



Tufts
UNIVERSITY

School of
Dental Medicine

**Accuracy of planned versus actual implant positions in mucosa supported
guided implant surgery**

A Thesis

Presented to the Faculty of Tufts University School of Dental Medicine

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Dental Research

by

Daniel Ben Yehuda

07/2019

© 2019 Daniel Ben Yehuda

THESIS COMMITTEE

Thesis Advisor

Panos Papaspyridakos, DDS, MS, PhD

Assistant Professor

Department of Prosthodontics

Tufts University School of Dental Medicine

Committee Members

Hans-Peter Weber, DMD, Dr. Med Dent,

Professor

Department of Prosthodontics

Tufts University School of Dental Medicine

Ali Muftu, DMD, MSc, PhD

Professor

Department of Prosthodontics

Tufts University School of Dental Medicine

Matthew Finkelman, PhD

Associate Professor

Department of Public Health and Community Service

Tufts University School of Dental Medicine

ABSTRACT

Purpose

The prosthodontically-driven placement of dental implants is an approach which has been increasing in popularity amongst dental clinicians. An important step towards the implementation of a fully digital workflow has been the development of computer-planned and template-guided implant surgery.

The purpose of this study was to assess the positional discrepancy present between the virtually planned and actually placed dental implants, in order to determine the accuracy of guided implant surgery. The discrepancy levels between maxillary and mandibular arches as well as between the placement of 4 vs 6 implants were analyzed to further understand whether these factors are associated with its accuracy and precision.

Materials & Methods

Stone casts of a total of 25 fully edentulous arches (14 maxillae and 11 mandibles) of patients treated with either 4 or 6 implants (9 and 16 arches respectively) for a total of 132 implants placed via the Nobel Biocare guided surgery protocol in the Postgraduate Prosthodontics clinics at of Tufts University School of Dental Medicine were included in the study. The casts derived from the guides used during the respective surgeries were scanned and superimposed to the casts derived from intraoral impressions after implant placement. A best-fit-alignment algorithm was used to quantify the positional discrepancy present between the planned vs placed implants. The data were then analyzed via a mixed-effects model ($\alpha = 0.05$) and descriptive statistics.

Results

Positional discrepancies between the virtually planned and placed implants were found. The mean root-mean-square error (RMSE) between all 25 arches was found to be 0.199mm, with a standard deviation (SD) of ± 0.154 . The mean RMSE between maxillary arches was 0.187mm (SD ± 0.151), and 0.214mm (SD ± 0.163) between mandibles. The discrepancy present between the maxillary and mandibular arches was not found to be statistically significant ($p > 0.05$). The mean RMSE between arches with 4 implants placed was 0.146mm (SD ± 0.058), whereas it was 0.228mm (SD ± 0.183) between arches with 6 implants placed. The discrepancy present between the arches with 4 vs 6 implants placed was found to be statistically significant ($p < 0.05$).

Conclusion

Within the limitations of this study, the following conclusions may be drawn:

1. 3-D discrepancies were found between the virtually planned implants positions and the surgically placed implants, using the Nobel Biocare guided surgery protocol.
2. When comparing the implant positional discrepancies found between maxillary and mandibular arches, no statistically significant differences were found.
3. When comparing the implant 3-D discrepancies found between arches containing 4 implants and arches containing 6 implants, statistically significant differences were found, with lower deviations in the group containing 4 implants.

TABLE OF CONTENTS

List of Tables	vi
List of Figures.....	vii
List of Symbols	viii
Introduction.....	2
Aims and Hypotheses.....	22
Materials and Methods.....	24
Results	29
Discussion	31
Conclusion	42
References.....	43
Appendices.....	51
Appendix A: Tables	52
Appendix B: Figures.....	54

LIST OF TABLES

Table 1: Patients distribution.....	52
Table 2: Implants positional discrepancies.....	52
Table 3: Arch comparison.....	53
Table 4: Number of implants comparison.....	53

LIST OF FIGURES

Figure 1: Edentulous mandibular arch.....	54
Figure 2: Pre-operative panoramic radiograph.....	54
Figure 3: Virtual implant planning on Nobel Clinician software.....	55
Figure 4: Surgical guide in place during implant surgery.....	55
Figure 5: Post-operative panoramic radiograph.....	56
Figure 6: Post-surgical master cast.....	56
Figure 7: Stereolithographic surgical guide with implant analogs mounted.....	57
Figure 8: Cast derived from the surgical guide.....	57
Figure 9: Laboratory Dental Scanner.....	58
Figure 10: Group I digitized cast.....	58
Figure 11: Group II digitized cast.....	59
Figure 12: Superimposition and RMSE calculated by 3D inspection software.....	59
Figure 13: Total casts RMSE distribution.....	60
Figure 14: Maxillae vs Mandibles RMSE distribution.....	60
Figure 15: 4 vs 6 Implants RMSE distribution.....	61

LIST OF SYMBOLS

μm = micrometer

α = level of significance

**Accuracy of planned versus actual implant positions in mucosa supported
guided implant surgery**

Introduction

1. Long term success of implants in the treatment of the edentulous jaw

In the past 50 years, the treatment of partially and fully edentulous patients with dental implants has undergone a remarkable evolution, starting in the 1960s with the first preclinical and clinical studies from Professor P. I. Brånemark from the University of Gothenburg (Sweden) and Professor André Schroeder from the University of Bern (Switzerland), to today's highly predictable implant survival rates.¹ A systematic review by Papaspyridakos et al., that assessed randomized controlled clinical trials and prospective studies ranging from 1997 to 2012 reported implant survival rates in the edentulous mandible ranging from 98.42% to 96.86% for five and ten-year follow-up respectively, with the use of rough surface implants.² With the use of smooth surface implants, similar survival rates of 98.93% and 97.88% for five and ten years respectively were obtained.² Five hundred and one patients and 2,827 implants were included in the review. The implant surface, the number of implants and their distribution had no statistically significant effect on implant survival. Neither did the veneering material, prosthesis type, design and loading protocol.² Overall, the authors concluded that the utilization of implants for the treatment of the edentulous mandible yields a survival rate of over 96% over a ten-year period.² Maló et al. reported in a retrospective longitudinal study of 471 patients with edentulous mandibles, rehabilitated with the All-on-4 concept, a cumulative implant survival of 93% after 18 years of follow up.³ A previous study from the same team reported a 94.8% cumulative implant survival rate after 10 years of follow-up.⁴ Another retrospective cohort study by Niedermaier et al. with 7 year follow up came to similar

conclusions.⁵ The study included 2,081 implants in 380 patients, and either 4, 5 or 6 implants were immediately loaded. The survival rate of the mandibular implants was 98.2% after a 7-year period. In this study, intragroup comparisons of the arches, and implant angulations, diameters and lengths did not result in significant differences with regards to the survival rate during the observation time.⁵

For the edentulous maxilla, Niedermaier et al. found an implant survival rate of 96% after 7 years. Lambert et al. conducted a systematic review and also reported dental implant treatment to be a reliable solution for the edentulous maxilla.⁶ This review assessed the implant survival rate up to a 15-year period of fixed implant rehabilitations in the edentulous maxilla, taking into consideration implant surface, bone grafting procedures, and prosthodontic factors in connection with the prosthesis design, materials, implant number and distribution.⁶ Data of a total of 1,320 patients and 8,376 implants, from thirty-three prospective and retrospective studies given the lack of randomized controlled trials, were analyzed for a period of one, three, five, ten, and 15 years. The analysis reported 10-year implant survival rates of 98.0% (95% CI: 96.6% to 99.3%) for rough surface and 89.3% (95% CI: 88.3% to 90.4%) for smooth surface. Additionally, less peri-implant bone loss was found throughout the study's term with rough surface implants, which would seem to indicate that rough surface implants are a more favorable choice when rehabilitating the edentulous maxilla.⁶

Prosthodontic data of 1,024 patients were analyzed, resulting in 98.2% prosthesis survival after one year, and 92.1% after ten years. Veneering material, design, and number of implants did not result in a statistically significant influence within the 15-year period. The number of implants supporting a prosthesis did not have any effect on implant survival, although six or more implants consistently had higher survival rates in all the articles reviewing scenarios with

less than six implants.⁶ Prostheses retained by implants distributed anteriorly to the mental foramina resulted in statistically significant lower survival rates compared to implants with a wider anterior-posterior spread. It was also noted by the authors that smooth (machined) implants placed in native bone resulted in superior survival rates compared to implants placed in grafted areas. However, the studies assessing rough surface implants seemed to have comparable results for native versus grafted sites.⁶ This is in accordance with the results obtained by Tran et al. according to a retrospective study that compared survival rates of implants inserted in native bone and grafted areas.⁷ A total of 2,729 implants (1,222 patients) were included in this study. At 5 and 10 years, for implants inserted in native bone, there resulted to be a cumulative survival rate of 92% and 87% respectively, whilst for implants inserted in grafted bone, a 90% and 79%, cumulative survival rate resulted. Implant placement in native bone resulted in higher survival rates. However, no statistically significant difference was found.⁷ It has to be noted that this study did not analyze maxillary and mandibular implants separately. Also, surface features of the implants were not taken into consideration in the study. Several prosthetic choices are available for the rehabilitation of an edentulous arch via a fixed implant solution. The use of a metal framework and acrylic resin teeth has been suggested by several authors. This protocol consisted principally of dental implants inserted in the anterior region and the use of distal cantilevers.⁸ However, an often reported complication has been wear as well as fracture of the acrylic resin veneer. Also, ageing of the acrylic base and discolorations at the contact area between teeth and acrylic base have been reported, resulting in poor esthetic results.^{8,9}

Metal-ceramics have been increasingly used for the restoration of edentulous arches in order to address the disadvantages of metal-acrylic restorations. However, a high incidence of chipping was found as a substantial complication with the metal-ceramic design.¹⁰

In modern prosthetic dentistry, there's been an increased use of zirconia-based implant restorations, which combine strength and biocompatibility to esthetics.¹¹ Ceramic-veneered zirconia prosthesis have been suggested for the rehabilitation of fully edentulous arches.¹¹ However, chipping is also reported as a frequent complication with these prostheses. In order to avoid this risk, monolithic zirconia options have been developed.⁸ The long-term outcome of these restorations has not been researched extensively at this point. A recent meta-analysis by Bagegni et al. attempted to evaluate the role the material chosen for a restoration has on both the implant and prosthesis survival of full-arch implant-supported fixed prostheses, as well as the related complications.⁸ The full arch fixed prosthesis were grouped into metal-ceramic, all-ceramic (monolithic zirconia or porcelain fused to zirconia) and metal-resin restorations.

Over a mean observation period of 5.3 years, the implant survival rate resulted being 97% for the metal-ceramic group. Over a mean observation period of 3.6 years, it resulted being 99% for the all-ceramic group, whereas over a mean observation period of 6.77 years, it resulted being 97% for the metal-resin group. The three groups were found to have statistically significant differences amongst them. The prosthetic survival rates were 95% for the metal-ceramic group, 97% for all-ceramic and 97% for metal-resin. The three groups were found not to have statistically significant differences amongst them. However, caution with interpretation is advised since the analysis suggested a publication bias in both cases.⁸ With regards to prosthetic complications, despite there being no statistically significant difference amongst the

groups regarding the chipping rate incidence, a clinical relevance was detected due to the higher chipping rates found in the metal-resin group of 22%, in comparison to 8% in the metal-ceramic group, and 15% in the all-ceramic group.⁸ The authors concluded that the selection of restorative materials does not appear to affect the prosthetic survival of implant-supported full-arch fixed prostheses in the rehabilitation of fully edentulous patients, and that metal-ceramic fixed prostheses appeared to yield higher implant survival compared to other material choices. Nevertheless, it also revealed higher chipping rates in comparison to the other two groups. However, the clinical relevance of these findings remains debatable.⁸

2. Evolution of implant placement protocols

When it comes to implant placement, multiple options are available regarding the timing and mode of insertion. According to the classification of morphologic, histologic, and dimensional changes following a tooth extraction published by Hammerle et al., type 1 is represented by immediate implant placement post-extraction. Type 2 is represented by early placement with soft tissue healing, type 3 by early placement with partial bone healing, and type 4 by late placement.¹²

It has been discussed that immediate implant insertion reduces treatment time and may reduce crestal bone resorption by keeping the periodontal structure, leading to better aesthetic results, especially in the interproximal area when combined with flapless approach.¹³ Nonetheless, there is no consensus with regards to the advantages of immediate implant placement within the scientific literature. A systematic review and meta-analysis by Mello et al. compared

implants placed right after tooth extraction to implants placed in fully healed sockets analyzing the implant survival rates and peri-implant tissue changes.¹³ Among the 3,049 dental implants included in the eligible studies, 95 failures (3.11%) were recorded, of which 69 were immediately placed implants (72.63%), and 26 were conventionally placed implants (27.37%). These results showed that despite the fact that immediately inserted implants resulted having high survival rates, conventionally placed implants demonstrated statistically better results.¹³ The authors also concluded that immediately placed implants do not yield significantly different results with respect to conventionally placed implants with regards to associated marginal bone loss or soft tissue changes.¹³

Choosing the type of placement is a decision which regards the benefits and risks each type offers.¹⁴ Type 1 provides the advantages of a reduced number of surgeries and diminished total treatment time in comparison to types 2, 3, and 4. Peri-implant defects often present as two- or three-walled defects, rendering them favorable for concurrent bone augmentation procedures. It also offers the possibility of delivering a fixed provisional restoration when indicated. The limitations include the difficulty of placing an implant in an ideal position due to the morphology of the site which may compromise the initial implant stability as well. Furthermore, the lack of soft tissue volume may make achievement of tension-free primary closure harder, increasing the risk of soft tissue recession.¹⁴

