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VIRTUAL THREE-DIMENSIONAL ANALYSIS OF DIGITIZED DENTAL IMPRESSIONS AND STONE REPLICAS

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About the cover – The Moorish mosaics, The Alhambra Palace, Granada, Spain. 12th -13th century.

This photo was taken by me on my holidays in January 2007, when I had learnt that a point-cloud from a digitization can be either triangulated or tessellated.

Tessellations are repeated patterns of distinct shapes. The word "repeated" means that the tessellation can be broken down into identical sections. These sections are repeated throughout the design.

The mosaics at the Alhambra Palace are a superb example of tessellation, created by the finest artisans of the day.

In stark contrast, in the present thesis, some 800 years later, you will find examples of triangulation, in point-clouds created by state of the art computer technology.

Happy reading!

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To my family and friends

"People often say that motivation doesn't last.
Well, neither does bathing – that's why we recommend it daily!"
Zig Ziglar

ABSTRACT

In response to increasing patient awareness of esthetic dental rehabilitation, the preference today is for all-ceramic restorations, which show superior biocompatibility and similar light characteristics to the natural tooth. The fit of a dental restoration depends on quality throughout the entire manufacturing process. The final result is affected by multiple factors, such as preparation of the tooth, the impression, production of a dental cast, fabrication of the restoration, chairside adjustment of the restoration and, finally, when the restoration is complete, the material and method used for cementation. By the use of CAD/CAM systems, the automation of the manufacturing process improves efficiency and enhances quality control.

In this thesis, a methodology for virtual three-dimensional analysis was developed and applied to stages involved in the production of fixed dental prostheses. The general aim was to measure the effect of different steps in the manufacturing process on the exactness of the CAD-model.

The main reason for undertaking *in vitro* studies was the need for a physical reference, a master model, and the opportunity to digitize it. Three different dental surface digitization devices were used in the studies, a laser scanner and two touch-probe scanners. The point-clouds resulting from the digitizations of the master dies of prepared teeth yielded virtual CAD-Reference-Models (CRMs) of each tooth shape. Best-fit alignment of the virtual point-clouds from the digitizations of the replicas to the corresponding CRM was performed.

The quality of data acquired by the dental surface digitization devices was evaluated by repeated digitizations of the master models in the laser scanner and the touch-probe scanners. The reliability was estimated by comparison of the digitizations within each scanner. The potential to obtain high quality data directly from the impression, eliminating the stone replica stage from the manufacturing process was investigated. The potential geometric difference in the resultant stone replica was also analyzed. Clinical conditions were simulated by the presence of neighboring and antagonistic teeth.

High quality data can be achieved directly from the digitized impressions with the optical digitization device used in the thesis. The results indicated that the discrepancies were of the same size as when digitizing stone replicas. Hence digitization of the impression may be a successful means of improving efficiency without affecting the quality of the final restoration.

The thesis brings a deeper understanding of the specific problems in the evaluation of CAD/CAM technology in dentistry. The methodology developed to evaluate exactness of digitizations will be of benefit in the ongoing process of validation of dental CAD/CAM systems. Virtual three-dimensional analysis allows for differentiated quality analysis of the manufacturing process as well as comparison of different digitization methods.

***Keywords*:** accuracy; alignment software; computer-aided analysis; computer-aided design; computer-aided manufacturing; fixed prosthodontics; precision; reliability; reproducibility; surface digitization devices

LIST OF PUBLICATIONS

This thesis is based on the following papers. They are referred to in the text by their roman numerals.

I. Anna Persson, Matts Andersson, Agneta Odén, Gunilla Sandborgh-Englund, “A three-dimensional evaluation of a laser scanner and a touch-probe scanner”. *Journal of Prosthetic Dentistry* (2006) 95:194-200.

II. Anna S.K. Persson, Matts Andersson, Agneta Odén, Gunilla Sandborgh-Englund, ”Computer aided analysis of digitized dental stone replicas by dental CAD/CAM technology”. *Dental Materials* (2008) Aug;24(8):1123-30. Epub 2008 Mar 11.

III. Anna S.K. Persson, Agneta Odén, Matts Andersson, Gunilla Sandborgh-Englund, ”Virtual three-dimensional analysis of digitized dental impressions”. *Submitted manuscript.*

IV. Anna S.K. Persson, Agneta Odén, Matts Andersson, Gunilla Sandborgh-Englund, ”Digitization of simulated clinical dental impressions: virtual three-dimensional analysis of exactness”. *Submitted manuscript.*

CONTENTS

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CAD/CAM	Computer- Aided Design/Computer- Aided Manufacturing
CI	Confidence interval
CRM	CAD- Reference- Model
RC	Repeatability Coefficient
SD	Standard deviation
SLA	Stereolithography
Y-TZP	Yttria-stabilized tetragonal zirconia

1 INTRODUCTION

In response to increasing patient awareness of esthetic dental rehabilitation, the preference today is for all-ceramic restorations, which show superior biocompatibility and similar light characteristics to the natural tooth. High strength ceramic materials (*e.g.* alumina and zirconia) are typically used in substructures for full-coverage restorations and fixed partial dental frameworks (Luthardt, *et al.*, 2002; Blatz, *et al.*, 2004; Denry & Kelly, 2008). CAD/CAM technology can compensate for the significant shrinkage of alumina and zirconia during sintering (Andersson & Oden, 1993; Brick, *et al.*, 2004), and in some systems the restoration can be produced directly, eliminating the need for temporary restorations (Leinfelder, *et al.*, 1989; Fasbinder, 2006). The marginal fit of copings made using dental CAD/CAM technology is clinically acceptable (Oden, *et al.*, 1998; Coli & Karlsson, 2004; Bindl & Mormann, 2005).

While the translucency of an all-ceramic crown is an esthetic advantage, after cementation, this translucency is affected by the color of the abutment tooth (Koutayas, *et al.*, 2003). Conventional metal abutments may cause gray discoloration of the surrounding gingiva. This issue can be circumvented by using alumina or zirconia ceramic implant abutments, which can be milled to meet individual requirements by using CAD/CAM technology (Yildirim, *et al.*, 2000).

The treatment planning phase is unquestionably the basis of contemporary dentistry (Mitrani & Kois, 2000). Whether treatment involves the restoration of a single tooth, an implant, or a full-mouth reconstruction, it is through the planning phase that various therapies are considered for the individual case. While the final plan may be reached through a variety of pathways, close communication between the clinician and the dental laboratory technician is essential for an optimal outcome. Modern communication methods and the use of CAD/CAM technology offer excellent potential for providing the patient with dental reconstructions of high quality.

1.1 DENTAL PROSTHETIC MANUFACTURING PROCESSES

A major determinant of the quality of fixed prosthodontics is close internal and marginal fit of the crowns. The fit of a dental restoration depends on quality throughout the entire manufacturing process. Accurate and precise replicas of the teeth are essential. The final result is affected by multiple factors, such as preparation of the tooth, the impression, production of a dental cast, fabrication of the restoration, chairside adjustment of the restoration and, finally, when the restoration is complete, the material and method used for cementation (Wang, *et al.*, 1992; Wolfart, *et al.*, 2003; Chen, *et al.*, 2004; Kenyon, *et al.*, 2005).

The traditional way of producing a dental restoration is by using the lost-wax casting technique (Fig. 1). The dentist prepares the tooth. An impression of the preparation and any adjacent proximal teeth is made to create a negative, three-dimensional replica of the teeth. The opposing, occluding teeth are also registered, either by a separate impression or by using a dual-arch impression tray. Finally, the prepared tooth is protected by inter-appointment temporary coverage while the final restoration is fabricated.

At the dental laboratory, dental stone is poured into the impressions, creating a positive stone replica of the patient's dentition. To facilitate the fabrication of the dental restoration by the dental technician, the dental stone model needs to be sectioned in order to isolate the replica. To maintain the correct position of the teeth after sectioning, a brass pin is placed in the stone model and a second layer of dental stone is added to the model, surrounding the pin. When the second layer has hardened, two thin cuts are made proximal to the prepared tooth. The section of the model with the preparation can now be removed and reinserted into the models and is called the die. Thereafter, excess dental stone below the margin is removed and the finish line is marked. To create space for the cement, the die is painted with a die spacer and separating medium is applied to the die. To form a wax pattern of the required restoration, the dental technician melts and carves wax over the die. The wax pattern is sprued and invested. A casting mould is made by burning out the wax after the investment material has hardened. Molten or softened restorative material is flowed or pressed into the casting mould. The raw casting is recovered, cleaned and polished. Depending on the type of restoration, it can now be ready to be tried in the patient's mouth, if it is a full metal crown, or complemented with dental ceramics to create the final shape and color of the restoration. The patient returns to the dental office, the temporary coverage is removed and the final restoration is adjusted and cemented into place.

