a stereolithography process.*

SL was used for manufacturing a mold for the soft orthodontic appliance and as a direct fabrication method for occlusal splints because of the need for high accuracy. The device for both applications was SLA 350 (3D Systems, Rock Hill, USA). Somos ProtoGen O-XT 18420 (DSM Functional Materials, Elgin, USA) was chosen for the material for mold because it has a very low shrinkage and it can withstand the hot temperatures (80 ºC) needed in the casting phase. After manufacturing the mold was placed in a postcure apparatus for 60 min. The mold was heat treated and covered with a lacquer. Silicone was used as the casting material. The occlusal splint was made from the Somos WaterShed XC 11122 (DSM Functional Materials, Elgin, USA), because it fulfills the ISO 10993-5 Cytotoxicity, ISO 10993-10 Sensitization and ISO 10993-10 Irritation regulations and has USP Class VI approval. After the manufacturing, the splint was soaked in isopropanol for 20 min and any excess resin was scrubbed off. Dry, compressed air was used to blow excess solvent away from the surfaces. The splint was placed in a postcure apparatus for 60 min after cleaning. The layer thickness for both applications was 0.05 millimeters.

3.4.5 Direct metal laser sintering (Paper II)

DMLS is a layer by layer process that uses a laser for sintering metal powder. The process consists of three steps: (1) a layer of powder is spread on the building platform with a sweeper, (2) the laser sinters the powder at the desired places, and (3) the building platform is descended by one layer and then continues from the beginning. The manufacturing system for implant was EOSINT M270 Ti (EOS GmbH - Electro Optical Systems, Krailling, Germany) and selected material EOS Titanium Ti64 ELI (EOS GmbH - Electro Optical Systems, Krailling, Germany) because it fulfills mechanical and chemical requirements of ASTM F 136 standard for surgical implants. Ti64 ELI is a pre-alloyed Ti6AlV4 alloy with particularly low levels of impurities. The layer thickness was 30 µm. Laboratory results from test piece confirm compliance with ASTM F 136 requirements. After manufacturing the implant was polished and sterilized using an autoclave. DMLS was selected for implant manufacturing because of its accuracy compared to other metal AM processes.

3.5 Coordinate measuring machine (Paper III)

A coordinate measuring machine (CMM) ZEISS C 700 (Carl Zeiss AG, Oberkochen, Germany) was used for accuracy measurements. The measuring tip was a touching RENISHAW PH 1 (Renishaw Plc, New Mills, United Kingdom). The diameter of the ruby measuring head was 4 millimeters and the measuring force was 68.7 mN. The used measuring software was Calypso 4.4.04.01 (Carl Zeiss AG, Oberkochen, Germany). The resolution for CMM was 0.1 micrometers and the accuracy was ± 2 + L/200 micrometers, where L is the measured length. The measuring and the object attachment setting are shown in Figure 4. A measuring program for the CMM was used to repeat the same measurements automatically. This eliminates the error caused by the measurer, and therefore repetitions of the measurements by multiple persons are not needed. Before each measurement, each skull was positioned in nearly same position and the CMM was used to locate the exact position of the measured skull. When the exact position of the skull was known, the program performed the measurements. There was a ball-to-ball contact between the measuring balls and the measuring head and the exact location of this contact varied. However, the distance between the measuring balls and the measuring head was exactly determined. The center points of the measuring balls were determined with multiple measurements of the distance between the measuring balls and the accurate location of the measuring head. The location of each measuring ball was determined with 12 measurements. After the first measurements, the medical skull models with highest and lowest maximum error were remeasured to verify the repeatability of these measurements.