Type 2 being an early placement, 6-8 weeks after tooth extraction offers the advantage of having healed soft tissues available, which facilitates suturing and flap closure as well as the predictability of the esthetic result. Furthermore, pathology present in the tooth site has time to resolve before the implant is placed. The disadvantages include a higher number of surgical

procedures and the still greater risk of not achieving primary implant stability due to bone formation still being at its primary stages.¹⁴

Type 3, on the other hand, presents partial bone healing that usually permits implant stability to be more easily achieved. Moreover, additional soft tissue volume allows for easier achievement of tension-free closure which can enhance soft tissue-esthetic results. The disadvantage of this type is the extended treatment time, the varying amounts of resorption that the socket walls may exhibit and the fact that the bone will have gone through a phase of remodeling which might diminish the amount of available bone for the implant placement.¹⁴

In the type 4 scenario, the amount of bone remodeling and resorption will be the highest, increasing the risk of insufficient bone quantities for the implant placement.¹⁴

A systematic review by Chen et al. that studied the esthetic results of implants placed in postextraction sites for single-tooth implants adjacent to natural teeth, concluded that immediate implant insertion (type 1) is related to a higher variability in results and a greater frequency of recession of >1 mm of the midfacial mucosa in comparison to early implant insertion (type 2 and type 3). Even though acceptable esthetic results can be attained with implants inserted following tooth extraction, recession of the midfacial mucosa represents a risk with immediate placement (type 1). Regarding the best suited biomaterials for the purpose of reconstructing the buccal bone and the correlation between long-term mucosal stability and buccal bone presence or absence, the width of the buccal bone, and the position of the buccal bone crest, further research is needed.¹⁵

3. Implant placement for the edentulous jaw - conventional, immediate, early

Regarding fully edentulous jaws, several studies reported no statistically significant differences in implant success and peri-implant marginal bone loss between immediate and delayed implant placement.¹⁶⁻¹⁸ Pellicer-Chover et al. evaluated peri-implant health, marginal bone loss and success of immediate and delayed implant placement for treatment with full-arch fixed prostheses, in a randomized clinical trial.¹⁶ Fifteen patients were allocated in two groups: in the first group implants were inserted right after extraction, whereas in the second group they were inserted six months post-extraction. Each patient had eight implants placed in the maxillary arch and/or six implants in the mandibular arch. The implants were then followed-up at one week, six months and one year after loading. At time of implant loading, the probing depth and the thickness of the keratinized mucosa were significantly greater in immediately placed implants in comparison to delayed implants. Yet, at six months and one year follow-up the differences between the two groups weren't present anymore. A bone loss of 0.54 ± 0.39 mm resulted for immediately placed implants and 0.66 ± 0.25 mm for delayed implants at one year follow-up. No statistically significant differences were found for the following studied parameters at the twelve-month follow-up: crevicular fluid volume, plaque index, gingival retraction, modified gingival index and presence of mucositis.¹⁶ The clinical studies by Oxby et al. and Krennmair et al. showed similar results, without statistically significant differences in mean marginal bone loss around the delayed implants and immediate implants, but reporting more soft tissue complications at the immediate implant sites.^{17,18}

4. Implant loading

Amongst the goals of dental treatment, the reduction of the time spent by the patient in the dental chair as well as the simplification of the dental procedures is an increasingly important objective. The extended healing time without implant loading correlated with the conventional loading protocol is disadvantageous from a patient perspective, especially in the fully edentulous patient, due to the functional and aesthetic disturbance associated with the need to use removable dentures.^{19,20} The protocol of immediate loading was initially developed for these patients, with the aim of improving comfort and achieving better immediate function and aesthetics.²⁰

There are altogether three types of protocols which have reached a consensus in the scientific literature: conventional loading, early loading, and immediate loading. Conventional loading consists of connecting the prosthesis after a minimum period of 2 months of healing after implant placement. Early loading refers to connecting the prosthesis to the implant within a period of 1 week to 2 months after implant placement. Lastly, immediate loading consists of connecting the prosthesis to the implants within the first seven days of implant placement.^{21,22}

A systematic review and meta-analysis by Papaspyridakos et al. analyzed the implant and prosthesis survival rate in accordance with the different loading protocols within the studied edentulous patient population that received a fixed prosthesis, as well as the failure rate and complications.¹⁹ A total of 2,695 patients, 2,757 edentulous arches, and 13,653 implants were analyzed. Implant survival was considered after one year from placement. For the maxillary arches, conventional loading resulted in a 99.6% survival rate, early loading led to a 99.3% survival rate, whereas immediate loading resulted in a 99.2% survival rate. For the mandibular

arches, conventional loading exhibited a 99.7% survival rate, 98.5% for early loading, and 99.3% for immediate loading. The authors' conclusion was that the survival rate is not affected by the protocol providing the fixed prosthesis supported by multiple implants as there was no statistically significant difference between the three different loading protocols.¹⁹ However, multiple requirements have been reported in the literature for the immediate implant load. Primary stability has been recommended as a crucial factor for successful osseointegration (an insertion torque of at least 30 Ncm or a ISQ of 60 is recommended). Also, the use of surface modified implants has shown to play an important role. Experimental studies have demonstrated an increased and quicker bone tissue response to surface-modified implants.¹⁹ Regarding the complications, no correlation was found with respect to loading protocol and encountered complications.¹⁹

A later systematic review by Sanz-Sanchez et al. studied the clinical efficacy of immediate implant loading protocols in comparison to conventional loading with regards to the restoration type.²⁰ They concluded that single teeth implants and partial restorations appear to have a greater failure risk and presented more crestal bone loss, in comparison to immediately loaded full arch prostheses in completely edentulous patients. The more favorable results with the full arch prostheses described in this review can be accounted for by the cross-arch stabilization achieved with these type of prostheses, which possibly limits the amount of micromotion at the bone-implant interface during bone healing.²⁰

5. Contemporary era of implant placement - guided surgery

Digital technologies as well as prosthodontically-driven approaches are gaining more prominence in implant dentistry. Cone-beam-computed-tomography (CBCT) scans allow clinicians to use Digital Imaging and Communications In Medicine (DICOM) data in conjunction with Standard Tessellation Language (STL) files attained from intraoral scanners in computer-aided design (CAD) software to plan prosthodontically optimal implant placement and design surgical templates for that purpose.²³

Today, multiple systems are available for the transfer of the digitally planned implant positions to the surgical room. For static computer-aided implant surgery (s-CAIS), static surgical implant templates are currently preferred to dynamic systems for navigation.²⁴ The s-CAIS protocol includes either a guided pilot drilling system or a completely guided system in which the entire drilling sequence is guided and the implant placed through the surgical template. The indications span from single implants to fully edentulous arches for treatment of both arches.²⁵ The surgical templates can be categorized according to their functional design: tooth-supported, mucosa-supported, or bone-supported or any combination of the three. Additionally, the implant insertion can be executed entirely flapless or with an open flap, spanning from small crestal incisions up to the elevation of a full-thickness mucoperiosteal flap with total display of the underlying alveolar bone.²⁶

However, the accuracy of guided surgery as well as the patients' perception of the treatment are still subject of debate.²³ A systematic review by Joda et al. analyzed patient-reported outcome measures, economics and surgical complications related to fully guided implant surgery. The authors concluded that the amount of surgical complications with s-CAIS appears

to be insignificant and akin to conventional implant surgery. s-CAIS can offer a beneficial treatment option in edentulous cases if a flapless protocol is possible, as it has been shown to be superior in terms of postoperative morbidity.²⁵

6. Guided surgery workflow

Digital planning of the implant surgery should be used as an adjunct to proper diagnosis and treatment planning, regardless of the decision to follow a guided surgery protocol.²⁷ It is the clinician's responsibility to decide on the final positions following a prosthodontically-driven approach and on the need for bone grafting procedures with the help of digital technology to facilitate better patient communication related to the planned procedure.²⁷

The steps within the digital workflow sequence for guided surgery are the following: 1) Cone beam computed tomography (CBCT) scan; intra or extraoral scanning; digital planning software and surgical template manufacturing via computer assisted milling (CAM) or 3-D printing.²⁸ To be able to discern the causes of positional errors occurring during implant insertion using a static guided surgical protocol, the clinician must both recognize and comprehend the limitations present in each step of the workflow.²⁸

6.1. CBCT scan:

To start with, the CBCT scan represents the first potential source of error. Despite the fact that the linear measurements on CBCT images appear to be precise, multiple factors can skew the final result, such as patient movements at the time of CBCT acquisition or the presence of

metallic restorations that can cause image distortion, artifacts and image quality degradation.

²⁸ In this step of the workflow, a radiographic guide may be used, especially for fully edentulous patients. As described by Marra et al., the patient's prosthesis can be used, when adequate. Otherwise, a new removable prosthesis or new diagnostic tooth arrangement (set-up) should be fabricated before CBCT examination. At least 6 radiopaque markers should be included in the scan prosthesis in different axial planes to serve as references. The patient should first be scanned while wearing the radiographic guide in a stable position. Afterwards, the radiographic guide alone is scanned. ²⁹

6.2. Surface scanning procedures:

Surface scanning procedures provide a way to capture the soft and hard intraoral tissues' morphology. The accuracy of intraoral scanners has been reported to variate in accordance to the type of scanner used, the need for intraoral powder coating, and the scanning sequence.²⁸ In a systematic review by Rutkunas et al., the accuracy of digital implant impressions with intraoral scanners was studied. This review identified the following as the factors potentially influencing the digital implant impressions ³⁰:

- Experience and performance of the operator.
- Scanning strategy and protocol: use of powder, calibration, scanning time, number of images, movement direction, scanning mode and sequence.
- Characteristics of the scan bodies: size, shape, implant/abutment level, repositioning accuracy and construction.

- Clinical factors: patient movements, saliva, blood, areas difficult to reach, tongue and mobile areas, fogging of the optics, scanning location, distance between implants, extent of the edentulous region, implant angulation and implant depth.
- IOS hardware: scanner type, scanner generation and scanning technology.
- IOS software version.
- 3-D printing/milling of the model: printing technology, resolution, layer thickness, milling technology, production strategy, material selection, distortion with time, implant analogue construction and positioning accuracy.

It was concluded that digital implant impressions present a proper alternative to conventional impressions for single and multi-unit implant-supported prostheses. However, the results were mostly based on in-vitro studies. Therefore, validation with in-vivo data should be carried out to evaluate and compare trueness and precision of modern IOSs.³⁰

6.3. Computer planning software:

Implant planning software, in combination with cone-beam computerized tomography, made it possible to virtually plan implants in the ideal position, prosthetically driven, taking into account the surrounding anatomical structures. This process enables the transfer of the planned virtual implant position from the computer to the patient. The use of IOSs is increasing in this treatment modality through the superposition of a file derived from IOS scan with a 3-D Digital Imaging and Communication in Medicine (DICOM) file derived from the CBCT data. The superimpositions are completed by matching mutual landmarks present on both digital images.³¹ However, a discrepancy in the superimposition of the data sets can take place when there is an inadequate number of distinctly discernible common features. This can happen

when CBCT or CT radiographs are taken without leaving sufficient interocclusal space between the maxillary and mandibular arches, as well as when metallic restorations are present in the patient's mouth which cause radiographic artefacts.²⁸

6.4. Surgical guide fabrication:

The premise for surgical guide creation is the planning software. Within the virtual plan each implant is spatially located according to four parameters for position and depth for the placement of the surgical guide sleeves. The master model representing the patient is fitted with the scan template.³¹

In general, based on the supporting surfaces, the following types of surgical guides are described in the literature:

- Tooth-supported surgical guides: supported by the remaining teeth.
- Mucosa-supported surgical guides: supported by the mucosa, mostly used in fully edentulous patients.
- Bone-supported surgical guide: supported by the underlying bone after opening a mucoperiosteal flap.
- Special supported guides: (mini) implant or pin-supported.

The latest evolution in digital fabrication of surgical templates is based on the superimposition of digital computerized tomography data and intra-oral scanning data.³¹ This approach makes it feasible to place implants in a pre-planned location with or without raising a flap, both of which have been shown to provide the same success when applied in appropriate indications (i.e. presence of sufficient width of alveolar bone and keratinized attached mucosa).³² The flapless surgery consists of a minimally invasive approach with reduced surgical procedure,

which consequently diminishes the postoperative pain and swelling.³³ This technique is only feasible for partially edentulous patients. For fully edentulous patients, the dual CBCT scan technique is the current standard of care.

7. Survival of implants placed with guided surgery

Several reviews evaluated the accuracy of flapless guided surgery in clinical studies. Generally, it can be concluded that the implant survival rate ranges from 91% to 100%.³¹ Tahmaseb et al., in a systematic review including 14 survival and 24 accuracy studies, reported an overall implant survival rate of 97.3% based on 1941 implants, after 12 months.²⁷ Nonetheless, in 36.4% of cases, intra-operative or prosthetic complications (such as template fracture, implant instability, need for non-planned grafting, prosthetic screw loosening, prosthetic misfit and prosthetic fractures) were reported. Based on the meta-analysis, the authors reported the lack evidence indicating that digitally-assisted surgery yields better results than conventional surgery in terms of safety, outcome, morbidity or efficiency.²⁷ The high implant survival rates reported in the previous review were confirmed in Balshi et al.'s study, in which 23 edentulous arches were restored via a guided protocol and resulted in a 97.6% survival rate, with four implants out of a total of 168 failing over a period of three years follow-up.³⁴ On the other hand, the prosthetic survival rate was 100%, as none of the failed implants affected the prosthesis survival, and no additional surgery was necessary.³⁴

The meta-analysis of Moraschini et al. reported on survival, crestal bone changes and complications with guided surgery based on 13 studies. The study revealed a cumulative

survival rate of 97.2% and a low marginal bone loss (1.45 mm) during 1–4 years of follow-up. Nevertheless, related surgical and prosthetic complications were frequently detected, and a learning curve is necessary to achieve treatment success.³⁵

8. Accuracy of static guided surgery

While the developments in static implant guided surgery appear to be favorable, doubts have been raised regarding the precision, accuracy, and overall reliability of this protocol. It has been reported in the literature that each stage, either within itself, or in cumulation with other stages in the digital workflow, can yield errors that may compromise the final outcome.²⁷

Tahmaseb et al. carried out a systematic review and meta-analysis that studied the accuracy of static computer-aided implant surgery. The review included 20 studies: one randomized controlled trial, 8 uncontrolled retrospective studies and 11 uncontrolled prospective studies. The systematic review included solely implants inserted in live patients, excluding cadaver or preclinical investigations.²⁸

A sum of 2,238 implants in 471 patients inserted with static guides were accessible for review.