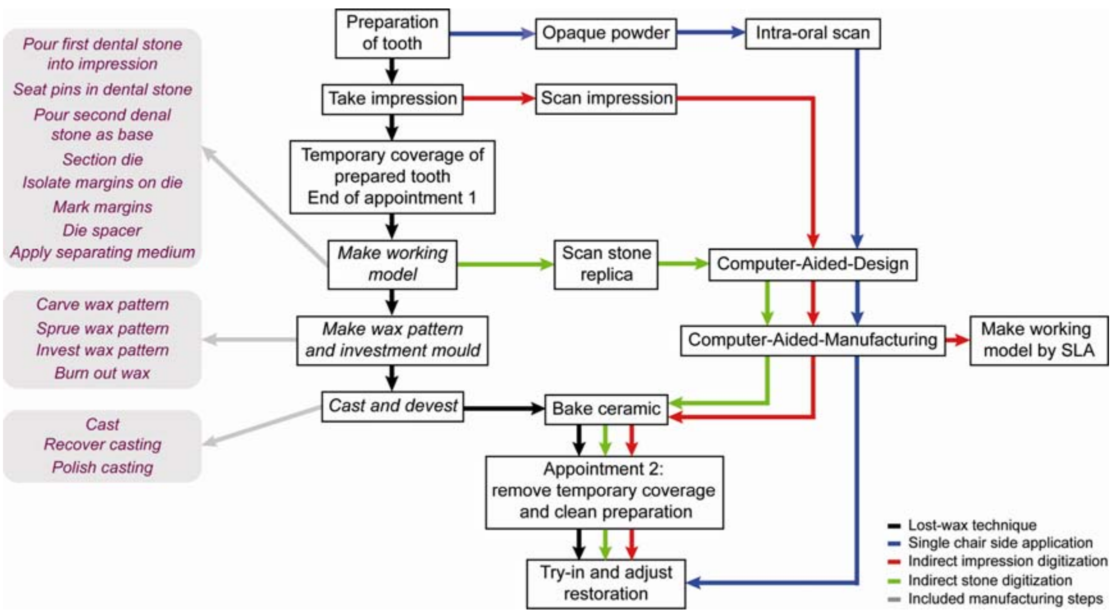

Figure 1. Flowchart of manufacturing process; lost-wax technique *vs.* CAD/CAM; intra-oral, impression and stone digitization.

1.2 DEVELOPMENT OF CAD/CAM IN DENTISTRY

With the CAD/CAM systems, restorations can be produced more quickly and the automation allows consistent quality (Fig. 1). CAD/CAM systems were applied to dentistry in the early 1980s. For some of the early visionaries in the field, the emphasis was on automation (Duret, *et al.*, 1988; Mormann, *et al.*, 1990; Rekow, *et al.*, 1991; Rekow, 2006). The technology has since evolved in two directions. One is chairside application, the provision of restorations in a single appointment, using prefabricated ceramic monoblocks. In parallel, CAD/CAM systems for commercial production centers and dental laboratories have emerged, allowing fabrication of dental reconstructions from materials such as densely sintered alumina. These materials have excellent clinical qualities but have proven very difficult to handle by conventional methods (Andersson, *et al.*, 1998; Oden, *et al.*, 1998; Wen, *et al.*, 1999; Odman & Andersson, 2001; De Jager, *et al.*, 2005; Kokubo, *et al.*, 2005a; Kokubo, *et al.*, 2005b).

1.2.1 Digitization devices and production systems

There are various methods available for digitizing the geometry of a body into a digital form. A dental surface digitization device can be based on non-contact or contact methods where three-dimensional images are captured. Thereafter the images are transformed into a three-dimensional construction file and transferred to the milling device.

The non-contact method uses an optical digitization device. The single chairside session method is a direct non-contact system which makes it possible to complete a restoration without the need for impressions, temporary coverage, or laboratory assistance (Fig. 1). The cavity preparation is digitized using an optical scanner. However, before digitization, the surfaces need to be dried and coated with an opaque substance such as titanium dioxide, to render the surface readable in the scanner: this coating process may introduce errors which have a negative influence on the result (Kurbad, 2000; Luthardt, *et al.*, 2005). The digitized data are sent to the milling device. Chairside time is potentially prolonged compared with the indirect method where the digitization step is performed at the dental laboratory. A prosthetic restoration produced directly by this method uses ceramic monoblocks (Kurbad & Reichel, 2006). However, the digitized information can also be sent to a dental laboratory for completion of the restoration (Kurbad, 2001).

An indirect non-contact method uses optical systems which can be based on either laser or white light (Suttor, *et al.*, 2001; Moreno Yeras, 2003; Persson, *et al.*, 2006; Vlaar & van der Zel, 2006). The laser or white pattern is projected onto the object and digital cameras register the information. This digitization method makes it possible to digitize negative shapes such as a dental impression (Fig. 1) and since it is not in contact with the surface, even soft or brittle materials can be scanned (Persson, *et al.*, 2008c; Persson, *et al.*, 2008b). However, the method can be sensitive to the optical characteristics of the digitized object *i.e.* translucency, color and surface roughness (DeLong, *et al.*, 2001).

A contact method is based on touch-probe scanning, where a probe is in contact with the surface and is moved around the object and registers points from the topography of the surface. Since the scanner registers a discrete point at the center of the probe, in order to obtain a correct 3D-model, there is a need to make a calculation based on the radius of the probe (Persson, *et al.*, 1995; Luthardt, *et al.*, 2001; Ristic, *et al.*, 2001; Lin & Sun, 2003) However, the touch-probe scanner has only limited potential to digitize soft or brittle materials (Quaas, *et al.*, 2007) and is therefore used mainly on stone replicas (Fig. 1) (Persson, *et al.*, 2006).

Regardless of the digitization method applied, the information is thereafter recalculated, designed and transformed into a milling file that is sent to a CAM system, which can either be central at a commercial production center, or local at a dental laboratory. An industrialized production process offers multiple advantages with respect to the unique sintering temperatures and conditions of high-strength ceramics and outsourcing of a critical laboratory procedure. However, production at a dental laboratory makes the manufacturing process independent of a supplier of the dental core.

The dental CAD/CAM systems involve digitization steps which might introduce new errors, but as some of the manufacturing steps are excluded, other sources of error are eliminated (Fig. 1). Excluding replication steps in the production process can be beneficial, improving efficiency by shortening the manufacturing process and reducing potential sources of error (Werrin, 2003; Goldstein & Werrin, 2007). One option would be to digitize the impression and substitute the stone replica with a CAD/CAM model *e.g.* a SLA model, manufactured by rapid prototyping (Hieu, *et al.*, 2005; Lee, *et al.*, 2008).

Hypothetically, if the number of steps in the manufacturing process is reduced, a higher degree of exactness in the fabricated restoration should ensue (Goldsby & García-Dastugue, 2003). However, this is dependent on the magnitude and distribution of the discrepancies.

1.3 CONTROL OF THE MANUFACTURING PROCESS

In order to achieve correct quality control of the manufacturing process, a valid measuring method with the ability to analyze the different steps is needed. The exactness of a measuring system is expressed by the accuracy and precision of the digitizations and the alignments (Vlaar & van der Zel, 2006; Kero, *et al.*, 2007a; Kero, *et al.*, 2008). Accuracy is the degree of veracity, *e.g.* how well the measured value represents the “truth”, while precision is the degree of reproducibility, *e.g.* the repeatability of the measurement system. Ideally a measurement device is both accurate and precise, with measurements all close to and tightly clustered around the true value.