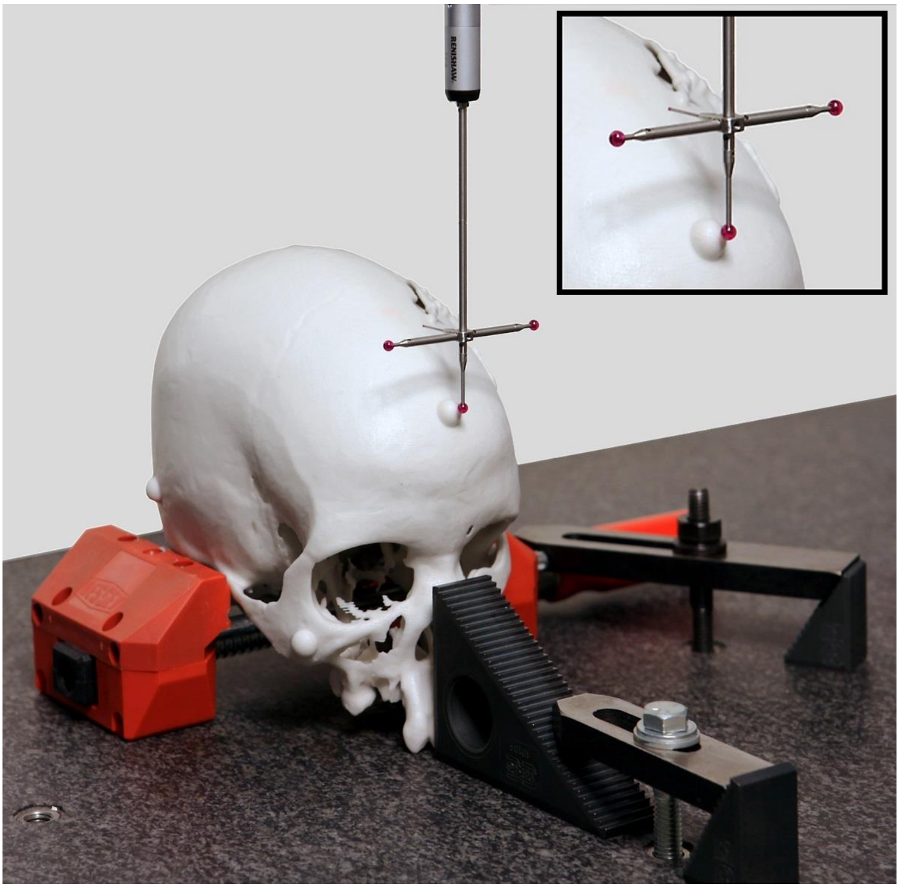

Figure 4 *Measuring attachment in accuracy measurements of medical models. (Paper III)*

As there were only two repeated observations, repeatability (Eq.1) was estimated by calculating the standard deviation of the obtained results and using a confident factor of 7 according to ISO/IEC 17025:2005.

$$repeatability\ (\%) = \overbrace{confident\ \ factor}^{=7} \times \sqrt{\sum_{i=1}^{n} (\frac{(measured\ value_i - average\ of\ measured\ values)^2}{(number\ of\ measurements - 1)}} \tag{1}$$

The diameters and center locations of the measurement balls were obtained from the measuring software. From the center locations of the measurement balls the distances between measuring balls were calculated. The calculations were compared to the distances measured from the 3D models. From the differences absolute value was taken and average error and standard deviation for error were calculated.

4 Results and discussion

4.1 Accuracy of medical skull models (Paper III)

When comparing the accuracy of PolyJet, 3DP and SLS for medical skull model fabrication, the dimensional error of the PolyJet model was the smallest: 0.18 ± 0.12% (average ± standard deviation) for the first measurement and 0.18 ± 0.13% for the repeated measurement. The error for SLS model was 0.79 ± 0.26% for the first model and 0.80 ± 0.32% for the second model. The error for 3DP was 0.67 ± 0.43% for the first measurement of the original model, 0.69 ± 0.44% for the repeated measurement of original model, 0.38 ± 0.22% for the moderate model and 0.55 ± 0.37% for the worse model. The repeatability of the used measurement method was 0.12% for the PolyJet and 0.08% for the 3DP. The repeatability of measurement for measuring ball diameters was 0.1 millimeters. The maximum, average and standard deviation for linear errors in the skull models are shown in Figure 5. The standard deviation represents the quality of the AM models, not the quality of the measuring method. In table 4, the results of this study are compared with the results obtained from the literature.