The meta-analysis of the accuracy resulted in the following total mean errors:

- Error at entry point (measured at the center of the implant): 1.2 mm (95% CI: 1.04 to 1.44). A statistically significantly smaller error resulted in partially edentulous patients in comparison to fully edentulous patients.

- Error at the apex: 1.4 mm (95% CI: 1.28–1.58). A strongly significant difference resulted between fully and partially edentulous patients, the discrepancy being smaller for partially edentulous cases.
- Angular deviation: 3.5 degrees (95% CI: 3.00–3.96), with no significant difference between fully edentulous and partially edentulous cases.
- Discrepancy in implant height at the entry point: 0.2 mm (95% CI: –0.25 to 0.57 mm).
- Discrepancy in implant height at the apex: 0.5 mm (95% CI: –0.08 to 1.13 mm).

The mean discrepancy for entry and apex point positions were close to the findings published in an antecedent systematic review.²⁷

In this review, vertical discrepancies were significantly higher in comparison to horizontal and angulation discrepancies. Despite the mean discrepancies appearing to be in a clinically admissible range, still some significant outliers were present, especially when treating fully edentulous maxillary arches. The authors reported that the main error occurred with implants not being inserted deeply enough.²⁸

There is variability in the articles included in this systematic review regarding the time intervals followed to perform the postimplant positional outcome analysis. One study completed the comparison directly after placement, while other studies were done at 10 days or up to 12 months after implant placement. Minimal implant movement might occur when the implants are not yet osseointegrated, which can be a potential source of error in accuracy studies that should be considered carefully.²⁸

Other sources of potential inaccuracies come from the amount of tolerance between both the sleeves in the surgical guides and the drill handles as well as the drill handles and the drills,

which seem to be diminished by the use of 3-D printing guides with a smaller sleeve diameter, improving the total accuracy in digitally-assisted template-guided implant surgery.²⁸

A factor frequently mentioned is the importance of drill guide stabilization during guided implant placement. Several studies included in the systematic review by Tahmaseb reported that mucosa-supported guides showed micro-movement, even when several anchor pins were placed, contributing therefore to inaccuracies.^{27,28}

Additionally, the method of comparison of the pre- and post-treatment implant position may not allow for a sufficiently accurate assessment. In many accuracy studies included in Tahmaseb's review, the postoperative implant position was evaluated by CT or CBCT scan. Beam hardening and radiographic artefacts are a possible source of error during comparison of implants positions. Furthermore, movements by the patient at the time of CT/CBCT taking can also originate errors during comparison of implant positions.²⁸

The authors concluded that in most clinical situations the use of s-CAIS yields an acceptable level of accuracy. Nevertheless, a safety range of a minimum of 2 mm should be allowed for during virtual planning. Also, a lack of homogeneity was encountered in the methods used between the various authors and the overall study designs. However, generally an increased accuracy level resulted in partially edentulous patients in comparison to fully edentulous patients.²⁸

9. Limitations of previous accuracy studies in the literature

Previous systematic reviews studying the accuracy of s-CAIS have limitations due to the absence of homogeneity in study designs among the available literature. A multitude of differing surgical variables and techniques are not standardized, which result in confounding factors when assessing the actual accuracy of guided surgery. Furthermore, there are a multitude of stages in the digital workflow itself that may cause errors that accumulate throughout the whole process, which can factor in the masking of the actual accuracy of the protocol.^{27,28} The sole use of radiographic techniques when comparing pre- and post-treatment implant positions is considered a potential source of error. Finally, a small number of studies have focused on the value of guided surgery in enabling the intended prosthetic plan or the final esthetic result.

Even though these limitations are generally recognized in the literature, there is indication that a digital workflow results in a higher level of accuracy,²⁸ hence justifying its use.

More studies are necessary to draw further conclusions. In the present study, the attention is focused on fully edentulous patients, since the percentage of older patients is constantly on the rise as life expectancy increases.³⁶ Hence, the incidence of the fully edentulism patient is growing as well, creating the need for simplifying fixed implant rehabilitation for this population.³⁶

Aim and Hypothesis

Aims

1. The primary aim was to assess the 3-D implant deviations between the implant analogs of the casts generated from the Nobel Biocare CAD/CAM surgical guides and the implant analogs of the post-surgical casts.
2. The secondary aim was to assess the 3-D implant deviations between the maxillary and mandibular arches.
3. The tertiary aim was to assess the 3-D implant deviations between arches with 4 implants placed in comparison to arches with 6 implants.

Hypotheses

1. The primary hypothesis is that there are measurable differences between the 3-D implant deviations of the virtually planned implants when compared to the actual implant positions in edentulous patients.
2. The secondary hypothesis is that for fully edentulous patients there are higher positional deviations in mandibular arches with respect to maxillary arches when comparing the 3-D implant deviations of the virtually planned implants and the actual implant positions.

3. The tertiary hypothesis is that for fully edentulous patients there are higher positional deviations in arches containing 6 implants with respect to arches containing 4 implants when comparing the 3-D implant deviations of the virtually planned implants and the actual implant positions.

Materials and Methods

Study population

The stone casts and surgical guides from 25 fully edentulous arches of patients treated in the postgraduate Prosthodontics clinics of Tufts University School of Dental Medicine were included in the study. IRB approval was attained for the study.

The 19 patients (25 jaws) had been treated between July 1st 2014 to November 30th 2018, and all included patients who underwent computer planned and template guided implant surgery following the Nobel Guide implant placement protocol (Nobel Biocare AB, Gothenburg, Sweden). Six patients received upper and lower full-arch implant rehabilitation. The indication for computer-planned/template-guided implant placement was confirmed for each patient and informed consent was obtained.

The treatment was conducted by postgraduate prosthodontics residents with the supervision of three experienced faculty members in the Department of Prosthodontics at Tufts University School of Dental Medicine.

Treatment sequence and study protocol

The medical history of each patient was recorded and suitability for implant placement was confirmed. All patients had to have adequate bone volume for the placement of at least 4 implants for restorability with an overdenture or a fixed prosthesis. A minimum of 50mm mouth opening was required for surgical instrumentation. Patients were excluded from treatment if the previous requirements were not met. (Figures 1 and 2)

The patients' dentures were examined intraorally to ensure proper occlusion and fit were present. All necessary adjustments were completed prior to their utilization as radiographic CBCT guides for the dual scan technique. A minimum of eight fiducial markers were placed on each denture. The dentures were stabilized with an inter-occlusal index (Blu-Mousse®, Parkell inc., Edgewood, NY) at the time of CBCT.

CBCT scan and surgical planning

A CBCT scan (i-CAT® FLX Cone Beam 3D system) was taken of each patient wearing the denture. A second CBCT scan was then taken of the denture alone. The two scans were then superimposed using the Nobel Clinician software (Nobel Biocare).

The virtual planning of the implant placement was subsequently completed and sent to Nobel Biocare for fabrication of the surgical guide to Nobel Biocare. (Figure 3)

Surgery

The Nobel Guide™ protocol was followed for implant placement with the use of the fabricated surgical guide. The guide was stabilized intraorally prior to surgery with an inter-occlusal index, and anchor pins were placed. All 25 edentulous jaws received 4 to 6 internal connection implants (Replace Conical Connection, Nobel Biocare). Following implant placement, the patients were seen for follow-up appointments. (Figures 4 and 5)

Group One (I)

Full-arch open tray splinted impressions were taken a minimum of three months post-surgery. Urethane dimethacrylate-based visible light-cured resin (Triad Gel; Dentsply Inc, York, PA)

was used to splint the implant level impression copings. The resin was standardized by using previously fabricated bars of standardized width which were then connected intra-orally. Polyether (Impregum, 3M ESPE, St Paul, MN, USA) was used as the impression material.

Plastic stock trays were used for the impressions. Windows were opened in the tray to allow the impression copings to be unscrewed. Paraffin wax was used to seal the windows, and tray adhesive was applied and allowed to dry. The trays were handheld during the polymerization time as per manufacturer's instructions. Once the polyether was set, the impression copings were untightened and the tray removed. Implant analogs were then screwed to the impression copings, soft-tissue material (Coltène® Gi-Mask) was applied, and the impression was poured with low expansion (0.06%) type IV die stone (New FujiRock® IMP GC Corp, Tokyo, Japan). (Figure 6)

Group Two (II)

The surgical guides used during the implant surgeries were poured with low expansion (0.06%) type IV die stone (New FujiRock® IMP GC Corp, Tokyo, Japan) for the fabrication of the test stone casts.

For the fabrication of the stone casts, implant analogs were mounted to the guide sleeves using the dedicated guided cylinders and connected with the guided cylinders pins. Soft-tissue material (Coltène® Gi-Mask) was then squirted around the guided cylinders and analogs using a small injection syringe, after which the type IV stone was poured on top. Once set, the guided cylinders pins were untightened and the casts separated from the guides.

(Figures 7 and 8)

Confidentiality

The collected casts and guides were completely de-identified prior to collection by the providers, and each cast received a matching randomly assigned numerical code to its corresponding guide.

Superimposition and accuracy measurements

Stone cast digitization procedures

Once the stone casts were set, a storage period of 1 week within secure containers at a constant temperature and humidity level was observed prior to measurements. A high-resolution extra-oral scanner (Activity 880 scanner; Smart Optics, Bochum, Germany) was then used to scan the models from group I and II. The Activity 880 scanner features a 3D transformation tool that aids in scanning and capturing the implants' 3-D positions and is equipped with a white light camera which captures multiple pictures that are then converted into a 3D image.

In order to capture the implant 3-D positions during the scanning, scan bodies were screwed into the analogs of each cast for both test groups. The scans were saved as STL digital files. (Figure 9)

STL superimposition procedures

The superimposition of the STL files of the corresponding casts of each group was performed using a reverse engineering inspection software (Geomagic), which calculated the root-mean-square error (RMSE) of the implant positions indicating the discrepancy between each corresponding pair of casts (post-insertion implant casts vs surgical guide casts).

(Figures 10 to 12)

Sample Size

A convenience sample comprising of casts of edentulous maxillae and mandibles of patients who underwent computer planned and template guided implant placement was used for the time frame of July 1st 2014 to November 30th 2018.

Statistical Analysis

Descriptive statistics were computed for all categorical variables, providing counts and percentages. For continuous variables the mean, median, standard deviation, interquartile range, minimum value, and maximum value were provided. Due to the presence of non-independent samples between maxillary and mandibular casts, a mixed-effects model was used. As will be described in the Results section, some analyses were conducted using log-transformed data due to evidence of non-normality. In cases in which log-transforming the data did not yield evidence of normality, the outliers were removed from the analysis, which resulted in no evidence of non-normality. The level of significance was set at $\alpha = 0.05$. The statistical software package R (Version 3.5.1) was used for the analysis.

Results

Nineteen patients and 25 arches were included in the study. A total of 14 maxillary arches (56%) and 11 mandibular arches (44%) were analyzed, of which 9 arches had 4 implants (36%) and 16 arches had 6 implants placed (64%). The mean age of the subjects was 63.6 years (SD ± 8.8), 7 subjects were female (36.8%) and 12 were male (63.2%). In total, 132 implants were placed, 74 in maxillary arches and 58 in mandibular arches. (Table 1)

A maxillary and a mandibular arch, both corresponding to the same subject, were outliers, with a reported RMSE of 0.692mm for the maxilla and 0.671mm for the mandible.

The analysis of the overall discrepancy between the planned implant positions with respect to the final implant positions yielded an RMSE mean of 0.199mm (SD ± 0.154), a median of 0.145mm, and an interquartile range of 0.082mm, a minimum value of 0.066mm, and a maximum value of 0.692mm. (Table 2) (Figure 13)

The discrepancy resulting from the comparison of maxillary arches versus mandibular arches yielded a RMSE mean of 0.187mm (SD ± 0.151) for the maxillae, and 0.214 (SD ± 0.163) for the mandibles. During the comparison between maxillary and mandibular arches, evidence of non-normality was found. The data were therefore log transformed, yet the evidence of non-normality persisted. Thus, a third analysis was conducted with the exclusion of the two outlier values, and no evidence of non-normality was found. No log-transformation was needed for the third analysis. In all three analyses, a p-value of >0.05 was found; hence the results were deemed not statistically significant. (Table 3) (Figure 14)

The discrepancy resulting from the comparison of arches containing 4 implants versus 6 implants yielded a RMSE mean of 0.146mm (SD ± 0.058) and 0.229 (SD ± 0.183). During the

comparison between arches containing 4 implants versus arches containing 6 implants, evidence of non-normality was found. The data were therefore log transformed, and no evidence of non-normality was found. In both analyses, a p-value of <0.05 was detected. Hence the results were deemed statistically significant. (Table 4) (Figure 15)

Discussion

Study description and analysis

Digital planning for implant surgery has transformed the surgical approach from bone driven placement to prosthetically driven placement. For this purpose, surgical guide templates have become an increasingly integral tool in implant dentistry, rendering their precision and accuracy of paramount importance. However, there is a paucity of clinical studies reporting on the accuracy of guided surgery for fully edentulous patients.