Traditional fabrication of a crown, with manual handling, makes it difficult to identify critical factors and achieve quality control. It is established that minor geometrical changes take place in the transfer of information, by means of an impression, from the clinical crown preparation *(in vivo)* or the master die *(in vitro)* to the stone replica (Lee, *et al.*, 1995; Anusavice, 2003; Shen, 2003; Luthardt, *et al.*, 2006). Dimensional changes occur in several steps of the manufacturing process. Overall, there is a balance between expansion and contraction, resulting in a satisfactory fit of the final product (Wataha, 2002).

A clinical evaluation by Samet *et al.* showed that the quality of an impression can vary (Samet, *et al.*, 2005). Significant correlations were found between impression material types and voids or tears at the finishing line as well as polymerization problems. There are several studies on the impact of different impression trays, impression materials and die materials (Davis & Schwartz, 1991; Price, *et al.*, 1991; Breeding & Dixon, 2000; Duke, *et al.*, 2000; Ceyhan, *et al.*, 2003; Kenyon, *et al.*, 2005). Analyses were made on the stone replica, which incorporates errors from both the impression and the replica. In contrast to three-dimensional measurements, which are taken all over the surface, in most of the above studies two-dimensional measurements were used to determine the geometrical changes (Fig. 2). Because measurements are taken at a limited number of sites, the object is only partly analyzed for geometrical changes.

Surface digitization devices continue to be improved. In the process based on CAD/CAM technology, the chain of transferring geometrical data starts with surface digitization of the preparation. However, it is important to establish the accuracy and precision of the digitization device. A proposed test method to quantify "digitizing quality" was evaluated by Vlaar *et al.* The accuracy and reproducibility of two dental surface digitization devices were evaluated (Vlaar & van der Zel, 2006). By repeated measurements of a precision ball (radius: 6 mm) both devices showed adequate accuracy and reproducibility. The test method was suggested to be suitable for calibration purposes. Still, it is difficult to assess the geometry and surface topography of an object with a complex form, such as a tooth, due to the various irregularities and geometric configurations that are unique for each tooth. Thus the measurements are compared without relation to an absolute reference: a discrepancy may be detected, but not necessarily correctly located.

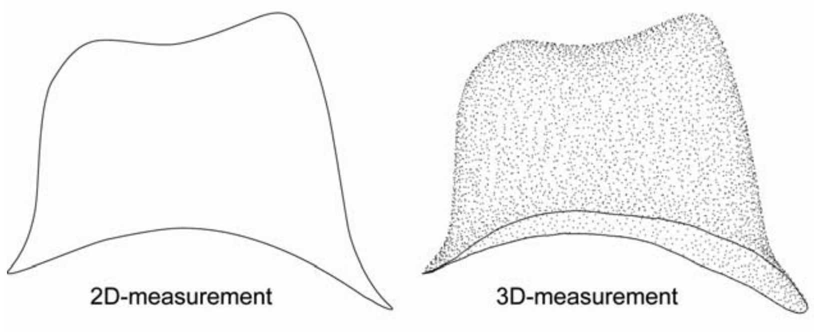

Figure 2. Illustration of two-dimensional measurements (limited no. of sites) *vs.* three-dimensional measurements (entire surface).

In a study three-dimensional measurements were performed on a prepared upper canine evaluating the effect of digitizing and surfacing on the accuracy (Rudolph, *et al.*, 2006). Three different dental CAD-systems were evaluated and the tooth shape was found to be the dominant factor limiting the attainable precision. Areas of strong changes of curvature showed the largest deviations, which has also been shown to be related to the density of the point-cloud (Persson, *et al.*, 2006; Persson, *et al.*, 2008a).

2 AIMS OF THE THESIS

In this thesis, a methodology for virtual three-dimensional analysis was developed and applied to stages involved in the production of fixed dental prostheses. The general aim was to measure the effect of different steps in the manufacturing process on the exactness of the CAD-model.

2.1 SPECIFIC AIMS

The aim of *Study I* was to evaluate the repeatability (precision) and relative accuracy of a laser and a touch-probe scanner.

The aims of *Study II* were to survey dimensional changes in the stone replicas and to determine the reliability of the three-dimensional virtual evaluation method. The influence of different preparation shapes on precision and accuracy was also investigated.

The aim of *Study III* was to compare digitized dental impressions and stone replicas with respect to exactness and possible geometric changes, using virtual evaluation. Moreover an experimental impression material was validated by comparison with stone replicas poured from a commercial impression material.

The aim of *Study IV* was to apply virtual three-dimensional analysis to compare the exactness of digitized simulated clinical dental impressions with that of digitized stone replicas of full crown preparations.

3 METHODOLOGY

The methods are briefly described in this section: detailed descriptions are presented in each individual paper.

The main reason for undertaking *in vitro* studies was the need for a physical reference, a master model, and the opportunity to digitize it. In Study I the quality of data acquired by different digitization devices was compared and in Study II geometrical differences between the stone replica and the master model were mapped. Study III investigated the potential to obtain high quality data directly from the impression, eliminating the stone replica stage from the manufacturing process. In Study IV clinical conditions were simulated by the presence of neighboring and antagonistic teeth; digitized impressions and stone replicas were evaluated and compared.

3.1 MASTER MODELS

In Study I, ten different dies prepared for crowns were selected from clinical files in the Procera production. The preparations were divided into two groups: anterior or posterior shapes. The dies were fabricated in presintered Y-TZP (Table 1). This material was chosen for good surface hardness as well as optical properties. All of the dies had preparations with either chamfer margins or deep chamfer margins. Four of the dies (of a maxillary incisor, a canine, a premolar and a molar) were selected, and slightly modified, to be used in studies II and III (Table 1).

In Study IV, arches of hard Frasaco plastic maxillary and mandibular teeth were used. Three of the teeth (a mandibular incisor, a canine and a molar) were prepared for full crowns (Table 1).

Table 1. Materials and digitization methods, summary of studies I-IV

Study	Master model material	Digitization method, CRM	Replica material	Digitization method, replica
I	Y-TZP	Laser	Y-TZP	Laser
I	Y-TZP	Touch-probe	Y-TZP	Touch-probe
II	Y-TZP	Touch-probe$_{high}$	Stone*	Touch-probe$_{high}$
III	Y-TZP	Laser	Impression	Laser
III	Y-TZP	Laser	Stone**	Laser
III	Y-TZP	Touch-probe$_{high}$	Impression	Laser
III	Y-TZP	Touch-probe$_{high}$	Stone**	Touch-probe$_{high}$
IV	Plastic	Touch-probe$_{high}$	Impression	Laser
IV	Plastic	Touch-probe$_{high}$	Stone**	Touch-probe$_{standard}$
IV	Plastic	Touch-probe$_{high}$	Stone**	Touch-probe$_{high}$

* Type IV stone replica (Vel-Mix) poured up from impression (PROVIL novo)

** Type IV stone replica (Vel-Mix) poured up from impression (forerunner to Fresh scan)

3.2 DENTAL SURFACE DIGITIZATION DEVICES

An experimental laser scanner (3Shape A/S, Denmark) was used in Study I. This scanner was upgraded (D250, 3Shape A/S, Denmark; Fig. 3) before application in studies III and IV. The scanner is a line-laser scanner, comprising a table with a model holder and a laser, together with two digital cameras that acquire images of the laser plane as it is projected onto the object. The model to be digitized is fixed in the holder. To ensure complete coverage of the object's geometry, the table can be rotated and tilted and moves along a horizontal axis during the registration procedure. The image processing software (ScanIt, 3Shape A/S, Denmark) processes the images and calculates, by triangulation, a point-cloud as a 3D model. The software automatically optimizes the data and reduces the number of points in the point-cloud.

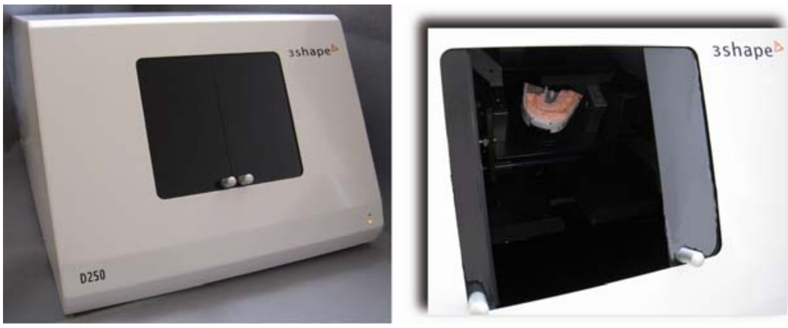

Figure 3. Laser scanner, (D250). Right: closeup of impression digitization.