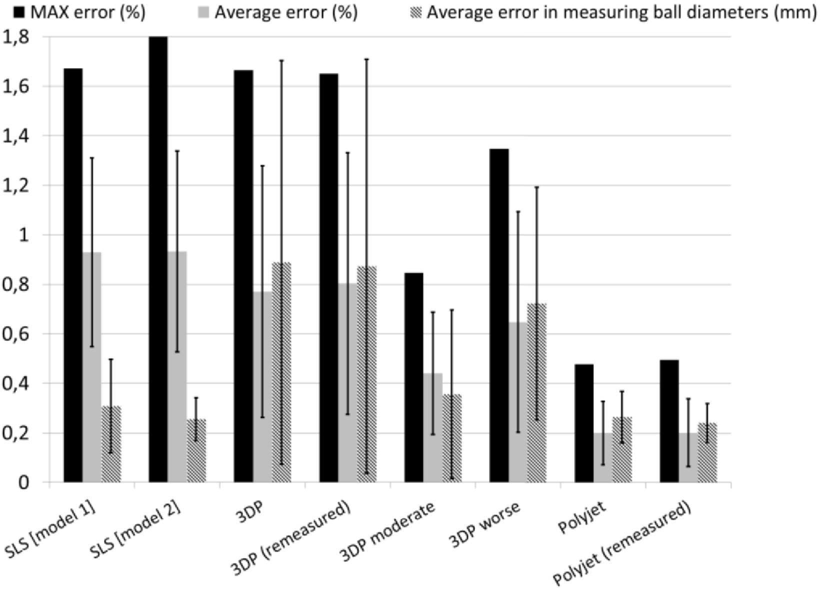

Figure 5 *Maximum, average and standard deviation errors in the skull models (%), and average error and standard deviation in the added measuring ball diameters (mm).*

Table 4 *Studies with accuracy measurement of AM models.*

Reference	Comparison	Mean difference (%)
(Paper III)	SLS - 3D model (original 1. & 2. model)	0.79 ± 0.26 & 0.80 ± 0.32
	3DP - 3D model (original, 1. & 2. measurement)	0.67 ± 0.43 & 0.69 ± 0.44
	3DP - 3D model (moderate)	0.38 ± 0.22
	3DP - 3D model (worse)	0.55 ± 0.37
	PolyJet - 3D model (original 1. & 2. measurement)	0.18 ± 0.12 & 0.18 ± 0.13
El-Katatny et al. (2010)	FDM - 3D skull model	0.24 ± 0.16
	FDM - 3D mandible model	0.22 ± 0.11
Ibrahim et al. (2009)	SLS - dry cadaver mandible	1.79
	3DP - dry cadaver mandible	3.14
	PolyJet - dry cadaver mandible	2.14
Silva et al. (2008)	SLS - dry cadaver skull	2.10
	3DP - dry cadaver skull	2.67
Nizam et al. (2006)	SL – dry cadaver skull	0.08 ± 1.25
Chang et al. (2003)	3DP – fresh cadaver skull	2.1 - 4.7
Choi et al. (2002)	SL - dry cadaver skull	0.56 ± 0.39
	SL - 3D skull model	0.82 ± 0.52
Asaumi et al. (2001)	3D model - dry cadaver skull	2.16
	SL - dry cadaver skull	0.63
Berry et al. (1997)	SLS – 3D model	0.64
Barker et al. (1994)	SL - dry cadaver skull	0.6 - 3.6
Ono et al. (1994)	SL - dry cadaver skull	3
Waitzman et al. (1992)	3D CT - dry cadaver skull	0.9 (min 0.1, max 3.0)

Medical models can be widely used e.g. in vascular surgery, orthopedics surgery, pediatric surgery and common surgery field (Rengier et al. 2009, von Tengg-Kobligk et al. 2008). In cranio-maxillofacial surgery medical models have a critical role and their use is increasing. (Faber et al. 2006, D'Urso et al. 2000b, Muller et al. 2003, Wagner et al. 2004, Poukens et al. 2003, Mavili et al. 2007). However, the accuracy of these models has not been sufficiently investigated. In preoperative planning or surgical simulation there is a possibility of fatal errors to occur, if the medical model is not sufficiently accurate. Results from such research demonstrate that different manufacturing methods may cause significant errors. Previous studies have shown that imaging and segmentation together can cause even larger errors than AM (Table 4). The PolyJet technique was found to be more accurate than SLS or 3DP. The previous studies did not comment on the repeatability of the measurements (Table 4). Location of anatomic landmarks in the human body are hard to measure exactly, because forms are usually smooth and exact points are difficult to find with commonly used measuring equipment, such as a caliber rule. By using the measuring balls described earlier and determining their centers, the repeatability of the developed measuring method was found to be excellent, since there were only minor variations in the repeated measurements. In SLS and PolyJet skulls, the most measurement ball dimensions were over 10 millimeters. In models made with 3DP there were variations over and below 10 millimeters. 3DP skull from original model had the largest error, and one measurement ball was approximately 11 millimeters and one was 9 millimeters in diameter. This explains the large errors and a poor result for 3DP skull and may have been caused by the post processing, where the models are dipped into a hardener liquid and dried. 3DP skull from worse model had a large (11 mm) measurement ball. The hardener may leave droplets to the 3DP model. The repeatability of the SLS process was good. This can be explained by the fact that the process was fully automatic and post-processing usually requires only cleaning of the parts. The main reason for the observed errors was the post-processing. The more manual work it includes, the more errors can occur. This explains the large variation in 3DP accuracy, because manual post processing was needed. Different principles and physics of AM processes significantly affect the accuracy. Some processes are developed to be more accurate than others, and in some processes high manufacturing speed is achieved using low accuracy. It has an effect on the accuracy, if the AM equipment is aimed to prototyping, tooling or production. Taft et al. (2011) imaged a dry cadaver skull with stainless steel spheres using multi detector computed tomography, and they produced seven SL skull models based on those images. When measuring the SL skulls with a Faro Gage CMM (FARO Technologies Inc, Lake Mary, USA), they found a significance difference in the Z direction of the additive build, but did not detect the same difference in the X and Y directions.