This study was therefore designed with the objective of comparing the pre-surgical software planned implant positions versus the post-surgical implant positions, in an effort to determine the reliability of one of the most commonly used static guided surgical protocols, specifically the Nobel Biocare system, in transferring the information present from the digital planning phase into the surgical phase.

Two additional aims were included into this study. The first was to analyze the potential discrepancy between guided implant placements completed in maxillary arches with those in mandibular arches. Of specific interest was the assessment whether their intrinsic anatomical differences correspond to a significant difference in the accuracy and precision of the implant placement. The second aim was the analysis of potential discrepancies when a differing number of implants are inserted through a guided protocol, specifically 4 versus 6 implants, with the objective of analyzing whether an increase in the number of implants placed within a single surgical procedure is associated with the overall accuracy and precision implant placement.

For the analysis of the aforementioned objectives, stone casts of the planned implant positions and of the placed implants were scanned and superimposed, and the overall 3-D discrepancy quantified with the Geomagic software by using its 'best-fit match' algorithm, which calculates the positional deviations in three dimensions. The positional deviations were subsequently recorded by the software via RMSE in millimeters.

Findings of the present study

When comparing the planned to the actually achieved implant positions, the mean \pm SD RMSE discrepancy was 0.199mm \pm 0.154mm. When comparing the RMSE of maxillary arches and mandibular arches, the difference was not found to be statistically significant. On the other hand, when comparing the RMSE of 4 versus 6 implants, the results showed statistical significance.

The mean RMSE for the maxillary arches was 0.187mm (SD \pm 0.151mm), and 0.214mm (SD \pm 0.163mm) for the mandibular arches, resulting in a mean difference of 0.027mm of increased discrepancy in the mandibular arches with respect to the maxillary arches. The mean RMSE for the arches containing 4 implants was 0.146mm (SD \pm 0.058mm) while it was 0.229mm (SD \pm 0.183mm) for the arches containing 6 implants, resulting in a mean difference of 0.083mm of increased discrepancy in the arches containing 6 implants. This demonstrated that the discrepancy amount between 4 versus 6 implants was more than three times higher than between maxillae and mandibles.

Clinical implications of present study

From a clinical perspective, these results suggest that surgical guides are a reliable tool for implant placement. Despite there being a statistically significant discrepancy between the placement of 4 versus 6 implants, the discrepancy is not clinically relevant with regards to anatomically important structures, such as the inferior alveolar nerve or the lingual artery. This is due to the 1.5mm safety zone the Nobel Clinician software automatically places around the virtual implant when planning an implant placement. This places the above analyzed discrepancies between the planned implant position and the placed implant safely within this range.

When considering prosthetic implications, a study by Jemt et al. has shown that there is a certain biologic tolerance of up to about 0.275mm to static forces in living bone in correlation to prosthetic misfit when splinting implants.³⁷ After a 5-years follow up, no correlation to bone loss was found due to prosthetic misfit.³⁷ A more recent study by Pappaspyridakos et al. demonstrated a 100% survival rate and no biological complications at the 5-year follow-up of 14 full arch one-piece implant prostheses and 2 full arch two-piece segmented prostheses.³⁸ The present results fell steadily within that range of discrepancy, the only exceptions being the two outlier measurements pertaining to the maxillary and mandibular arches of a single patient. This would seem to suggest that during the virtual implant planning phase, it is feasible for the clinician to fabricate an immediate postoperative prosthesis via CAD/CAM an immediate postoperative prosthesis in accordance to the virtual plan despite the presence of a certain level of discrepancy present between the planned implant positions and their final positions.

Comparison with other studies

This present study's results are in disagreement with other studies on the accuracy of guided implant placement, which showed higher levels of discrepancy between the planned and final implant positions.

Cassetta et al. compared the preoperative digitally planned implant positions with respect to the postoperative positions on fourteen arches, with the placement of 116 implants in both the maxilla and the mandible.³⁹ The analysis of the postoperative CT scan resulted in a mean global deviation in the coronal and the apical portions of 1.47mm and 1.83mm respectively, and mean angular deviation of 5.09 degrees.³⁹ Statistically significant deviations between the implant positions in all measurements except for angular discrepancy in correlation to apical discrepancy were found.³⁹ A comparison between maxillary arches and mandibular arches yielded a statistically significantly increased discrepancy in mandibular arches,³⁹ which is in contrast with the present study that found no statistical significance in that comparison, although mandibular arches did result having a higher mean discrepancy with respect to maxillary arches. Mucosa supported guides produced statistically significantly increased accuracy with respect to both bone and tooth supported guides. Furthermore, in fully edentulous arches, a decreased amount of discrepancy in comparison to partially edentulous patients was observed.³⁹ The discrepancy values reported in that study were significantly higher than the discrepancy values found in the present study, although some limitations of the cited study such as the lack of use of fixation screws, a guided drilling sequence, but not guided implant insertion may have significantly impacted the overall accuracy of the implants placed. In the present study all implants were placed with a fully guided approach. Furthermore,

fixation pins were used in all surgeries, eliminating a possible source of error with template placement and stability.

Similar results were found in the two studies by Petterson et al.. In the first study 145 implants were placed in edentulous cadavers in both arches using the Nobel Biocare guided protocol. In the second study, 139 implants were placed in both arches using the same protocol but on live edentulous patients.^{40,41} All implants in both studies were compared to the planned positions via a postoperative CBCT scan. The first study presented a mean discrepancy of 1.06mm coronally and 1.25mm apically, whereas the second study presented a mean discrepancy of 0.80mm coronally and 1.09mm apically.^{40,41} When differentiating between arches, the second study found a mean coronal discrepancy of 0.80mm for both maxillae and mandibles, and a mean apical discrepancy of 1.05 mm for the maxillary, and 1.15 mm for the mandibular implants.^{40,41} In accordance with the present study, the preoperative and postoperative implant positions displayed a positional discrepancy, but when analyzing the discrepancy values between maxillae and mandibles, the results were not statistically significant.

A study by Di Giacomo et al. in which 62 implants were inserted in both the maxillary and mandibular arches of 12 edentulous patients and subsequently analyzed via a postoperative CBCT scan, found an average coronal discrepancy of 1.35mm, and a mean apical discrepancy of 1.79mm.⁴² The discrepancies between planned and final implant positions were found to be statistically significant.⁴² When comparing the discrepancies between maxillae and mandibles, statistically significant angular deviations were found, but they were not statistically significant for lateral deviations.

In a study by Arisan et al. 108 implants were placed, 64 in the maxilla and 44 in the mandible, on 11 patients with a total of 18 arches.⁴³ Due to titanium-related heavy beam scattering only

102 implants could be measured for deviations, out of which 50 were measured with the use of a postoperative CT scan, and 52 by means of a postoperative CBCT scan.⁴³ The authors found a mean linear deviation of 0.75mm at the implant shoulder, and 0.80mm at the apex in the CT group, whereas the mean linear deviations in the CBCT group were in 0.81mm at the implant shoulder and 0.87mm at the apex. These differences between the two groups were not statistically significant.⁴³ When the results for the maxillary implants between the CT and CBCT groups were compared to those for the mandibular implants in both groups, no statistically significant difference was found,⁴³ which is in agreement with the present study.

Explanation of discrepancies

Despite the results of the aforementioned studies being similar with regards to the presence of discrepancy and lack of statistical significance when comparing maxillary arches to mandibular arches, and the similarity in surgical approaches through the use of mucosa supported guides stabilized via fixation pins or screws on fully edentulous patients, the discrepancy amounts appear to be considerably inferior in the present study. An overall mean discrepancy of 0.199mm was found with respect to the cited studies which reported discrepancy values hovering around the 1mm range. A possible explanation for this observation might be the differing methods used to analyze the discrepancy. The previous studies all used a postoperative CBCT scan for the superimposition between planned and placed implants. This method is subject to several problems, such as patient movement during the scanning procedure, which can significantly impact the accuracy of the scan and therefore of the subsequent measurements, as demonstrated by Pettersson et al.⁴¹ A further element of error can be caused by the presence of metallic restorations, which produce artefacts and image

degradation which significantly impacts the image quality resulting in frequent misrepresentations of the areas of interest, as concluded by Tadinada et al.⁴⁴ Additionally, the segmentation of the data set as well as the image cleaning have to be performed carefully, introducing a further source of possible inaccuracy when utilizing this method for post-surgical implant position analysis,⁴⁵ such as incorrect grey density thresholds which can yield gross deformation of an SLA guide.⁴⁶ Manual segmentation should also always be the preferred segmentation method over default segmentation by the planning software, in order to try and further minimize errors.⁴⁷ Lastly, another major disadvantage of using the voxel-based registration method is the need for the patients to undergo a second CT/CBCT scan, unnecessary for treatment purposes, exposing them to an additional dose of radiation.⁴⁸

These possible sources of error were not present in this study, since the implant positions were not analyzed via a secondary CT/CBCT, but rather through the superimpositions of stone casts poured in type 4 dental die stone with a setting expansion of 0.06% and scanned via an extraoral scanner with capturing capabilities of up to 10 microns. The scanning of stone casts by means of an extraoral scanner has been shown to be accurate regardless of implant positional distance or arch size,⁴⁹ whereas intraoral scanners have been shown to increase in error the larger the scanned section is,⁵⁰ hence the choice to utilize an extraoral scanner for the purposes of this study. This same implant discrepancy analysis method was used by Komiyama et al. in a study which analyzed 25 arches and 139 implants, 89 implants in 15 maxillae and 50 implants in 10 mandibles.⁴⁸ Casts obtained by pouring the stereolithographic guides were scanned and superimposed with casts obtained by intraoral impressions after the implants' insertion, thus determining the respective implants' positions.⁴⁸ Geomagic software was used to quantify the discrepancy levels using the software's best-fit-alignment algorithm.⁴⁸ The overall mean

discrepancy values for the 25 arches were 0.51mm for both the implant shoulder and implant apex, yielding no statistically significant difference between the two, whereas there was a statistically significant difference between the planned positions and the final positions.⁴⁸ When comparing the mean values of the maxillae with respect to the mandibles, the mean values at the implant shoulder were 0.59mm in the maxilla and 0.39mm in the mandible, and 0.59mm in the maxilla and 0.40mm in the mandible at the apical level, yielding a statistically significant difference,⁴⁸ which was not found in the present study.

In comparison to the studies in which implant positions were compared by the use of a postoperative CT/CBCT scan, the results found in the study by Komiyama et al. yielded much closer discrepancy values to the present study. In the Komiyama study, the overall discrepancy for 25 arches was found to be 0.199mm and 0.187mm for the 14 maxillary arches analyzed and 0.214mm for the 11 mandibular arches. Possible reasons for the higher discrepancy values shown in that study in comparison to the present one can be found under the possible accumulation of errors due to a number of different factors. The postoperative intraoral impressions were taken without splinting the impression copings, which has been shown to introduce a higher chance of distortion and decreased impression accuracy and implant stability when taking an impression of multiple adjacent implants.⁵¹⁻⁵⁷ Furthermore, splinting prevents rotational movement of the impression copings at the time of analog fastening.⁵⁸ In the present study all implants were splinted for the purpose of impression taking. Another element of consideration is that in the Komiyama study the implants were immediately loaded after placement, which could have resulted in minor implant movement of the not yet osseointegrated implants either by the implant abutment or prosthesis connection.^{59,60} In the present study as all implants were loaded after osseointegration was completed. Lastly, the

accuracy of the lab scanner used was of 12 μ m, whereas the lab scanner used in the present study presents an accuracy of 10 μ m.

With respect to the third aim of this study, the comparison between arches containing 4 implants with respect to 6 implants, no other study that the present authors were able to find reported on this specific comparison, where a statistically significant difference was found. The authors hypothesize that the greater deviations found in implant positions in arches containing 6 implants may be due to the added stress and flexure of the guide during the drilling sequence, which could have affected the accuracy of the guide itself, despite the insertion of fixation pins.^{27,59,61-63} It is widely recognized that there is a need for adequate drill guide stabilization during guided implant placement,^{39,43,59,61-66} yet fixation pins are traditionally located in the anterior and buccal portion of the arch, therefore inherently subjecting the posterior and lingual portions of a guide to decreased stabilization, which could explain why when placing a greater number of implants and particularly moving further distally into the arch there can be an increased possibility of guide flexure and micro-movement and hence of implant placement inaccuracy.

Studies by Malo et al., Lopes et al., and Hopp et al. on the all-on-4 concept with follow-ups of between 5 to 18 years on over two thousand patients, have shown that the restoration of fully edentulous arches with the placement of only 4 implants yields a prosthetic success rate of up to 99%, and an implant survival rate of up to 95%.⁶⁷⁻⁷⁰ Furthermore, the placement of tilted implants of up to 45 degrees showed no increased bone loss when compared to axially placed implants, while helping prevent complicated and lengthy bone grafting procedures for the patient, thus both reducing the patient's morbidity as well as the financial burden of the overall

treatment.⁶⁷⁻⁷⁰ The present study's results showed a statistically significant decrease in positional implant discrepancy when placing 4 implants in comparison to 6 implants via a fully guided approach. These findings, coupled with the aforementioned studies, suggest that in cases in which bone volume deficiencies are present, the placement of 4 implants is not only acceptable, but may actually be preferable due to the increased level of accuracy shown in the surgically guided implant placements.