In Study I, a commercially available touch-probe scanner (M50, Nobel Biocare AB, Sweden; Fig 4) was used. A sapphire ball with a radius of 1.25 mm forms the tip of the scanner probe that contacts the surface of the die as it rotates around a vertical axis. The probe is positioned, with light pressure, at a 45-degree angle to the axis of rotation. The scanner collects 360 points around the circumference of the die. During each turn, the probe is continuously elevated 200 µm. The resulting point-cloud is processed with the software provided (Procera System C3D, Nobel Biocare AB, Sweden). The 3D model is calculated using an offset of the point-cloud, based on the radius of the sapphire ball.

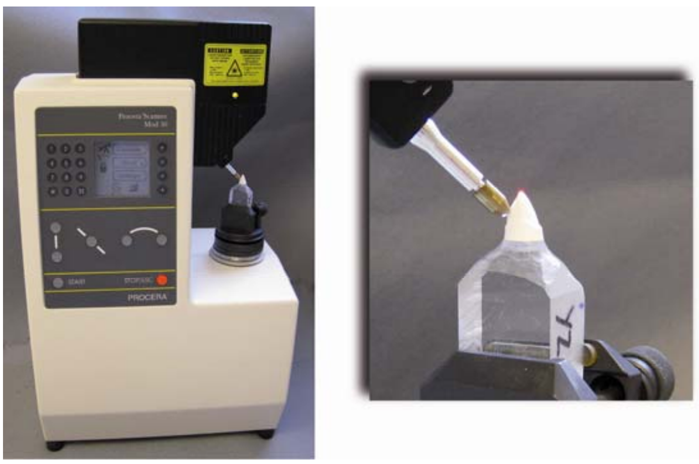

Figure 4. Touch-probe scanner (M50). Right: closeup of master die (Y-TZP) digitization.

In studies II, III and IV a commercially available touch-probe scanner (Procera® Forte, Nobel Biocare AB, Sweden; Fig. 5) was used. In the standard resolution setting, a sapphire ball with a radius of 1.25 mm forms the tip of the scanner probe. The probe rotates around the die and contacts the surface with a light pressure, using a scan speed of 240º per second. During each turn, the probe is elevated by 200 µm and 360 points are collected around the circumference of the die. The standard resolution setting was used for the repeated digitizations in Study IV. However, in order to achieve virtual models with high resolution, the settings of the scanner were adjusted. In the high resolution setting, the sapphire ball had a radius of 0.5 mm (Fig. 5); the scan speed was reduced to 100º per second and the elevation was decreased to 50 µm. This high resolution setting was used in studies II, III and IV.

Figure 5. Touch-probe scanner, Forte. Right: closeup of master die (Frasaco hard plastic) digitization, using high resolution setting

3.3 CAD- REFERENCE- MODELS

The point-clouds resulting from the digitizations of the master dies of prepared teeth yielded virtual CRMs of each tooth shape (Fig. 6).

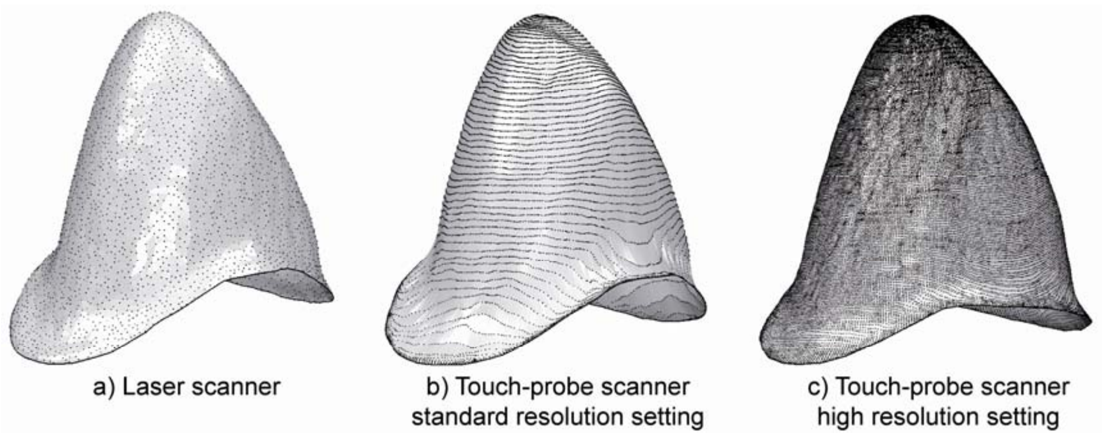

Figure 6. Examples of point-clouds of different origin and different densities

In Study I, three readings of each master die were performed in both scanners and all the digitizations were used as CRMs.

In studies II, III and IV, the prepared teeth, *i.e.* the master dies, were digitized in the touch-probe scanner (high resolution setting), where the resulting point-clouds generated virtual CRMs of each tooth shape. Six repeated digitizations of the master dies were performed in Study II and the resulting point-cloud from the first scan was used as the CRM. These CRMs were also used in Study III, together with a supplementary digitization of the master dies in the laser scanner *i.e.* CRM_{laser}.

In Study IV the prepared teeth were digitized in the touch-probe scanner at the high resolution setting, and inspected with the preparation alignment feature (CadDesign, Procera, Nobel Biocare AB, Sweden) to ensure a correct alignment with no undercuts.

3.4 REPLICA MANUFACTURING AND DIGITIZATION

In Study I, three repeated digitizations of the master models in the laser scanner and the touch-probe scanner were compared within each scanner and relative to the other scanner.

In Study II, the potential geometric difference between the master model and the stone replica was analyzed by taking eight vinyl polysiloxane impressions (PROVIL novo, Heraeus Kulzer, Germany) of each master die. To standardize the impression procedure, the master die and the tray were fixed in an articulator (Fig. 7).

Figure 7. Standardized impression procedure.

Small perforated plastic cups were used as impression trays and the master die was centered in the middle of the cup. Light body (C:D. 2 fast set, PROVIL novo, Heraeus Kulzer, Germany) was syringed onto the surface of the master die. Thereafter the impression tray was filled with heavy body (Putty soft, fast set, PROVIL novo, Heraeus Kulzer, Germany) and inverted over the master die: the articulator was then closed to stabilize the position of the master die during setting. The impressions were poured up in Type IV stone (Vel-Mix Stone, Kerr, UK), mixed according to the manufacturer’s instructions. The stone replicas were digitized in the touch-probe scanner using the high resolution setting.

Study III was of similar design to Study II, and the same master models and CRMs were used. The standardized impression procedure was used, but the impression material comprised an experimental vinyl polysiloxane based monophase material. It was a forerunner of Fresh scan (Dreve Dentamid GmbH, Germany) specifically designed to optimize the light reflection of the laser light. The eight impressions of each master die were digitized in the laser scanner to generate virtual point-clouds. The stone replicas were digitized in the laser scanner and in the touch-probe scanner using the high resolution setting.

Figure 8. Frasaco hard plastic model teeth in simulated clinical occlusion used for standardized impression procedure.

In order to simulate clinical conditions in a laboratory environment, in Study IV arches of maxillary and mandibular model teeth of plastic were mounted in a plane line articulator (Fig. 8). Following the trial of the experimental impression material in Study III, the viscosity and wettability had been modified. Eight impressions were taken of the prepared plastic teeth in simulated clinical occlusion. Impression material was syringed onto the surfaces of the three preparations. Thereafter a plastic dual-arch impression tray filled with impression material was inverted over the preparations and the articulator was closed. The eight impressions of the master model were digitized in the laser scanner to generate point-clouds. One impression of each preparation was subjected to eight repeated detail digitizations. The impressions were poured up in Type IV stone (Vel-Mix Stone, Kerr, UK), mixed according to the manufacturer's instructions. The stone replicas were digitized in the touch-probe scanner using both the standard and high resolution settings. One stone replica of each tooth shape was subjected to eight repeated digitizations with the touch-probe scanner using the standard resolution settings.

3.5 VIRTUAL THREE- DIMENSIONAL ANALYSIS

Two different software programs were used in these studies. The first (NSI Registration, version 1.1; 3Shape A/S, Denmark) was used in Study I. Commercial software (CopyCAD 6.504 SP2; Delcam Plc, UK) was used in studies II, III and IV. Using this system, supplementary analysis of some of the digitizations in Study I has been undertaken to allow in-depth evaluation and direct comparison between Study I and the subsequent studies.