There are early studies related to the accuracy of AM (Pham & Gault 1998, Ippolito et al. 1995), but the AM technologies and processes have developed so fast that more and more studies are needed. The medical field has set up its own requirements for accuracy and engineering structures are more angular and have straight surfaces when compared to the structures of nature. An enormous improvement in accuracy and material properties has been seen and the development is speeding up. However, there is a need for standardized method for measuring and verifying medical models made by AM.

4.2 Soft orthodontic appliances with rapid tooling (Papers III)

Orthodontic appliances are used to straighten teeth. Soft removable orthodontic appliances made by rapid tooling were studied in the mouth of the patient repeatedly for 2 min to understand various aspects regarding the use of the appliance such as comfort and convenience. Two soft appliances were tested, one causing a high force and one causing a low force onto the teeth. The appliance with the stronger force was more efficient but caused a slightly unpleasant sensation. The appliance with the weaker force did not create as much effect as version with high force, but was more comfortable to use. Both appliances were of exact fitting and the surface quality was user-friendly even without any finishing. The appliance between plaster model and the finished appliance are shown in Figure 6.

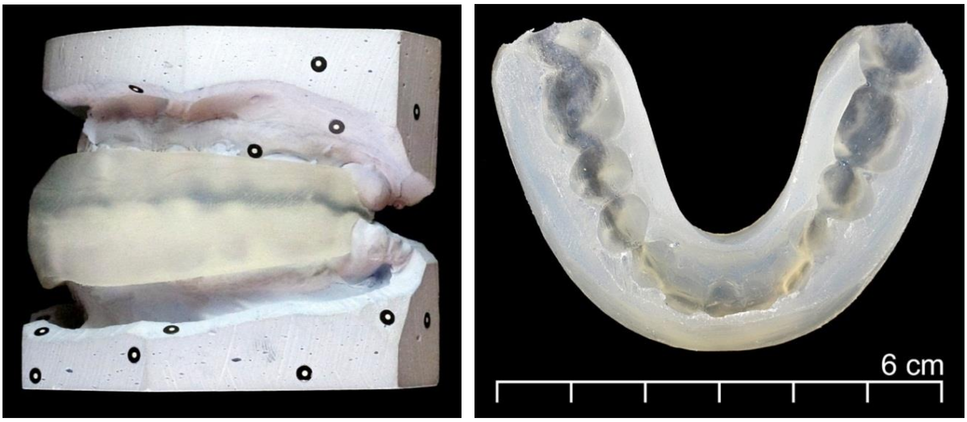

Figure 6 *The appliance between plaster models and the finished orthodontic appliance.*

The accuracy of soft orthodontic appliances is visualized in Figure 7. The maximum dimensional error of ca. 1 millimeter was observed at thin walls and sharp edges when comparing the physical appliance with the 3D model. The scale in Figure 7 varies from red (+1.0 mm) to blue (-1.0 mm). The geometry of the soft appliance was accurate when compared with the 3D model (Figure 7). Since the soft material is flexible, an accuracy ashigh as that in the hard appliances is not needed.