The findings of the present and previous studies may possibly indicate that despite the efforts to minimize error in fabrication and during the surgical procedure, a complete elimination of error may not be possible due to physiological factors such as mucosal resiliency,⁷¹ tolerance within the template,⁷² and radiographic distortion.⁷³ Despite this, no complications were reported in association with any critical anatomical structures in the cited investigations, the present one included. Thus, the use of SLA guides can be deemed safe and warranted for a more accurate and safe surgical implant placement.⁶⁰

Amongst the strengths of the present study was the exclusive comparison of mucosa supported guides. Multiple studies have been conducted on partially edentulous patients and both bone and tooth supported surgical templates, yielding varying results,^{62,74-84} though it has been shown that bone supported guides are the least accurate, whereas mucosa supported and tooth-supported guides positively compare to each other.⁸⁵

Limitations of the present study

A major limitation of the current study was the use of the general RMSE given by the best-fit-alignment for the analysis and comparison of the implant positions, which did not allow for a breakdown of the deviations in accordance to specific implant points such as the implant shoulder or apex, as well as its angular misfit. Another limitation was the use of a single surgical template system, which therefore does not provide for precise accuracy estimates for other systems. Due to differences in protocol and template fabrication, results may show different amounts of discrepancy. Lastly, methodological limitations such as the fabrication of the stone casts at different times as well as the storage of the guides could have had some impact on their accuracy.

Suggestions for future investigations

Future investigations should compare different systems and protocols of guided implant surgery as well as include a larger pool of arches and implants. Another aspect which could be analyzed in future studies is the discrepancy between implants placed in the anterior region of the maxilla and mandible relative to implants placed in the posterior region, to evaluate whether the discrepancy is mostly derived from a specific region due to flexure and micro-movements of the templates or whether it is homogenous.

Conclusion

Within the limitations of this study, the following conclusions may be drawn:

1. 3-D discrepancies were found between the virtually planned implant positions and the surgically placed implants using the Nobel Biocare guided surgery protocol.
2. When comparing the implant positional discrepancies between maxillary and mandibular arches, no statistically significant differences were found.
3. When comparing the implant 3-D discrepancies between arches containing 4 implants and arches containing 6 implants, statistically significant differences were found, with lower deviations in the group containing 4 implants.

References

1. Buser D, Sennerby L, De Bruyn H. Modern implant dentistry based on osseointegration: 50 years of progress, current trends and open questions. *Periodontol 2000*. 2017;73(1):7-21.
2. Paspaspyridakos P, Chen C-J, Gallucci GO, Doukoudakis A, Weber H-P, Chronopoulos V. Accuracy of implant impressions for partially and completely edentulous patients: a systematic review. *Int J Oral Maxillofac Implants*. 2014;29(4):836-845. doi:10.11607/jomi.3625
3. Malo P, de Araujo Nobre M, Lopes A, Ferro A, Botto J. The All-on-4 treatment concept for the rehabilitation of the completely edentulous mandible: A longitudinal study with 10 to 18 years of follow-up. *Clin Implant Dent Relat Res*. March 2019. doi:10.1111/cid.12769
4. Malo P, de Araujo Nobre M, Lopes A, Moss SM, Molina GJ. A longitudinal study of the survival of All-on-4 implants in the mandible with up to 10 years of follow-up. *J Am Dent Assoc*. 2011;142(3):310-320.
5. Niedermaier R, Stelzle F, Riemann M, Bolz W, Schuh P, Wachtel H. Implant-Supported Immediately Loaded Fixed Full-Arch Dentures: Evaluation of Implant Survival Rates in a Case Cohort of up to 7 Years. *Clin Implant Dent Relat Res*. 2017;19(1):4-19. doi:10.1111/cid.12421
6. Lambert FE, Weber H-P, Susarla SM, Belser UC, Gallucci GO. Descriptive Analysis of Implant and Prosthodontic Survival Rates With Fixed Implant-Supported Rehabilitations in the Edentulous Maxilla. *J Periodontol*. 2009;80(8):1220-1230. doi:10.1902/jop.2009.090109
7. Tran DT, Gay IC, Diaz-Rodriguez J, Parthasarathy K, Weltman R, Friedman L. Survival of Dental Implants Placed in Grafted and Nongrafted Bone: A Retrospective Study in a University Setting. *Int J Oral Maxillofac Implants*. 2016;31(2):310-317. doi:10.11607/jomi.4681
8. Bagegni A, Abou-Ayash S, Rucker G, Algarny A, Att W. The influence of prosthetic material on implant and prosthetic survival of implant-supported fixed complete dentures: a systematic review and meta-analysis. *J Prosthodont Res*. March 2019. doi:10.1016/j.jpor.2019.02.001
9. Mertens C, Steveling HG. Implant-supported fixed prostheses in the edentulous maxilla: 8-year prospective results. *Clin Oral Implants Res*. 2011;22(5):464-472. doi:10.1111/j.1600-0501.2010.02028.x
10. Kinsel RP, Lin D. Retrospective analysis of porcelain failures of metal ceramic crowns

and fixed partial dentures supported by 729 implants in 152 patients: patient-specific and implant-specific predictors of ceramic failure. *J Prosthet Dent.* 2009;101(6):388-394. doi:10.1016/S0022-3913(09)60083-4

11. Papaspyridakos P, Lal K. Immediate loading of the maxilla with prefabricated interim prosthesis using interactive planning software, and CAD/CAM rehabilitation with definitive zirconia prosthesis: 2-year clinical follow-up. *J Esthet Restor Dent.* 2010;22(4):223-232. doi:10.1111/j.1708-8240.2010.00343.x
12. Hammerle CHF, Chen ST, Wilson TGJ. Consensus statements and recommended clinical procedures regarding the placement of implants in extraction sockets. *Int J Oral Maxillofac Implants.* 2004;19 Suppl:26-28.
13. Mello CC, Lemos CAA, Verri FR, Dos Santos DM, Goiato MC, Pellizzer EP. Immediate implant placement into fresh extraction sockets versus delayed implants into healed sockets: A systematic review and meta-analysis. *Int J Oral Maxillofac Surg.* 2017;46(9):1162-1177. doi:10.1016/j.ijom.2017.03.016
14. Chen ST, Beagle J, Jensen SS, Chiapasco M, Darby I. Consensus statements and recommended clinical procedures regarding surgical techniques. *Int J Oral Maxillofac Implants.* 2009;24 Suppl:272-278.
15. Chen ST, Buser D. Esthetic outcomes following immediate and early implant placement in the anterior maxilla--a systematic review. *Int J Oral Maxillofac Implants.* 2014;29 Suppl:186-215. doi:10.11607/jomi.2014suppl.g3.3
16. Pellicer-Chover H, Penarrocha-Oltra D, Bagan L, Fichy-Fernandez A-J, Canullo L, Penarrocha-Diago M. Single-blind randomized clinical trial to evaluate clinical and radiological outcomes after one year of immediate versus delayed implant placement supporting full-arch prostheses. *Med Oral Patol Oral Cir Bucal.* 2014;19(3):e295-301. doi:10.4317/medoral.19536
17. Oxby G, Oxby F, Oxby J, Saltvik T, Nilsson P. Early Loading of Fluoridated Implants Placed in Fresh Extraction Sockets and Healed Bone: A 3- to 5-Year Clinical and Radiographic Follow-Up Study of 39 Consecutive Patients. *Clin Implant Dent Relat Res.* 2015;17(5):898-907. doi:10.1111/cid.12210
18. Krennmair S, Seemann R, Weinlander M, Krennmair G, Piehslinger E. Immediately loaded distally cantilevered fixed mandibular prostheses supported by four implants placed in both in fresh extraction and healed sites: 2-year results from a prospective study. *Eur J Oral Implantol.* 2014;7(2):173-184.
19. Papaspyridakos P, Chen C-J, Chuang S-K, Weber H-P. Implant loading protocols for edentulous patients with fixed prostheses: a systematic review and meta-analysis. *Int J Oral Maxillofac Implants.* 2014;29 Suppl:256-270. doi:10.11607/jomi.2014suppl.g4.3
20. Sanz-Sanchez I, Sanz-Martin I, Figuero E, Sanz M. Clinical efficacy of immediate implant loading protocols compared to conventional loading depending on the type of

the restoration: a systematic review. *Clin Oral Implants Res.* 2015;26(8):964-982.
doi:10.1111/clar.12428

21. Weber H-P, Morton D, Gallucci GO, Rocuzzo M, Cordaro L, Grütter L. Consensus Statements and Recommended Clinical Procedures Regarding Loading Protocols. *Int J Oral Maxillofac Implants.* 2009;24:180-184.
22. Esposito M, Grusovin M, Maghaireh H, Worthington H. Interventions for replacing missing teeth: different times for loading dental implants (Review). *Cochrane Database Syst Rev.* 2013;(3):3-5. doi:10.1002/14651858.CD003878.pub5. Copyright
23. Wismeijer D, Joda T, Flugge T, et al. Group 5 ITI Consensus Report: Digital technologies. *Clin Oral Implants Res.* 2018;29 Suppl 1:436-442.
doi:10.1111/clar.13309
24. Vercruyssen M, Fortin T, Widmann G, Jacobs R, Quirynen M. Different techniques of static/dynamic guided implant surgery: modalities and indications. *Periodontol 2000.* 2014;66(1):214-227. doi:10.1111/prd.12056
25. Joda T, Derksen W, Wittneben JG, Kuehl S. Static computer-aided implant surgery (s-CAIS) analysing patient-reported outcome measures (PROMs), economics and surgical complications: A systematic review. *Clin Oral Implants Res.* 2018;29 Suppl 1:359-373. doi:10.1111/clar.13136
26. Laleman I, Bernard L, Vercruyssen M, Jacobs R, Bornstein MM, Quirynen M. Guided Implant Surgery in the Edentulous Maxilla: A Systematic Review. *Int J Oral Maxillofac Implants.* 2016;31 Suppl:s103-17. doi:10.11607/jomi.16suppl.g3
27. Tahmaseb A, Wismeijer D, Coucke W, Derksen W. Computer Technology Applications in Surgical Implant Dentistry: A Systematic Review. *Int J Oral Maxillofac Implants.* 2014;29(Supplement):25-42. doi:10.11607/jomi.2014suppl.g1.2
28. Tahmaseb A, Wu V, Wismeijer D, Coucke W, Evans C. The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clin Oral Implants Res.* 2018;29 Suppl 1:416-435. doi:10.1111/clar.13346
29. Marra R, Acocella A, Rispoli A, Sacco R, Ganz SD, Blasi A. Full-Mouth Rehabilitation With Immediate Loading of Implants Inserted With Computer-Guided Flap-Less Surgery. *Implant Dent.* 2013;22(5):444-452.
doi:10.1097/ID.0b013e31829f1f7f
30. Rutkunas V, Geciauskaite A, Jegelevicius D, Vaitiekunas M. Accuracy of digital implant impressions with intraoral scanners. A systematic review. *Eur J Oral Implantol.* 2017;10 Suppl 1:101-120.
31. D'haese J, Ackhurst J, Wismeijer D, De Bruyn H, Tahmaseb A. Current state of the art of computer-guided implant surgery. *Periodontol 2000.* 2017;73(1):121-133.
doi:10.1111/prd.12175

32. Malo P, de Araujo Nobre M, Lopes A. The use of computer-guided flapless implant surgery and four implants placed in immediate function to support a fixed denture: preliminary results after a mean follow-up period of thirteen months. *J Prosthet Dent.* 2007;97(6).
33. Kupeyan HK, Shaffner M, Armstrong J. Definitive CAD/CAM-guided prosthesis for immediate loading of bone-grafted maxilla: A case report. *Clin Implant Dent Relat Res.* 2006;8(3):161-167. doi:10.1111/j.1708-8208.2006.00018.x
34. Balshi SF, Wolfinger GJ, Balshi TJ. Guided implant placement and immediate prosthesis delivery using traditional Brånemark System abutments: a pilot study of 23 patients. *Implant Dent.* 2008;17:128-135. doi:10.1097/ID.0b013e318177798e
35. Moraschini V, Velloso G, Luz D, Barboza EP. Implant survival rates, marginal bone level changes, and complications in full-mouth rehabilitation with flapless computer-guided surgery: a systematic review and meta-analysis. *Int J Oral Maxillofac Surg.* 2015;44(7):892-901. doi:10.1016/j.ijom.2015.02.013
36. Papaspyridakos P, Rajput N, Kudara Y, Weber HP. Digital Workflow for Fixed Implant Rehabilitation of an Extremely Atrophic Edentulous Mandible in Three Appointments. *J Esthet Restor Dent.* 2017;29(3):178-188. doi:10.1111/jerd.12290
37. Jemt T, Book K. Prosthesis misfit and marginal bone loss in edentulous implant patients. *Int J Oral Maxillofac Implants.* 1997;11(5):620-625.
38. Papaspyridakos P, Lal K. Computer-assisted design/computer-assisted manufacturing zirconia implant fixed complete prostheses: Clinical results and technical complications up to 4 years of function. *Clin Oral Implants Res.* 2013;24(6):659-665. doi:10.1111/j.1600-0501.2012.02447.x
39. Cassetta M, Stefanelli L V, Giansanti M, Calasso S. Accuracy of implant placement with a stereolithographic surgical template. *Int J Oral Maxillofac Implants.* 2012;27(3):655-663.
40. Pettersson A, Kero T, Gillot L, et al. Accuracy of CAD/CAM-guided surgical template implant surgery on human cadavers: Part I. *J Prosthet Dent.* 2010;103(6):334-342. doi:10.1016/S0022-3913(10)60072-8
41. Pettersson A, Komiyama A, Hultin M, Näsström K, Klinge B. Accuracy of Virtually Planned and Template Guided Implant Surgery on Edentate Patients. *Clin Implant Dent Relat Res.* 2012;14(4):527-537. doi:10.1111/j.1708-8208.2010.00285.x
42. Di Giacomo GA, da Silva J V., da Silva AM, Paschoal GH, Cury PR, Szarf G. Accuracy and Complications of Computer-Designed Selective Laser Sintering Surgical Guides for Flapless Dental Implant Placement and Immediate Definitive Prosthesis Installation. *J Periodontol.* 2012;83(4):410-419. doi:10.1902/jop.2011.110115