In both systems, digitized data below the preparation margin in the CRM as well as obvious noise in the incisal/occlusal aspect were deleted. Best-fit alignment of the virtual point-clouds from the digitizations to the corresponding CRM was performed.

3.5.1 NSI Registration (Study I)

The matching-software NSI Registration works by minimizing a distance criterion. The points in the CRM were used as references and the distance to the points in the point-cloud in the compared model were minimized. A starting position was marked on the CRM and a similar position was marked on the corresponding model. Thereafter, the results of the alignment and matching were automatically presented in the point quality feature by mean, SD, absolute mean, median and 95th percentile of the discrepancies.

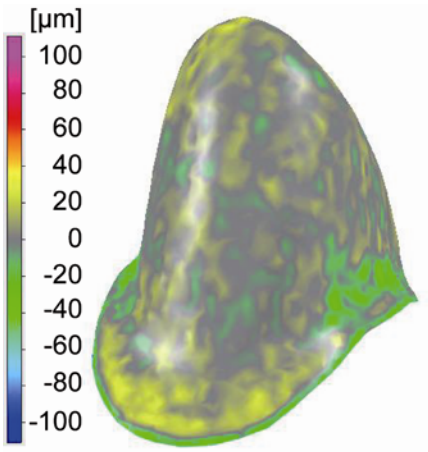

Figure 9. Example of color-difference-map, NSI Registration.

The distribution of the discrepancies, presented as color-difference-maps (Fig. 9), formed the basis for the qualitative analysis. Positive values in the color-difference-map (yellow to red) illustrate that the compared point-cloud is larger than the CRM. Negative values (green to blue) indicate that the points in the compared point-cloud are located inside the points in the CRM. Grey areas indicate that there is no difference.

3.5.2 CopyCAD (Studies II-IV)

The alignments performed with CopyCAD started with a manual alignment where the CRM was chosen as the reference model and thereafter the corresponding model was selected as the alignment model and was moved into position by moving and rotating it on x, y and z axes to provide an approximate alignment with the reference model. CopyCAD displays both models on the screen and it is possible to tweak the alignment until the alignment model fits the reference model. Subsequently, a best-fit alignment was performed. The mismatch between the models was examined and the greatest gap between them was estimated and entered as the maximum initial deviation. Thereafter the maximum acceptable deviation between the aligned models was set to stop the iteration when a certain mean error value was reached. Since the software uses point-to-point alignment the points below the margin in the corresponding model were deleted in order to reduce interference in the alignment process. A repeated best-fit alignment was performed to optimize the alignment.

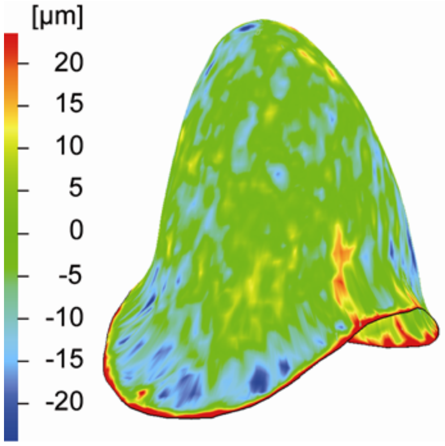

Figure 10. Example of color-difference-map, CopyCAD.

After the best-fit alignment, the shortest distance from each point in the CRMs to the points in the corresponding point-cloud was measured and calculated. In the error analysis feature, the results of the alignment and matching were exported as ASCII text files, with the coordinates of the points in the point-cloud from the CRM and the error distance to the compared model from each point. In the qualitative analysis, the distribution of the discrepancies was presented as color-different-maps (Fig. 10). Positive values in the color-difference-map (yellow to red) illustrate that the CRM is larger than the compared point-cloud. Negative values (turquoise to blue) illustrate that the CRM is smaller than the compared point-cloud. Green areas indicate that there is no difference.

3.5.3 Alignment and Matching

In Study I, to analyze the accuracy and precision of the repeated digitizations in each scanner, all three readings were used as CRMs, aligned and compared to the other two (Table 1). To assess the relative accuracy and precision of the two digitization devices, the CRM from the laser scanner was aligned and compared to digitizations from the touch-probe scanner and *vice versa*.

The reliability of the measuring method used in Study II was assessed by using the resulting point-cloud from the first scan of the master model as virtual CRM in a best-fit alignment to the following five digitizations. To evaluate the reproducibility of the eight stone replicas, the discrepancies between the corresponding CRM and the digitized stone replicas were measured and analyzed (Table 1). In order to make a detailed quantitative analysis, the points in the CRM were separated into cervical, jacket and occlusal surfaces. The boundaries were adjusted by visual inspection, so that the rounded slope of the chamfer and the gingival margin of the crown preparation were in the cervical surface, the jacket surface comprised the middle aspect and the occlusal or incisal aspect of the preparation included the occlusal surface.

Since the stone replicas in Study III were digitized by both digitization methods they were evaluated and compared to the corresponding CRM, using the same digitization method, whereas the digitized impressions$_{laser}$ were compared to both types of CRMs (Table 1). A complementary analysis was made of the result from Study II, where the experimental impression material was validated by comparison with stone replicas poured from a commercial impression material, using the same digitization method.

In Study IV the discrepancies between the digitized simulated clinical impressions and the corresponding CRM were calculated and compared with that of digitized stone replicas (Table 1). To investigate the reliability of the digitized impressions *vs.* digitized stone replicas eight repeated digitizations were performed by both methods and compared to the corresponding CRM (Table 1).

3.6 STATISTICS

The SD and mean of absolute values of the discrepancies were used for the quantitative analysis of the repeatability in Study I. The median and the 95th percentile of the discrepancies were used to assess the relative accuracy of the two surface digitization devices.

In studies II, III and IV the systematic disagreement was expressed as the accuracy within the digitized replicas and the CRM, calculated by the overall mean of the discrepancies. The 95 % CI of the mean was determined for each preparation. The RC was estimated, using ANOVA repeated measures design. RC describes the precision: it estimates the size of the discrepancy of a registration with a 0.95 probability (Bland & Altman, 1999). In Study II the variation of measurements within each preparation was estimated by calculation of the $RC_{within\ shape}$ (Bland & Altman, 1986). This value expresses the precision of the repeated digitizations *i.e.* the reliability of the measurements, as well as the precision of the eight stone replicas *i.e.* their reproducibility. In studies III and IV the $RC_{within\ replica}$ was estimated, which is a measure of the variation within each replica or digitization. Since this measure is a more relevant description of the precision of the replicas, a supplementary calculation on the material in Study II was undertaken in Study III.

The differences in precision were analyzed using ANOVA repeated measures design; shape was set as the dependent variable and the within factor was the $RC_{within\ replica}$ for the digitized impressions and stone replicas in pairs.

4 RESULTS AND DISCUSSION

The results are briefly described in this section. The detailed results are presented in the individual papers. Each study is briefly discussed and the inter-study relationships are then presented, including a complementary analysis.

4.1 STUDY I

The repeatability of the laser scanner and the touch-probe scanner was within 10 µm, based on SD and absolute mean values. There were dissimilarities between the anterior and the posterior group in both scanners. The repeated readings of the master dies from the anterior group digitized in the touch-probe scanner revealed the smallest discrepancies; the readings in the posterior group were less precise. In the laser scanner the discrepancies showed a larger numerical value, but with less variation.

One conceivable reason for the dissimilarity between the groups and digitization devices is that the number of points in the CRMs differed. Digitizations by the laser scanner resulted in point-clouds with less density (Fig. 6a). The points were evenly distributed over the surface, whereas the point-clouds originating from the touch-probe scanner varied with shape and curvature of the preparation (Fig. 6b).

The relative accuracy of the two surface digitization devices was within ±6 µm, based on median values of the discrepancies. The qualitative evaluation indicated that the laser scanner technique had a tendency to round off sharp edges, such as the margin, whereas the touch-probe scanner was more efficient in reproducing edges and less precise in the chamfer aspect. The contact angle between the probe and the surface depends on the inclination gradient of the surface. Since the ascent in the helical movement of the probe was constant, independent of the inclination of the digitized surface, the distribution of the points in the rounded slope was less dense (Fig. 6b). As a consequence the resultant cement space will be greater at the chamfer, as has been shown in previous studies (Kokubo, *et al.*, 2005a; Kokubo, *et al.*, 2005b).