With soft appliances it may be possible to achieve a larger orthodontic tooth movement and therefore reduce the amount of aligners compared to hard ones. When using thermoplastic appliances tipping movements are predictable, but controlling of roots may cause trouble (Hahn et al. 2010). The material and the thickness of the appliance influence the tooth movement (Barbagallo et al. 2008, Hahn et al. 2009a, 2009b). When comparing the soft and hard appliance, no substantial difference in the completion rate was observed (Bollen at al. 2003). The soft occlusal splints have been used as treatment for migraine and other headaches (Quayle et al. 1990).

With Invisalign hard and clear orthodontic custom-made aligners over 100 000 patients had been successfully treated by 2004 (Beaman et al. 2004) and more than 80 million custom aligners have been produced (Wohlers & Caffrey 2013). The Invisalign process is such that a dentist takes a dental impression and sends it to a laboratory to be scanned. Based on the scan, the treatment is virtually designed and molds are manufactured with SL. By vacuum forming a set of aligners is created and sent to the patient. In the future, it is possible that the aligners are made by AM.

However, with these types of removable orthodontic appliances, treatments are limited to patients with mild orthodontic problems, and severe orthodontic problems cannot be treated with removable appliances. One manufacturing possibility for orthodontics appliances is thermoforming a soft slab of appliance over a straightened model made by AM.

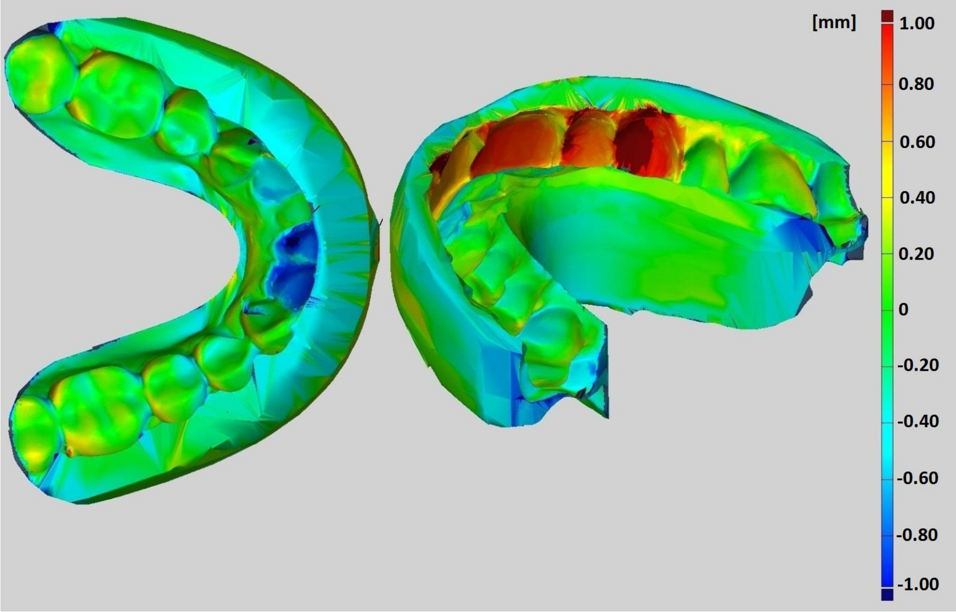

Figure 7 *Accuracy of orthodontic appliance compared with the designed 3D model.*

4.3 Occlusal splints with direct additive manufacturing (Paper IV)

Occlusal splints are used for the treatment of sleep apnea, temporomandibular disorder and bruxism. The occlusal splint made in this study by direct AM was used by a patient for six months nightly. After five days of use the splint was trimmed, because there was a slight pressure on the upper right canine and pressure between the upper and lower right premolars. The patient reported that the splint felt tight in the beginning of every use, but the pressure eased after a few minutes. This is typical of a conventional splint made in a dental laboratory. The patient adapted to the splint well and found it comfortable to use. The bite muscle tension of the patient was relieved by the use of the splint. At the follow-up visits (one, three and six months) only minor grinding was needed. No sign of tooth wearing, remarkable splint wear or other problems were detected after the six month test period. Minimal plaque deposits were noticed on the splint on a patient. The occlusal splint is shown in Figure 8.

Figure 8 *Occlusal splint made by additive manufacturing in use.*

After six months of use the splint was compared with the 3D model from which it was made (Figure 9). The maximum trim needed was approximately 1 millimeters and the wear can be estimated to be smaller than 0.2 millimeters. The wear can be estimated from occlusion plane in the areas without a need for trimming. The overall accuracy of the described system can be estimated from the areas with no trimming or wearing. Dimensional errors of approximately 1 millimeter were found at thin walls and sharp corners when comparing the splint with the 3D design. The accuracy in the others areas was better than 0.3 millimeters.