43. Arisan V, Karabuda ZC, Pişkin B, Özdemir T. Conventional Multi-Slice Computed Tomography (CT) and Cone-Beam CT (CBCT) for Computer-Aided Implant Placement. Part II: Reliability of Mucosa-Supported Stereolithographic Guides. *Clin Implant Dent Relat Res*. 2013;15(6):907-917. doi:10.1111/j.1708-8208.2011.00435.x
44. Tadinada A, Jalali E, Jadhav A, Schincaglia G, Pietro, Yadav S. Artifacts in Cone Beam Computed Tomography Image Volumes: An Illustrative Depiction. *J Mass Dent Soc*. 2015;64(1):12-15.
45. Makins SR. Artifacts interfering with interpretation of cone beam computed tomography images. *Dent Clin North Am*. 2014;58(3):485-495. doi:10.1016/j.cden.2014.04.007
46. Stumpel LJ. Deformation of Stereolithographically Produced Surgical Guides: An Observational Case Series Report. *Clin Implant Dent Relat Res*. 2012;14(3):442-453. doi:10.1111/j.1708-8208.2010.00268.x
47. Flügge T, Att W, Metzger M, Nelson K. Precision of Dental Implant Digitization Using Intraoral Scanners. *Int J Prosthodont*. 2017;29(3):277-283. doi:10.11607/ijp.4417
48. Komiyama A, Pettersson A, Hultin M, Nasstrom K, Klinge B. Virtually planned and template-guided implant surgery: an experimental model matching approach. *Clin Oral Impl Res*. 2011;22:308-313. doi:10.1111/j.1600-0501.2010.02001.x
49. Flügge T, Derksen W, te Poel J, Hassan B, Nelson K, Wismeijer D. Registration of cone beam computed tomography data and intraoral surface scans - A prerequisite for guided implant surgery with CAD/CAM drilling guides. *Clin Oral Implants Res*. 2016;1-6. doi:10.1111/clr.12925
50. Joda T, Lenherr P, Dedem P, Kovaltschuk I, Bragger U, Zitzmann NU. Time efficiency, difficulty, and operator's preference comparing digital and conventional implant impressions: a randomized controlled trial. *Clin Oral Implants Res*. 2017;28(10):1318-1323. doi:10.1111/clr.12982
51. Misch CE. *Dental Implant Prosthetics*. Elsevier; 2014.
52. Del'Acqua MA, Chavez AM, Castanharo SM, Compagnoni MA, Mollo F de A. The effect of splint material rigidity in implant impression techniques. *Int J Oral Maxillofac Implants*. 2010;25(6):1153-1158.
53. Assif D, Marshak B, Schmidt A. Accuracy of implant impression techniques. *Int J Oral Maxillofac Implants*. 1997;11(2):216-222.
54. Cabral LM, Guedes CG. Comparative analysis of 4 impression techniques for implants. *Implant Dent*. 2007;16(2):187-194. doi:10.1097/ID.0b013e3180587b3f
55. Vigolo P, Majzoub Z, Cordioli G. Evaluation of the accuracy of three techniques used

- for multiple implant abutment impressions. *J Prosthet Dent.* 2003;89(2):186-192. doi:10.1067/mpr.2003.15
56. Assuncao WG, Gennari Filho H, Zaniqueili O. Evaluation of transfer impressions for osseointegrated implants at various angulations. *Implant Dent.* 2004;13(4):358-366. doi:10.1097/01.id.0000144509.58901.f7
 57. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. An evaluation of impression techniques for multiple internal connection implant prostheses. *J Prosthet Dent.* 2004;92(5):470-476. doi:10.1016/j.prosdent.2004.08.015
 58. Wee AG. Comparison of impression materials for direct multi-implant impressions. *J Prosthet Dent.* 2000;83:323-331.
 59. D'haese J, Van De Velde T, Elaut L, De Bruyn H. A Prospective Study on the Accuracy of Mucosally Supported Stereolithographic Surgical Guides in Fully Edentulous Maxillae. *Clin Implant Dent Relat Res.* 2012;14(2):293-303. doi:10.1111/j.1708-8208.2009.00255.x
 60. Tahmaseb A, Wu V, Wismeijer D, Coucke W, Evans C. The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clin Oral Implants Res.* 2018;29(May):416-435. doi:10.1111/clr.13346
 61. Cassetta M, Di Mambro A, Giansanti M, Stefanelli L V., Cavallini C. The intrinsic error of a stereolithographic surgical template in implant guided surgery. *Int J Oral Maxillofac Surg.* 2013;42(2):264-275. doi:10.1016/j.ijom.2012.06.010
 62. Cassetta M, Giansanti M, Di Mambro A, Calasso S. Accuracy of Two Stereolithographic Surgical Templates : A Retrospective Study. *Clin Implant Dent Relat Res.* 2013;15(3):448-459. doi:10.1111/j.1708-8208.2011.00369.x
 63. Cassetta M, Stefanelli L V, Giansanti M, Di Mambro A, Calasso S. Accuracy of a Computer-Aided Implant Surgical Technique. *Int J Periodontics Restor Dent.* 2013;33(3):317-325. doi:10.11607/prd.1019
 64. Choi Y-S, Kim S-H, Lee J-B, Han J-S, Yeo I-S. In vitro evaluation of fracture strength of zirconia restoration veneered with various ceramic materials. *J Adv Prosthodont.* 2012;4(3):162-169. doi:10.4047/jap.2012.4.3.162
 65. Geng W, Liu C, Su Y, Li J, Zhou Y. Accuracy of different types of computer-aided design/computer-aided manufacturing surgical guides for dental implant placement. *Int J Clin Exp Med.* 2015;8(6):8442-8449.
 66. Vercruyssen M, Coucke W, Naert I, Jacobs R, Teughels W, Quirynen M. Depth and lateral deviations in guided implant surgery: an RCT comparing guided surgery with mental navigation or the use of a pilot-drill template. *Clin Oral Implants Res.* 2015;26(11):1315-1320. doi:10.1111/clr.12460

67. Maló P, de Araújo Nobre M, Lopes A, Ferro A, Nunes M. The All-on-4 concept for full-arch rehabilitation of the edentulous maxillae: A longitudinal study with 5-13 years of follow-up. *Clin Implant Dent Relat Res.* 2019;(February):1-12. doi:10.1111/cid.12771
68. Maló P, de Araújo Nobre M, Lopes A, Ferro A, Botto J. The All-on-4 treatment concept for the rehabilitation of the completely edentulous mandible: A longitudinal study with 10 to 18 years of follow-up. *Clin Implant Dent Relat Res.* 2019;(October 2018):1-13. doi:10.1111/cid.12769
69. Lopes A, Maló P, de Araújo Nobre M, Sánchez-Fernández E, Gravito I. The NobelGuide®All-on-4®Treatment Concept for Rehabilitation of Edentulous Jaws: A Retrospective Report on the 7-Years Clinical and 5-Years Radiographic Outcomes. *Clin Implant Dent Relat Res.* 2017;19(2):233-244. doi:10.1111/cid.12456
70. Hopp M, de Araújo Nobre M, Maló P. Comparison of marginal bone loss and implant success between axial and tilted implants in maxillary All-on-4 treatment concept rehabilitations after 5 years of follow-up. *Clin Implant Dent Relat Res.* 2017;19(5):849-859. doi:10.1111/cid.12526
71. D'haese J, De Bruyn H. Effect of smoking habits on accuracy of implant placement using mucosally supported stereolithographic surgical guides. *Clin Implant Dent Relat Res.* 2013;15(3):402-411. doi:10.1111/j.1708-8208.2011.00353.x
72. Misch CE. Density of bone: effect on surgical approach and healing. *Proc Contemp Implant Dent.* 1999:371-384.
73. Arai Y, Tammissalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac Radiol.* 1999;28:245-248.
74. Di Giacomo G a. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol.* 2005;76(April):503-507.
75. Platzer S, Bertha G, Heschl A, Wegscheider WA, Lorenzoni M. Three-Dimensional Accuracy of Guided Implant Placement: Indirect Assessment of Clinical Outcomes. *Clin Implant Dent Relat Res.* 2013;15(5):724-734. doi:10.1111/j.1708-8208.2011.00406.x
76. Vasak C, Watzak G, Gahleitner A, Strbac G, Schemper M, Zechner W. Computed tomography-based evaluation of template (NobelGuide™)-guided implant positions: A prospective radiological study. *Clin Oral Implants Res.* 2011;22(10):1157-1163. doi:10.1111/j.1600-0501.2010.02070.x
77. Van Assche N, Van Steenberghe D, Guerrero ME, et al. Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: A pilot study. *J Clin Periodontol.* 2007;34(9):816-821. doi:10.1111/j.1600-051X.2007.01110.x

78. Behneke A, Burwinkel M, Behneke N. Factors influencing transfer accuracy of cone beam CT-derived template-based implant placement. *Clin Oral Implants Res.* 2012;23(4):416-423. doi:10.1111/j.1600-0501.2011.02337.x
79. Kühl S, Zürcher S, Mahid T, Müller-Gerbl M, Filippi A, Cattin P. Accuracy of full guided vs. half-guided implant surgery. *Clin Oral Implants Res.* 2013;24(7):763-769. doi:10.1111/j.1600-0501.2012.02484.x
80. Ersoy AE, Turkyilmaz I, Ozan O, McGlumphy E a. Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *J Periodontol.* 2008;79(August):1339-1345. doi:10.1902/jop.2008.080059
81. Dreiseidler T, Neugebauer J, Ritter L, et al. Accuracy of a newly developed integrated system for dental implant planning. *Clin Oral Implants Res.* 2009;20(11):1191-1199. doi:10.1111/j.1600-0501.2009.01764.x
82. Ozan O, Turkyilmaz I, Ersoy AE, McGlumphy EA, Rosenstiel SF. Clinical Accuracy of 3 Different Types of Computed Tomography-Derived Stereolithographic Surgical Guides in Implant Placement. *J Oral Maxillofac Surg.* 2009;67(2):394-401. doi:10.1016/j.joms.2008.09.033
83. Nickenig HJ, Wichmann M, Hamel J, Schlegel KA, Eitner S. Evaluation of the difference in accuracy between implant placement by virtual planning data and surgical guide templates versus the conventional free-hand method - A combined in vivo - In vitro technique using cone-beam CT (Part II). *J Cranio-Maxillofacial Surg.* 2010;38(7):488-493. doi:10.1016/j.jcms.2009.10.023
84. Ozan O, Orhan K, Turkyilmaz I. Correlation Between Bone Density and Angular Deviation of Implants Placed Using CT-Generated Surgical Guides. *J Craniofac Surg.* 2011;22(5):1755-1761. doi:10.1097/SCS.0b013e31822e6305
85. Raico Gallardo YN, da Silva-Olivio IRT, Mukai E, Morimoto S, Sesma N, Cordaro L. Accuracy comparison of guided surgery for dental implants according to the tissue of support: a systematic review and meta-analysis. *Clin Oral Implants Res.* 2017;28(5):602-612. doi:10.1111/clr.12841

APPENDICES

Appendix A: Tables

Appendix B: Figures

Appendix A: Tables

Patient Distribution			
Patient Gender	Sample Size	Sample Size %	Mean Age (\pm SD)
Male	12	63.2	63.6 (\pm 8.8)
Female	7	36.8	

Table 1: Patient distribution

Guides vs Placed Implants						
Arch N	Implant Count	RMSE Mean (\pm SD) mm	Median (mm)	Inter Quartile Range (mm)	Minimum Value	Maximum Value
25	132	0.199 (\pm 0.154)	0.145	0.082	0.066	0.692

Table 2: Implant-positional discrepancy

Maxillae vs Mandibles								
Arch Type	Arches (%)	Implant Count	RMSE Mean (\pm SD) mm	Median (mm)	Inter Quartile Range (mm)	Min. Value	Max. Value	P-Value
Maxilla	14 (56)	74	0.187 (\pm 0.151)	0.142	0.052	0.096	0.692	0.665 *
Mandible	11 (44)	58	0.214 (\pm 0.163)	0.145	0.115	0.066	0.671	0.974 ** 0.428 ***

Table 3: Arch comparison

* Before log transformation

** After log transformation

*** Without outliers

4 Implants vs 6 Implants								
Implant N	Arches (%)	Implants Count	RMSE Mean (\pm SD) mm	Median (mm)	Inter Quartile Range (mm)	Min. Value	Max. Value	P-Value
4	9 (36)	36	0.146 (\pm 0.058)	0.136	0.071	0.066	0.267	0.006 *
6	16 (64)	96	0.229 (\pm 0.183)	0.151	0.110	0.096	0.692	0.036 **