4.2 STUDY II

The reliability of the virtual and three-dimensional evaluation method, used to analyze the accuracy and precision of dental stone replicas of crown preparations (Y-TZP), proved to be both accurate and precise. The main findings in this study were that the dimensional changes between the replicas and the CRM were limited and that no unambiguous, systematic geometrical changes were noted. The accuracy of the eight stone replicas in each shape ranged between -0.5 and 2.0 µm. However, the incisor was the only shape that showed systematic differences, indicating that the stone replicas tended to be smaller than the CRM.

The precision presented as the $RC_{\text{within shape}}$ was on average 15 µm (2-25 µm) greater for the replica-to-master alignment than for the repeated digitizations of the master. However, because the study encompasses both impression taking and fabrication of the stone replicas, it is difficult to identify the source of errors. The greatest reproducibility was seen in the canine replicas, showing good accuracy and the lowest $RC_{within\ shape}$. Hypothetically, it might be due to the favorable shape of the preparation: a uniform cone shape, which is uncomplicated to digitize with the touch-probe scanner and results in a fairly even distribution of the points in the point-cloud (Fig. 6c). The contact angle between the probe and the surface depends on the inclination gradient of the surface: a vertical surface results in a distance of 50 µm between the revolutions, whereas the distance will be greater in less inclined areas. The repeated measurements of the master dies confirmed that the jacket surface of the dies was digitized with the greatest precision.

4.3 STUDY III

The results from this laboratory study indicated that digitizing the impression can be an alternative, efficient means of registering the surface of a crown preparation. With the exception of two of the replicas, the random disagreement for the digitized $impressions_{laser}$ and stone $replicas_{laser}$ compared to the CRM_{laser} resulted in discrepancies of similar magnitude, with a mean ±SD within 20 µm. The accuracy indicated the stone replicas to be greater than the CRM since all shapes resulted in a negative mean value. However, the canine shape was the only one with systematic differences.

The noise from the manufacturing process, including the digitization, expressed in terms of the $RC_{within\ replica}$, was less in digitized impressions than in digitized stone replicas, even though the difference was not significant. However, when two deviant impressions were excluded, the $RC_{within\ replica}$ was significantly lower for the impressions. This is most likely related to the reduction in the number of steps in the manufacturing process.

There was no obvious correlation between the discrepancies in the impressions and those in the corresponding stone replicas. This lack of congruence in discrepancy distribution reflects the combined effects of the volumetric change of the dental stone and the differing conditions for digitization.

In an in-depth analysis of how different CRMs may affect the measurement of the discrepancies in the impressions, both CRMs were used in the alignment and error analysis. When the laser digitized impressions were evaluated with the CRM_{laser} there was significantly less noise.

Comparison of the stone $replicas_{touch\text{-}probe}$ poured from the experimental impression material with those from Study II, made from a commercial impression material, disclosed significantly better precision, *i.e.* lower $RC_{within\ replica}$ for the latter. However, the random disagreement was low in both groups with a mean ±SD within 22 µm.

4.4 STUDY IV

The random disagreement for the digitized simulated clinical dental impressions and the stone replicas compared to the CRM were of similar magnitude, with a mean ±SD within 40 µm, except for two of the digitized molar impressions. The precision *i.e.* the noise within each individual digitization, expressed by the $RC_{within\ replica}$ for the three preparations, did not differ significantly between the digitized impressions and the stone replicas. Within the limitations of this laboratory study and in comparison with earlier studies (Brosky*, et al.*, 2003; Kenyon*, et al.*, 2005), the discrepancies of the digitized impressions and stone replicas may be regarded as clinically acceptable. Hence the quality of the final restoration will be as good as present CAD/CAM systems (Odman & Andersson, 2001; Bindl & Mormann, 2005; Kokubo*, et al.*, 2005b), since elimination of the steps involved in making and digitizing stone replicas would increase laboratory efficiency and reduce sources of error from the manual handling (Goldsby & García-Dastugue, 2003; Persson*, et al.*, 2008c). A systematic disagreement was observed in the digitized impressions of all three tooth shapes. Since there was no correlation to the discrepancies of the digitized stone replicas, this might be a combined result of the digitization and the best-fit alignment.

In the analysis of a number of different impressions or stone replicas the errors and variations from the manufacturing process as well as the digitization and alignment process are included. To exclude the variation from the manufacturing process, repeated digitizations of a selected impression and a stone replica were performed and the reliability of the different digitization methods was assessed. The range of the noise in the repeated digitizations of the impression and the stone replica was very low, indicating that the variation due to digitization is low in both digitization methods. The precision did not differ significantly between the impressions and the stone replicas but was influenced by the shape. An interaction effect between the digitization sources indicates that the digitization methods favor preparations of different shapes.

A general finding was that the stone replicas were wider than the CRM, especially in the jacket surface and in particular in the chamfer aspect in all three tooth shapes. This can partly be explained by the digitization method (Table 1), where the helical movement is influenced by the shape and the inclination gradient towards the surface. However, the high resolution setting, with the closer distance between the revolutions in the helical movement and the smaller diameter of the contact probe, resulted in a more accurate digitization (Fig. 6c).

4.5 GENERAL DISCUSSION

The possibility of digitizing free-form objects, such as teeth, allows for accurate measurement of small changes. The applicability of CAD technology in dentistry exposes new opportunities *e.g.* as a virtual evaluation method to analyze geometrical changes of the digitized preparation and the final restoration, presenting the disagreements three-dimensionally (Rudolph*, et al.*, 2002; Luthardt*, et al.*, 2003; Luthardt*, et al.*, 2006; Persson*, et al.*, 2008a). In the field of dental drill- and implant-guided surgery, it has become a valuable tool, which has facilitated and improved communication with the dental laboratory (van Steenberghe*, et al.*, 2002; Kramer*, et al.*, 2005; van Steenberghe*, et al.*, 2005; Kero*, et al.*, 2007b). The use of computer-assisted virtual treatment planning and flapless surgery have been shown to decrease the patient's post-operative discomfort; however, the study suggests that further improvements and investigations are needed (Komiyama*, et al.*, 2008).

To estimate the exactness of two compared objects, both the accuracy *i.e.* the systematic disagreement, and the precision, *i.e.* the noise, must be known. If a measurement is precise but not close to zero, it indicates that there is a systematic disagreement. The exactness is determined by how close to and tightly clustered the deviations are around the true value.

Depending on the system used, there are several ways to analyze the exactness (Dahlmo*, et al.*, 2001; Bornemann*, et al.*, 2002; Rudolph*, et al.*, 2002; DeLong*, et al.*, 2003; Luthardt*, et al.*, 2004; Shah*, et al.*, 2004; Vlaar & van der Zel, 2006; Kero*, et al.*, 2007a; Kero*, et al.*, 2008). In Study I it was not possible to receive data from the alignment and matching as raw data. The absolute value was used to avoid influence of positive and negative discrepancies. To obtain more detailed information of the discrepancies, the matching software was changed after Study I. The alternate software allowed a more in-depth statistical analysis, given that the errors were presented from each point in the CRM. Since the discrepancies were normally distributed in studies II, III and IV, the mean discrepancy within each replica was calculated using all data, both positive and negative discrepancies. In other studies the mean values of the negative and positive deviations have been calculated separately (Luthardt*, et al.*, 2003; Luthardt*, et al.*, 2005; Quaas*, et al.*, 2007). If a mean value close to zero is achieved, then the sums of the negative and positive discrepancies are about the same size, but the distribution can differ. Moreover, by extending the analysis with a measure for the precision *i.e.* the $RC_{within\ replica}$, the exactness can be evaluated. The qualitative evaluation, presented in color-difference-maps, shows the distribution and the size of the discrepancies (Figs. 9 and 10).

In papers II and III an experimental impression material was used (and modified slightly between the two studies). As stated previously, the optical properties of the material are important when a non-contact digitizing method is used. It has previously been shown that opaque and not too shiny surfaces are more readily digitized (DeLong*, et al.*, 2001). These characteristics are therefore of immediate importance when digitizing impression materials. Moreover, since color may affect the digitization properties, the impression material should be a monophase impression material.