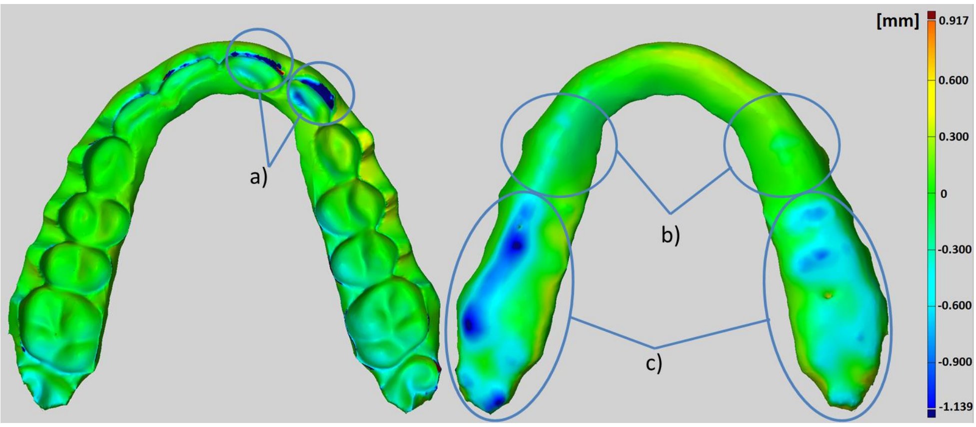

Figure 9 *The accuracy, wear (b) and the trim needed (a,c) when compared the used splint with the designed 3D model.*

In adults, temporomandibular disorder ranges from 25 to 50% (Carlsson 1999) and it is a common clinical observation (De Kanter et al. 1993, Kuttila et al. 1998). Therefore, the need of occlusal splints is increasing. Traditionally splints have been manufactured by hand in a dental laboratory. The lead time for traditional process is one week and handwork makes it expensive. AM and 3D scanning opens up new possibilities to manufacture splints more cost-efficiently by reducing the amount of handwork and the lead time. This may improve the accuracy of the splint and therefore reduce the time needed for a dentist to trim the splint. Digital technology is widely used and well-known for making ceramic inlays, such as Cerec (Siemens, Germany) (Pallasen et al. 2000). There are studies on the use of AM in the so called next generation dental device manufacturing (Van Noort. 2012). Using these next generation technologies it is possible to manufacture hard and clear removable orthodontic appliances directly with AM.

4.4 Inert implants (Paper II)

The digitally designed orbital wall implant made by AM was used in a surgical operation. The patient was pleased with the results on the 3 week follow-up visit. The displacement of the eyeball was dismissed. Some swelling and scars were observed after the surgery, but the eye ball was at its correct position (Figure 10, right). Later on, new artificial eye ball was made (not shown in Figure 10), because the old one was made for different height of orbital floor. Preoperative and postoperative photos of the patient are shown in Figure 10.

Figure 10 *The patient before surgery and 3 weeks after surgery. Reconstructed left eye floor raised eye back to normal position.*

After the surgery a new CT was performed and a new 3D model using the CT images was created. This model showed that the position of the implant was similar to the designed one. An exact fitting of the implant and clinical outcome were seen after only one surgical operation. No bleeding or infection complications were encountered. The designed 3D model with implant (left) and 3D model created from postoperative CT (right) are shown in Figure 11.