Table 4: Comparison of number of implants per arch

* Before log transformation

** After log transformation

Appendix B: Figures

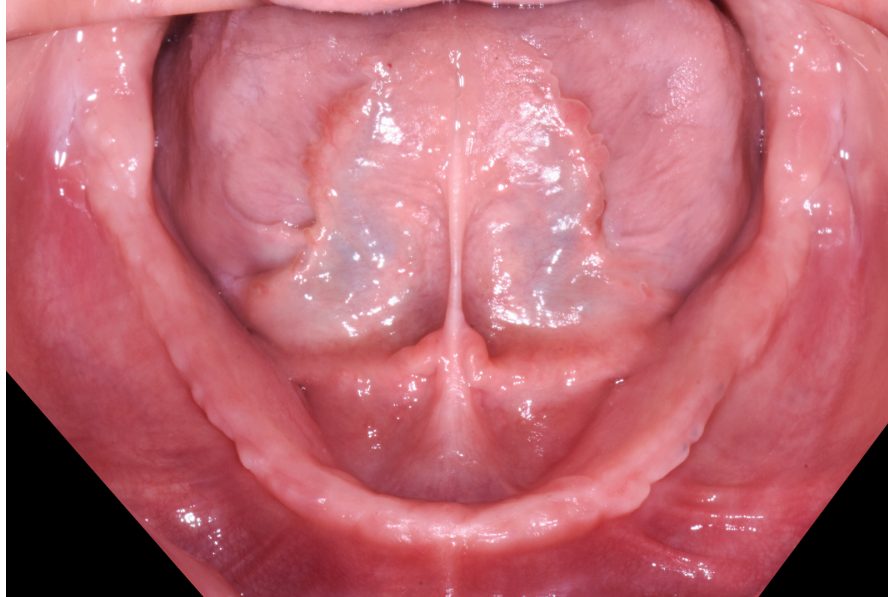


Figure 1: Edentulous mandibular arch

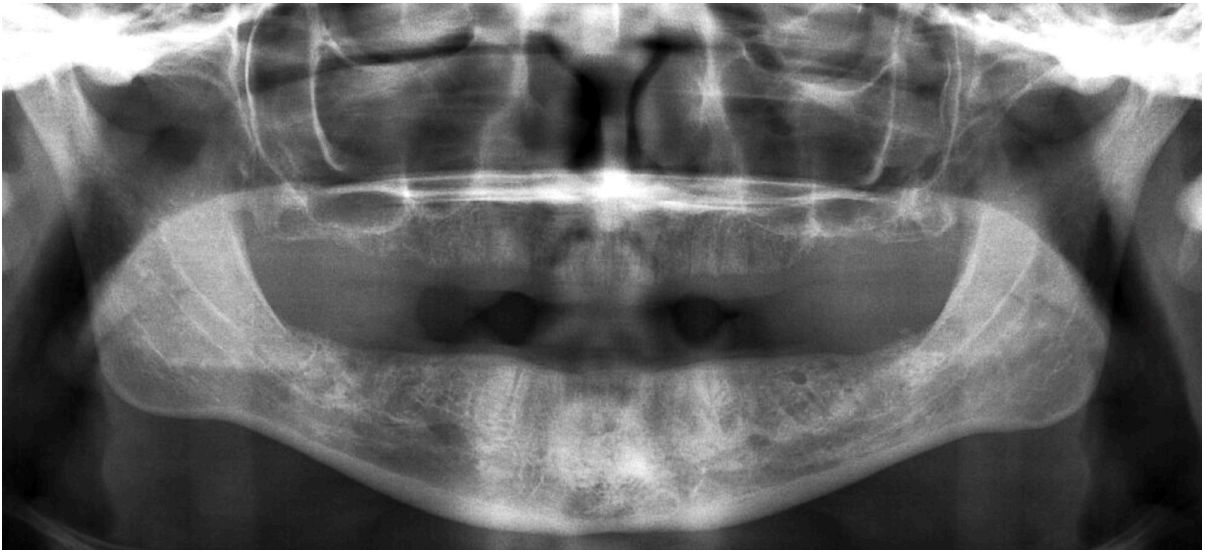


Figure 2: Pre-op panoramic radiograph

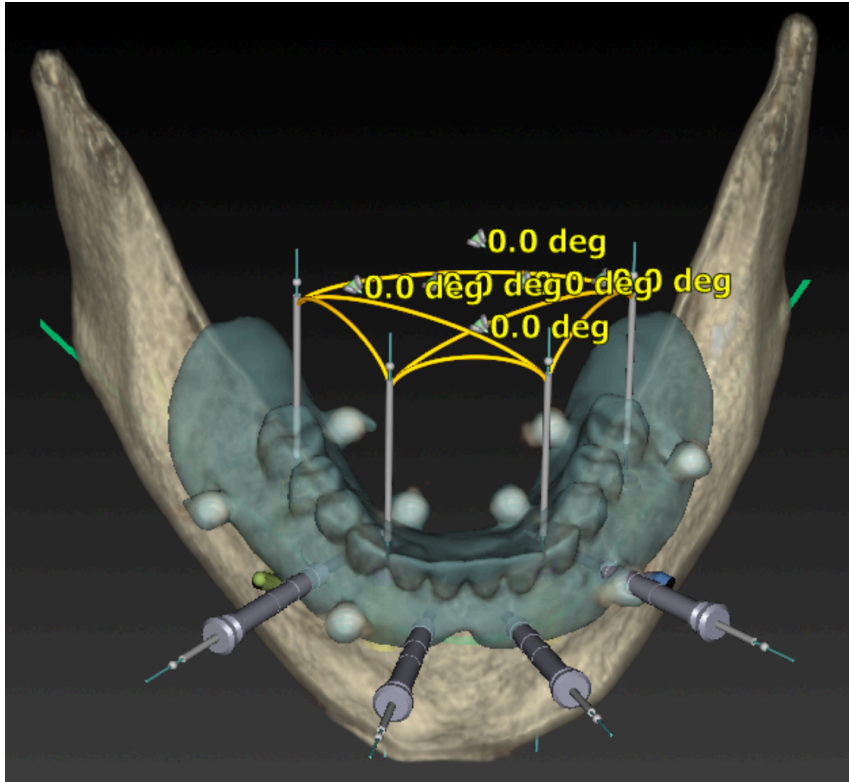


Figure 3: Virtual implant planning on Nobel Clinician

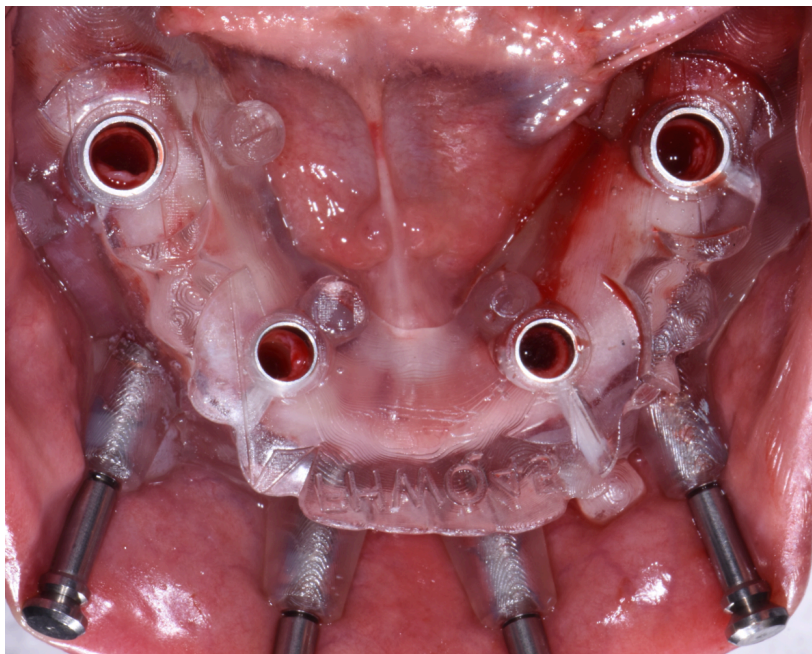


Figure 4: Surgical guide in place during implant surgery

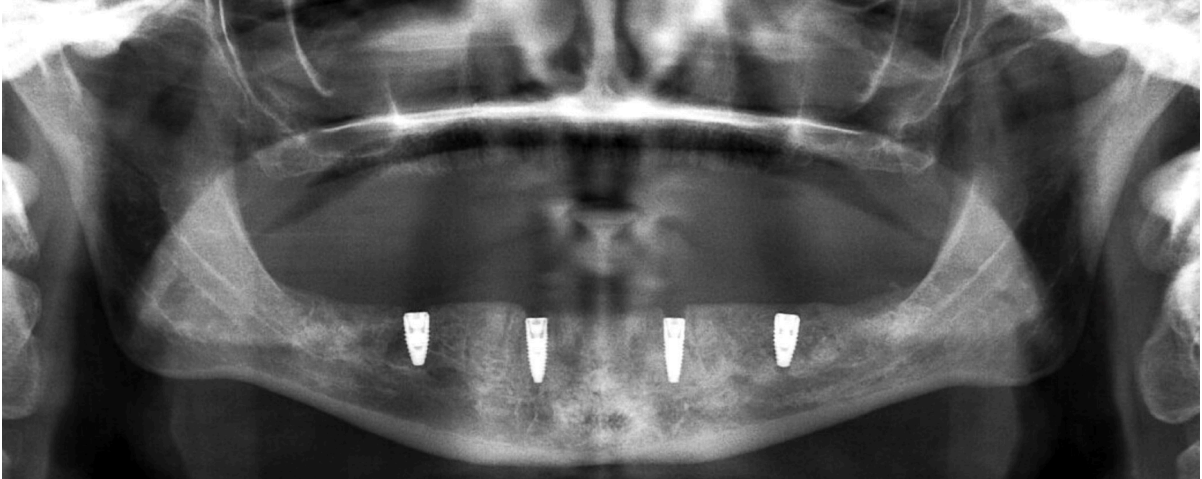


Figure 5: Post-op panoramic radiograph

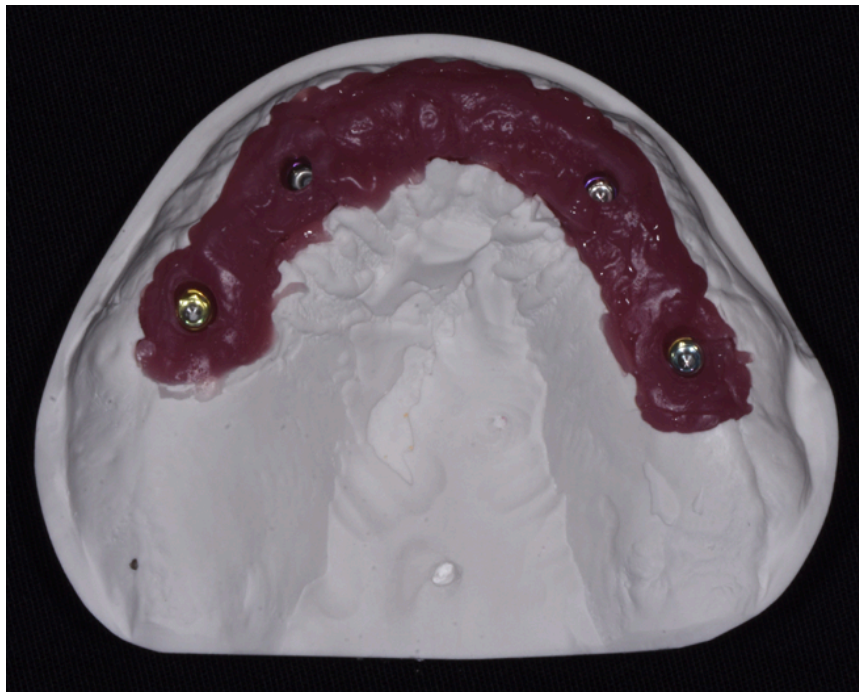


Figure 6: Post-surgical master cast fabricated using low expansion (0.06%) type IV die stone (New FujiRock® IMP GC Corp, Tokyo, Japan)

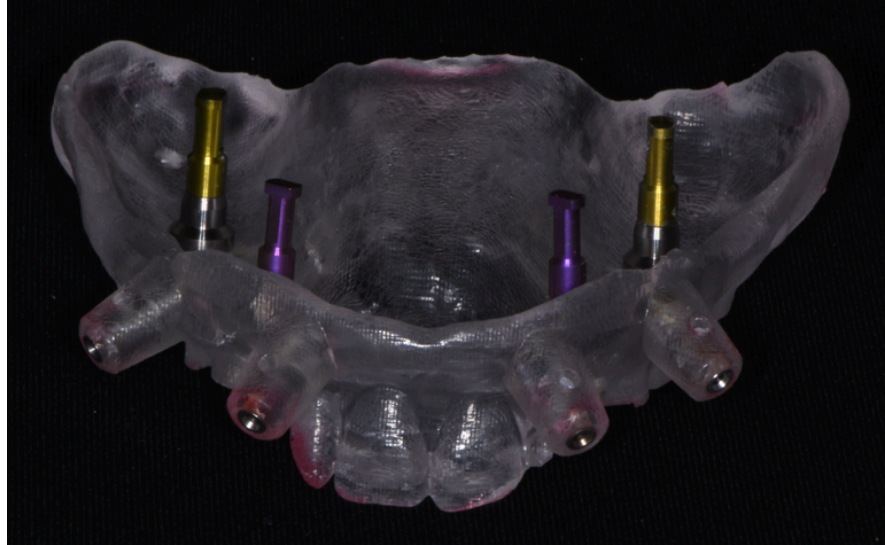


Figure 7: Stereolithographic surgical guide with implant analogs mounted onto guidance cylinders

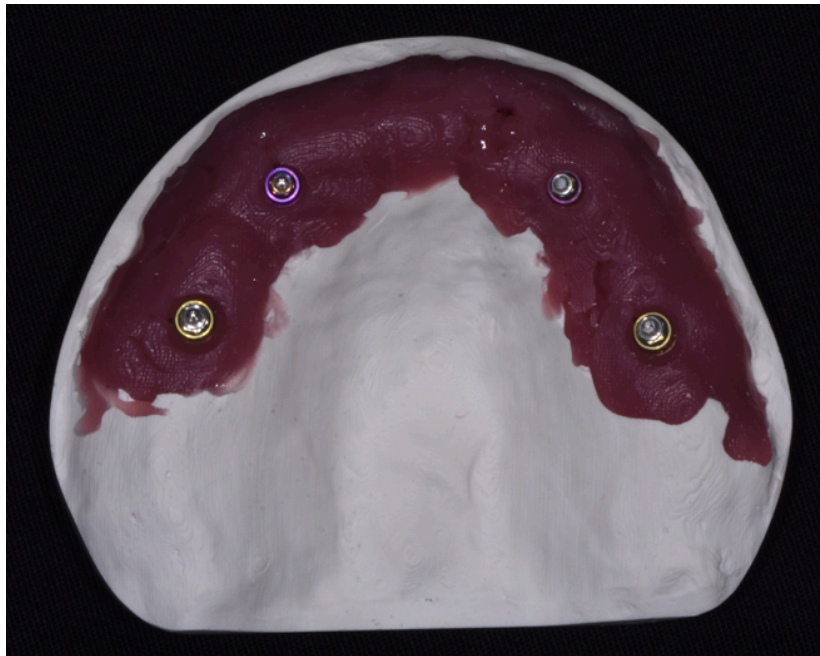


Figure 8: Cast derived from the surgical guide using low expansion (0.06%) type IV die stone (New FujiRock® IMP GC Corp, Tokyo, Japan)