4.5.1 Supplementary analysis

The supplementary analysis of Study I, using the alternate software for realignment and matching, was performed on four selected dies. Figure 11 presents the results from the repeated digitizations of the master dies with the three surface digitization devices used in studies I and II.

The discrepancies from the repeated digitizations in the laser scanner (Study I) appeared similar despite the preparation shape, whereas the discrepancies from the repeated digitizations in the touch-probe scanner (Study I) resulted in greater deviations in the posterior shapes (premolar and molar; Fig. 11). Thus, the re-analysis by the CopyCAD software is in agreement with the analysis using the NSI Registration software.

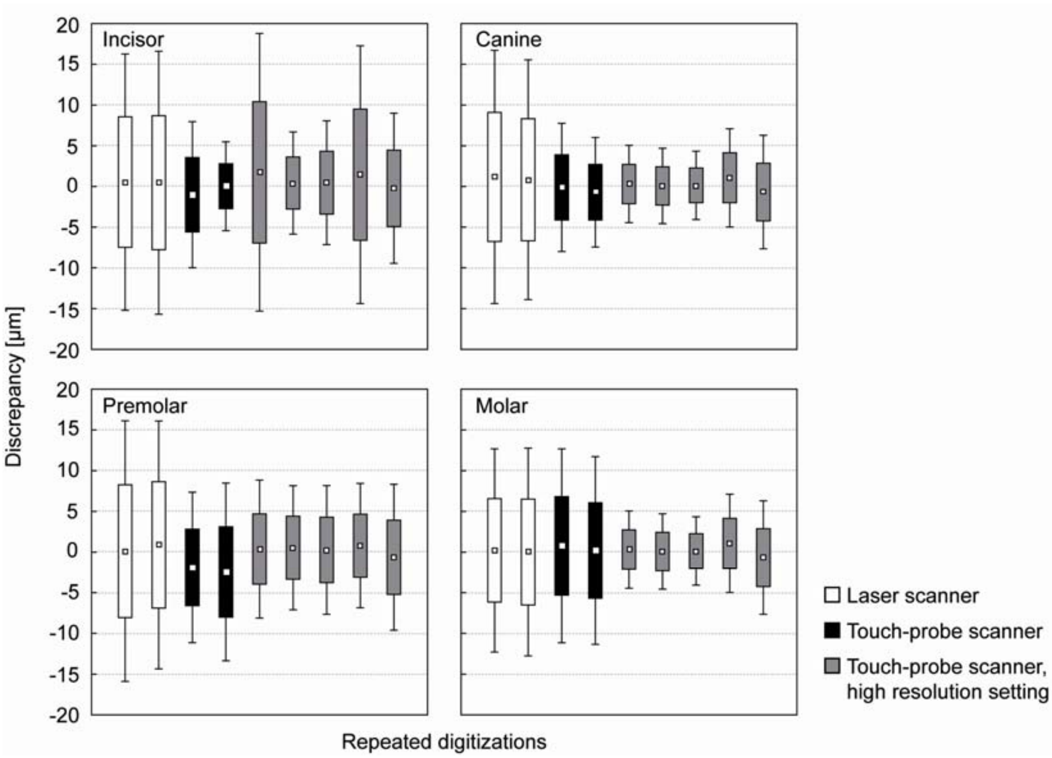

Figure 11. Deviations (µm) between the first registration and the repeated digitizations of the master models (Y-TZP). Dots: Mean; Box: SD; Whisker: 95 % CI. White and black boxes Study I, grey boxes Study II.

The repeated digitizations in Study II with the touch-probe scanner, using the high resolution setting, revealed the overall smallest discrepancies (Fig. 11). The digitization of the incisor shape was sensitive, as reflected by the discrepancies in two of the digitizations being of similar size to those by the laser scanner in Study I (Fig. 11). This is also demonstrated by the noise, expressed as the $RC_{within\ replica}$, for the repeated digitizations. The repeated digitizations in the laser scanner (Study I), touch-probe scanner (standard resolution setting, M50; Study I) and touch-probe scanner (high resolution setting; Study II) ranged from 12.5 to 16.2 µm, 5.5 to 12 µm and 4.2 to 17.4 µm, respectively.

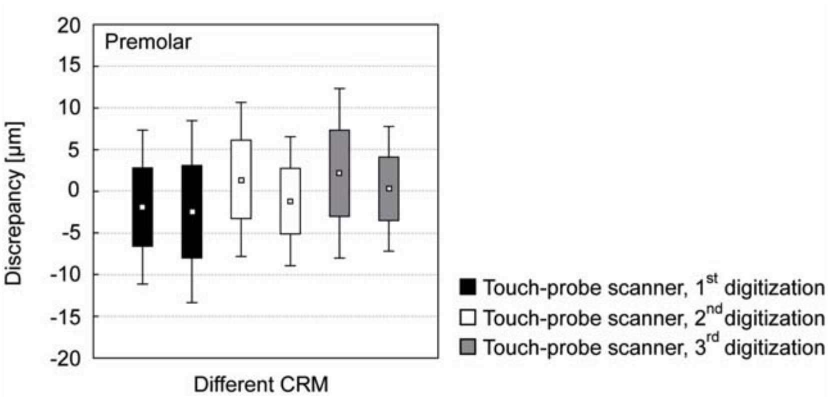

Figure 12. Deviations (µm) between the repeated digitizations of the premolar master model (Y-TZP) using different CRMs (Study I). Dots: Mean; Box: SD; Whisker: 95 % CI.

The resultant mean value was close to zero, except for the premolar digitized with the touch-probe scanner in Study I (Fig. 11). The alignments of the premolar digitizations were dominated by negative discrepancies, indicating that the CRM was smaller than the corresponding model. To analyze the impact of the chosen CRM, a supplementary analysis was performed by evaluating alignments of the repeated digitizations using nos. 2 and 3 as CRMs (Fig. 12). The highest precision was achieved when the third reading was used as CRM and aligned to the second digitization: This combination resulted in a $RC_{within\ replica}$ of 7.5 µm, instead to 16 µm when the first reading was used as CRM.

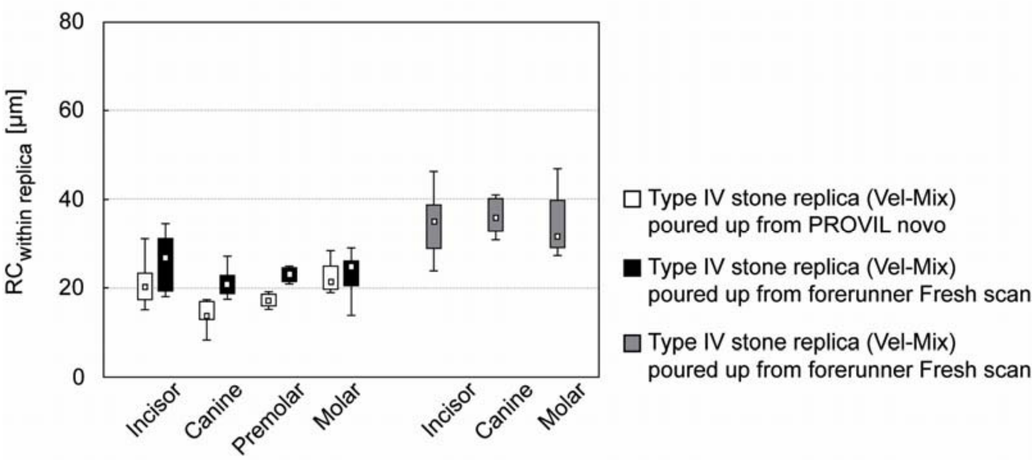

Figure 13. Noise within each individual digitization of stone replicas compared to the $CRM_{touch\text{-}probe}$ the $RC_{within\ replica}$ (µm) presented as box plots. White boxes Study II, black boxes Study III and grey boxes Study IV. Dots: Median; Box: Interquartile range; Whisker: Non-outlier range.

When a digitization by the opposing scanner was used as CRM $RC_{within\ replica}$ *i.e.* the relative accuracy, ranged between 24 and 37 µm for both scanners. Thus, the noise was 10 to 24 µm greater than for the repeated digitizations.