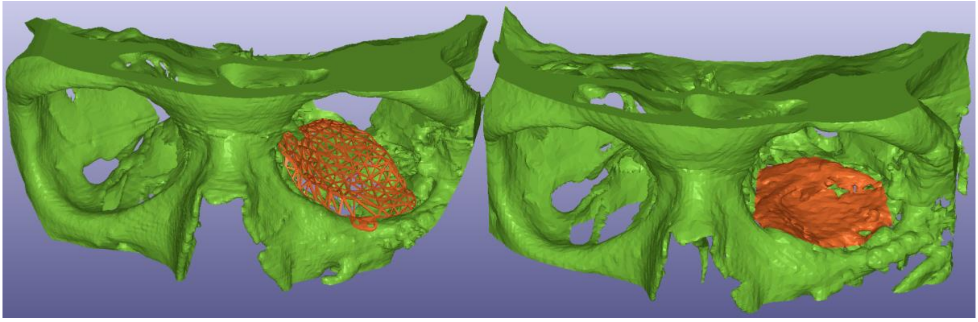

Figure 11 *The designed implant and 3D model from CT images after surgery.*

Traditionally implants are mass produced standard items with variable sizes or handcrafted individual implants made by a surgeon from implant slab before or during the surgery. Common fabrication methods for the implants or slabs are subtractive manufacturing methods. Titanium is one of the most commonly used material for dental and orthopedic applications (Lausmaa et al. 1990). For orthopedic implants metallic alloys based on iron, cobalt and titanium are commonly used (Galante et al. 2005). AM offers a new way to manufacture implants from the same materials that are already commonly used. It opens up a possibility to customize each implant for a specific patient, as there is no need for manufacturing tools such as molds or cutting tools.

Implants made by using AM are still relatively rarely used in surgical field. Recently, an accumulating amount of articles on metal implants has been published (Ciocca et al. 2011, Mangano et al. 2012, Figliuzzi 2012). The geometry and porosity of the implants are being intensively investigated. Stübinger et al. (2013) analyzed osseointegrative properties of porous titanium implants made by DMLS in a sheep. Witek et al. (2012) compared laser sintered metal surface with other commercially available surfaces from implants. They found higher bone-to-implant contact and bone area fraction occupancy for laser sintered surface than traditional ones after a week, whereas no differences were observed after three and six weeks. AM allows optimizing the geometry and topology of the implant if the optima can be somehow estimated or simulated. This may lead to better customized implants and treatment results.

An accumulating amount of research is carried out related to AM of tissues and organs (Melchels et al. 2012, Marga et al. 2012, Dean et al. 2012) and using AM possibilities combined with stem cells (Andersen et al. 2013, Sándor et al. 2013). In the future this may lead to more natural implants, which resorb away when they are no longer needed, or even AM of real living tissues and organs. There is already some research on fabricating miniaturized "walking" biological machines from hydrogels and cardiomyocytes using SL (Chan et al. 2012).

4.5 General discussion

Medical models can improve the communication between patients and surgeons. By using medical models it is more feasible and understandable to demonstrate to the patient what the surgeons are planning to do. Patient specific implants expedite the surgery and therefore improve the recovery, as the operation time affects the time needed for recovery. As scanning of the patient is possible also outside of the hospital, it may eliminate traveling costs. For example with occlusal splint, if digitalization of the occlusion is sufficient and the process well examined, the patient may have the splint mailed without a visit to a dentist. In facial prostheses digital workflow may reduce travelling and dependence on model storage and cataloguing (Eggbeer 2008). The cost of remakes is reduced because fewer models or molds are lost or damaged (Eggbeer 2008). Combining all this to robotics may in the future lead to virtual surgery performed in remote locations with experts from all over the world participating in the planning of the operation. The robot can perform the surgery in real time or at another point of time. These visions may enable surgeries in places as remote as space stations, or anywhere else where doctors are far away.

Using medical applications of AM requires a multidisciplinary team of experts. Problems may occur because usually people are experts only in their own area, and currently there is no common terminology between doctors and engineers. If the aspects are not clear and there is too much room for interpretation, misunderstandings may occur. This can be solved by further educating both doctors and engineers. In dentistry and at least in cranio-maxillofacial surgery there is a significant amount of craftsmanship involved. Digital processes may reduce the need for handcrafting. This change can be compared to mechanical design where drawing boards and pencils have been replaced with computers.

4.6 Future work

In the future we will try to open up and develop new applications in medicine by using AM. For medical implant manufacturing laboratory tests are needed to investigate the effect of the manufacturing method on surface quality. We are planning to carry out cytotoxicity test with DMLS and EBM parts to compare with commercially available standard implants.

In facial allotransplantation the donor receives significant visible disfigurement. There is ongoing work to solve this problem using 3D scanning, digital design and AM. It is possible to digitize the donor’s face and then produce a replica using AM.

More and more allografts have been used in human knee joint operations. Since every person has different size joints, digital design and AM can be considered to expedite the surgery and improve the results. There is a possibility to use medical models, saw guides or jigs during the operation.

There is an ongoing project to develop a 3D-digitalization of ankle movement and a CAD-method for producing patient specific external ankle support by AM. By measuring the ankle movement, a personally designed ankle support can be made using AM and conventional manufacturing processes.