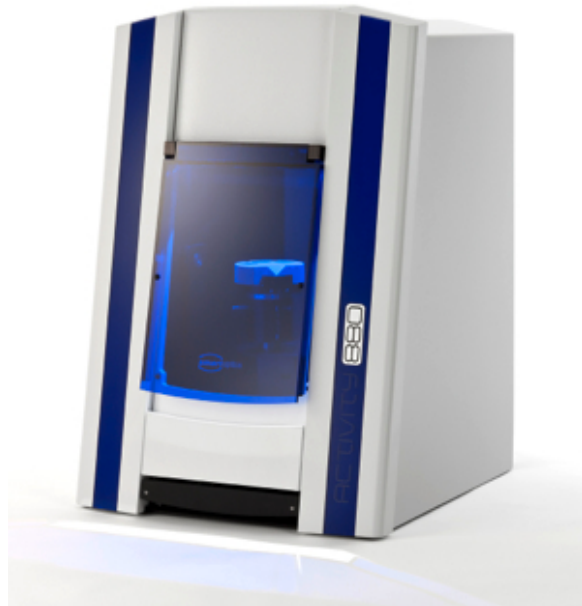


Figure 9: Laboratory Dental Scanner (Activity 880 scanner; Smart Optics, Bochum, Germany)

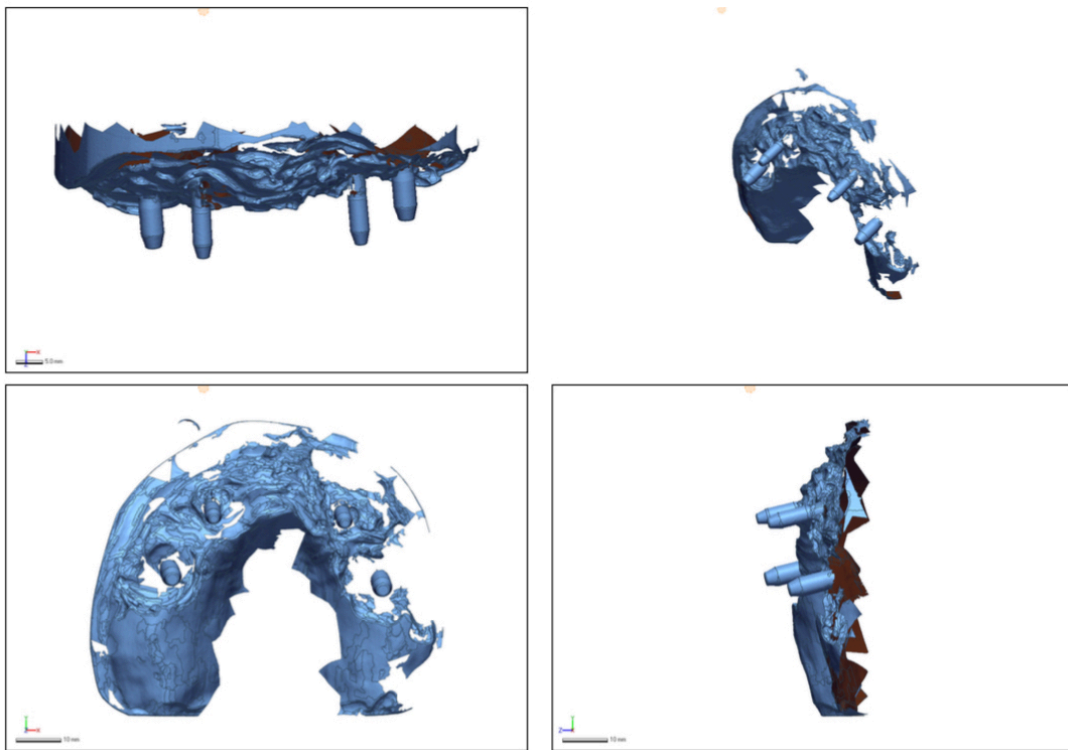


Figure 10: Group I casts and digitized and saved as STL files

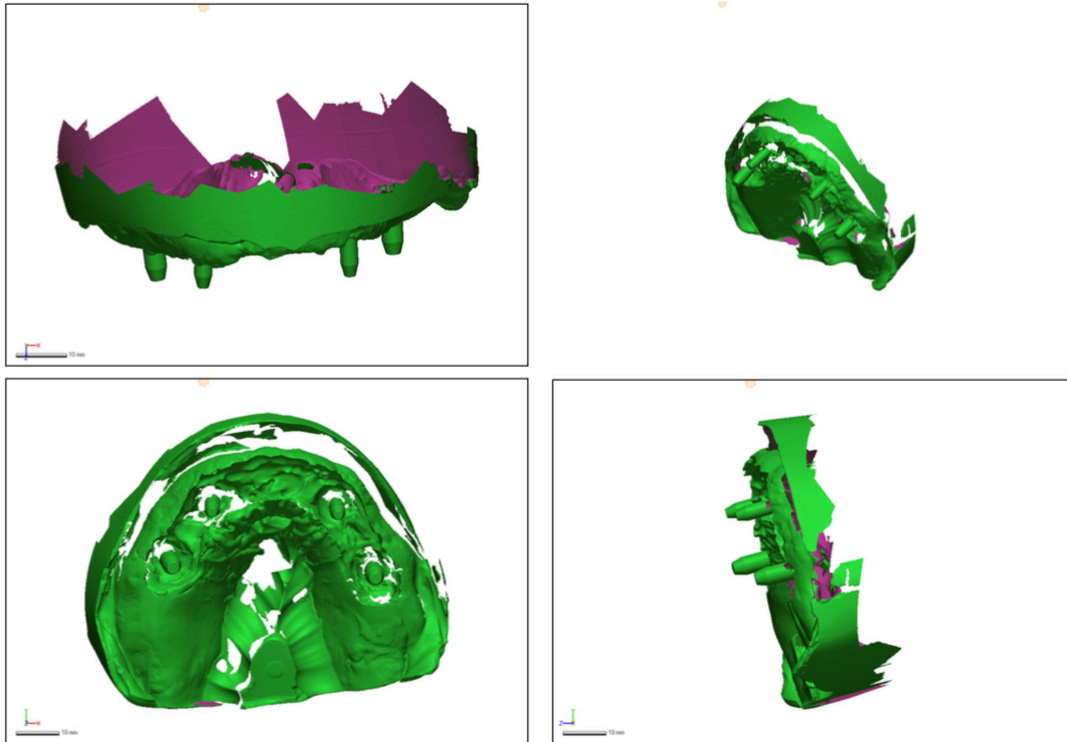


Figure 11: Group II casts and digitized and saved as STL files

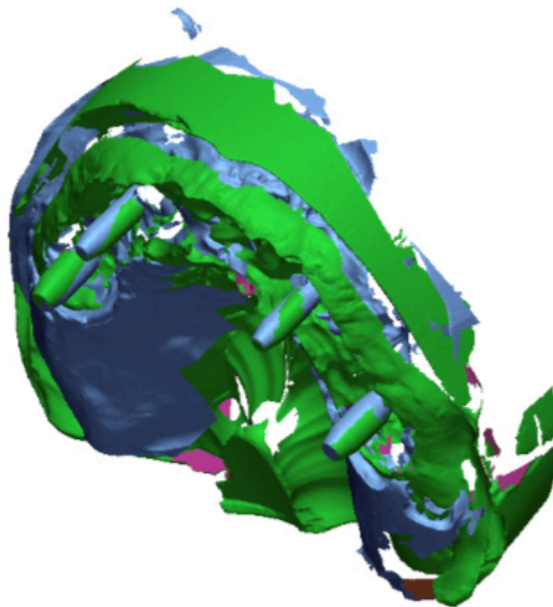


Figure 12: Superimposition of STL files of Goup I and Group II and root-mean-square error (RMSE) calculated by 3D inspection software (Geomagic® Control™) for all casts of both groups

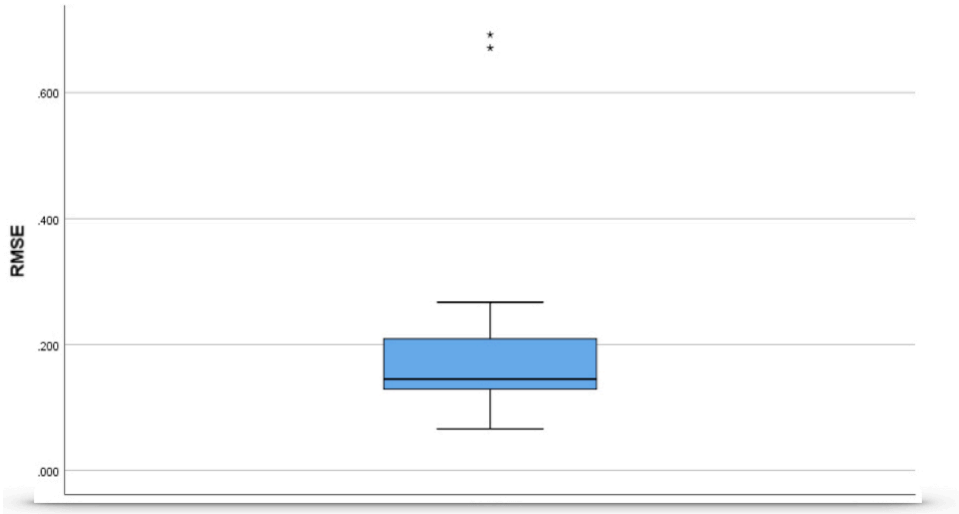


Figure 13: Total casts RMSE distribution

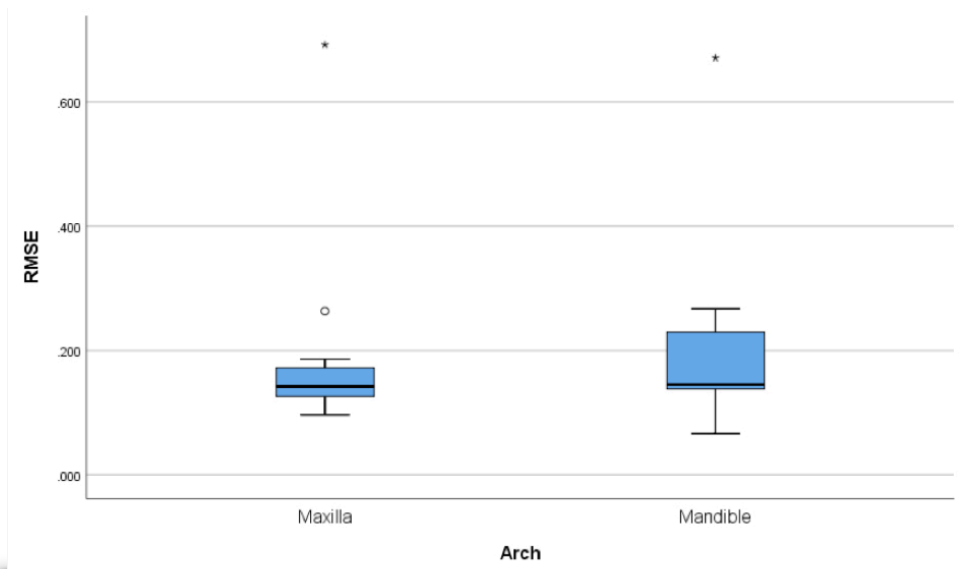


Figure 14: RMSE distribution for maxillae vs mandibles

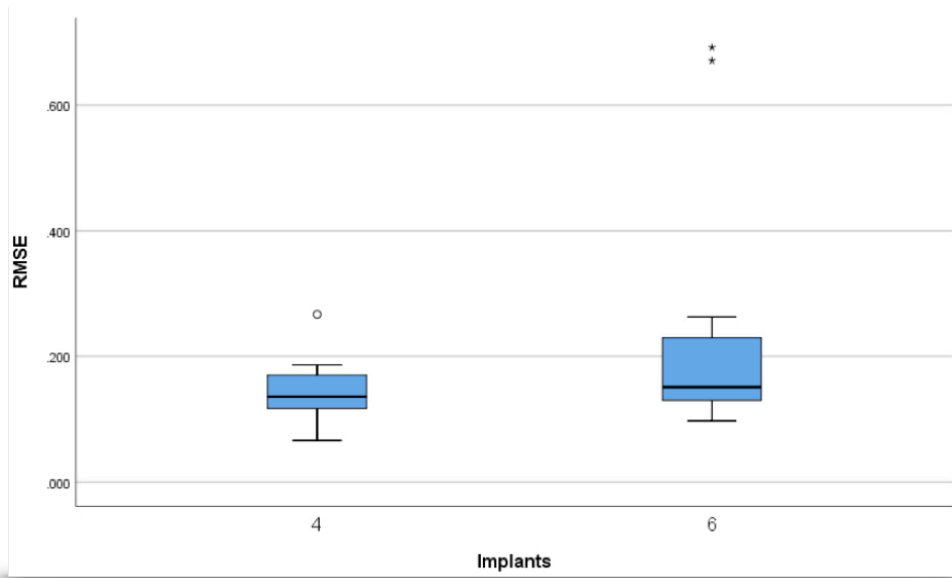


Figure 15: RMSE distribution for 4 vs 6 implants