5 Conclusions

In the medical field, every patient is unique and therefore for certain purposes, mass production of products is not the optimal solution. AM technology is superior in applications involving single or only few parts, as when manufacturing these, only the 3D model will need to be changed. Digital design methods and AM offer the medical and dental professionals new tools to improve treatment results and therefore, to enhance the quality of life of patient.

The general conclusions of this research are:

i) CT, laser scanning and structured light scanners were successfully used to achieve data from patient-specific geometries. Communication with radiologist is crucial since usually there is no need for thin slice thickness that AM requires.

ii) Patient data from CT was successfully reconstructed to a 3D model and models from 3D scanners were fully repaired and fixed using three software. For reconstruction Osirix was found to be suitable. STL model repairing 3Data Expert and Viscam RP was found to be suitable.

iii) Medical modeling was performed, with four software using a 3D model of the patient as a geometric reference. Rhinoceros was suitable for surface modeling by referring patient geometry. 3Data Expert and Viscam RP were good in Boolean operations and measurements. Pro Engineer was suitable for repositioning of teeth and placing the measurement balls accurately.

iv) AM processes were investigated and the best suitable process was selected for each purpose. This forms a crucial principle of using AM for medical applications. For medical models 3DP, SLS, Polyjet was used. Rapid tooling and direct occlusal splint manufacturing was made using SL. AM process for inert implants was DMLS.

The specific conclusions of the research are:

1. In surgical procedures implants are usually handmade or modified from standard products during operation. By digitally designing and manufacturing implants before the operation will reduce operating time, improve accuracy, reduce morbidity and give

improved fitting of the implants. A process consisting four steps was successfully used. First the CT-images are taken from the patient and second step is to reconstruct those images to the 3D model. Third step is to perform medical modelling according patient geometry in 3D model. Final step is using AM method DMLS. Volumetric net allows tissues and cells to grow through to and from surrounding tissues and reduce sensitivity for hot and cold temperatures. By reducing manual work phases human errors decrease and final result improve. Accuracy of process is adequate for manufacturing oral appliances and occlusal splints where tight tolerances are ordinary. There is a need for standardization for implants made by AM. For example it is not clear where the 3D model of the patient and implant is stored and how long. It is a question how the mechanical durability is noticed in design or how to trace all the data of the implant if the starting point is only implant itself. If something goes wrong it is important to be able to track where it happened and why.

2. When using AM in medical model fabrication, surgeons should be aware of errors related to the AM technology, materials and the instance of machine use. The error sources should be noticed when making any medical devices by AM. The main errors were caused by the AM technology used. PolyJet was found the most accurate when comparing to SLS and 3DP. The second most important source of error was the quality of the STL model measured by the amount of triangles. The smallest error was caused by the instance of the machine used. This study did not include errors in medical imaging, which may be a major source of errors when compared to the imaged object. Post processing and handwork relating to models may cause significant errors. The measuring procedure for medical models is complicated. By using the proposed measuring method, which determines the center point of ball, an excellent repeatability was achieved. There is a need for a standard method for measuring and verifying medical models and devices fabricated by AM.

3. By making a mold with AM, the mold can be used indirectly to manufacture medical devices. The customized soft orthodontic appliances made from silicone were manufactured by making molds with SL. The appliance causing a higher force was more efficient but caused a slightly unpleasant sensation. The version with reduced force was more comfortable to use. Both appliances were well tolerated by the patient and

convenient to use. In the future the use of AM technology may reduce costs because the need for handicraft is reduced. Soft appliances require fewer versions of the appliance because the movements of teeth can be larger when compared to the hard ones. There is a need to investigate the force mechanism of the soft aligner to verify how much movement it can cause to teeth and what the limitations are.

4. AM was directly used to manufacture medical devices. Clinically functional occlusal splints can be manufactured by modern digital technology without manual working phases in a dental laboratory. In the future this may reduce costs, working time of dental technician and chair-side time of dentist. Accuracy can be improved, since one manual work phase is reduced. The material Somos WaterShed XC 11122 proved to be suitable for occlusal splint manufacturing. The mechanical properties could stand the forces from teeth and jaws, and the consistency of the material was fairly optimal. The accumulation of dental plaque on various splint materials used in the AM process should be investigated. Minimal plaque deposits were noticed on the splint on a patient after six months of testing. For commercial production more clinical studies are needed to verify how much the variation of forces from teeth and jaws affects the material.

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