In Study II, $RC_{within\ shape}$ *i.e.* the precision, was used to evaluate the variation of the stone replicas within each preparation. However, this calculation is a description of the variation of the eight stone replicas altogether. In contrast, the $RC_{within\ replica}$ describes the variation within one digitization *i.e.* the precision of each replica, and is therefore a better way of detecting deviating replicas or digitizations. Figure 13 shows the precision of the stone replicas from Study II, III and IV, evaluated by the $CRM_{touch\text{-}probe}$.

In studies II and III as regards the accuracy, the $CRM_{touch\text{-}probe}$ tended to be smaller than the stone replicas for all shapes except for the incisor (Study II) which was greater in the bucco-lingual direction (Table 2). Evaluation by the laser scanner (Study III) confirmed the result by systematic differences in all shapes, indicating the CRM_{laser} to be smaller than the stone replicas. Both methods indicated the stone replicas to be greater than the corresponding CRM. In this context it should be noted that the impression material was intended only for digitization and not as a mould to fabricate stone replicas and therefore did not compensate for the expansion of the dental stone. Moreover, an even greater difference was seen in Study IV, indicating that the stone replicas were greater than the CRM, except for the molar (Table 2). However, this might be due to the simulated clinical situation resulting in less surrounding impression material, especially in the proximal part.

Table 2. Systematic disagreement presented by the accuracy of the stone replicas (n=8) from alignments between the points in the $CRM_{touch-probe}$ and the points in the virtual point-clouds, summary of studies II-IV

Master die Tooth shape	Study	Overall mean	CI range* +95% CI	+95% CI
Incisor	II	2.0	1.2	2.9
	III	-1.9	-3.9	0.1
Canine	II	-0.1	-0.8	0.6
	III	-1.8	-3.4	-0.3
Premolar	II	-0.5	-1.5	0.6
	III	-1.8	-5.1	1.5
Molar	II	-0.2	-1.4	1.1
	III	-0.8	-2.5	0.9
Incisor	IV	-2.7	-4.3	-1.1
Canine	IV	-2.9	-5.1	-0.7
Molar	IV	1.4	-0.4	3.3

* The accuracy, expressed by the overall mean value and the 95% CI calculated from mean discrepancy of the eight aligned stone replicas. When the 95% CI excludes 0, the discrepancies between the replicas and the CRM are determined as systematically higher (0 to the left) or lower (0 to the right).

4.5.2 Alignment and matching challenges

Since there is no gold standard for validating surface digitization devices, the question arises as to which CAD-file should be selected as a reference. Use of a sphere as a calibration tool can be useful (Vlaar & van der Zel, 2006), in particular to determine the accuracy of the digitizations. To analyze free-form objects such as teeth, however, there is a need for an additional procedure. One option is to choose the CAD-file used to manufacture the master die (Luthardt, *et al.*, 2003), but this does note take into account possible manufacturing errors. An object manufactured from a CAD-file, and thereafter digitized, may not be absolutely identical to the original file because of the geometrical variation in the manufacturing process (Kero, *et al.*, 2007b). In the present studies it was decided to digitize the physical die to achieve a CRM. In this way errors that might have been introduced in the manufacturing process are not included and will not affect the evaluation.

Choosing the digitization method for the CRM is not without complications. In Study II and parts of studies I and III, the same digitization method was used both for the CRM and the corresponding model. This procedure may be questioned due to the risk of systematic bias of the results. The supplementary analysis of the repeatedly digitized premolar in Study I (all three readings used as CRMs, aligned and compared to the other two) shows that the choice of CRM clearly affected the result, as presented in

Figure 12. This highlights the sensitivity of the method. In studies I and III, two dissimilar digitization systems were used to obtain CRMs. However, using dissimilar digitization methods for the CRM and the replica complicates the evaluation, since different densities in the point-clouds may affect the result (Persson, *et al.*, 2006). The lack of a gold standard is obvious.

In the evaluation of the relative accuracy in Study I, different digitization methods were used for the CRM, which resulted in the $RC_{within\ replica}$ being 10-24 µm greater than the $RC_{within\ replica}$ for the repeated digitizations evaluated *i.e.* the repeatability. In Study III, the evaluation of the digitized $impressions_{laser}$ was performed by alignment to CRMs from two digitization methods. The $RC_{within\ replica}$ was 5-10 µm greater when the master and the replica were digitized by different devices than when they were digitized by the same digitization method (Fig. 14). In Study IV, the practical limitations were that the digitized $impressions_{laser}$ could only be evaluated by CRMs from a dissimilar digitization method (touch-probe high resolution setting; Table 1). Thus, in Study IV the dissimilarity of the digitization methods presumably affects the determined $RC_{within\ replica}$ by 5-10 µm.

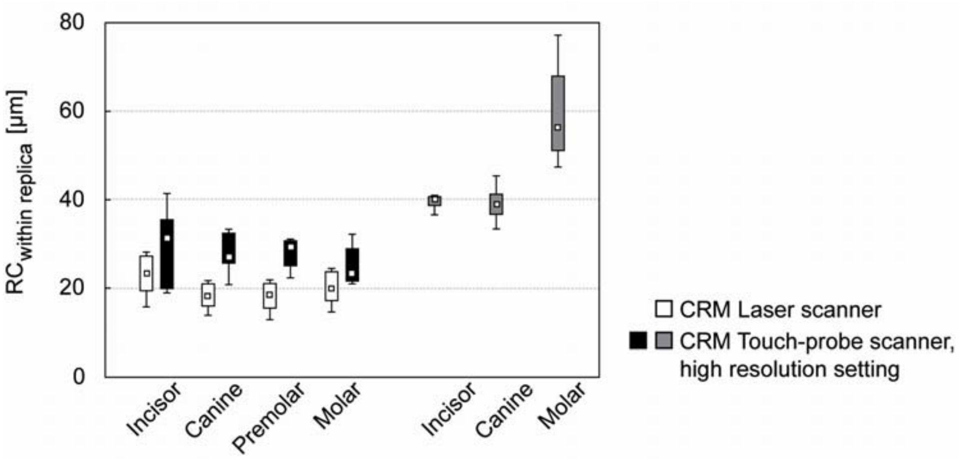

Figure 14. Noise within each individual digitization of impressions compared to different CRMs the $RC_{within\ replica}$ (µm) presented as box plots. Black and white boxes Study III and grey boxes Study IV. Dots: Median; Box: Interquartile range; Whisker: Non-outlier range.

One conceivable reason for the different precision mentioned above, is the difference in point-cloud density of the CRMs (Fig. 6), since the error analysis uses measurements from point-to-point. If the point-cloud in the CRM is denser than the compared point-cloud then several measurements will be made to the same points, resulting in deviations greater than in reality. This partly explains why the discrepancies are smaller when the CRM_{laser} is used and compared to digitizations made by the laser scanner, having a less dense point-cloud (Fig. 14). An alternative and more valid method would be to measure from the points in the CRM perpendicular to a compared surface. In these studies it was not possible to transform the point-clouds into surface models. However, a negative aspect that must be considered when recalculating and converting the point-clouds to a surface model: errors may arise by the transformation process.

5 IMPLICATIONS FOR FUTURE STUDIES

The research on which this thesis is based represents pioneering work, intended to bring a deeper understanding of the specific problems associated with the evaluation of CAD/CAM technology in dentistry. The thesis examines in detail various difficulties and problems in establishing proper data on scanner reliability and exactness of dental replicas. The methodology developed to evaluate exactness of digitizations will be of benefit in the ongoing process of validation of dental CAD/CAM systems.

It is difficult to apply traditional two-dimensional analysis to quality assurance of the geometry of free-form objects. In the virtual three-dimensional analysis the prerequisites are better, but there are pitfalls. An example is that the discrepancies can be wrongly interpreted when comparing two objects with an irregular geometrical deviation: for example if the original shape is a sphere and the object being compared is egg-shaped (Fig. 15). Using all points in a virtual best-fit alignment would make the sphere end up positioned like an egg yolk, whereas when a selected part of the CRM is used, in would be correctly positioned in the rounded part at the bottom. The asymmetrical change of shape complicates determination of which part to select. To avoid some of the errors in the alignment process, one option is to use “weighted” points during the matching step: by letting the points around the finishing line have a higher impact than those in the jacket surface. Another option is to introduce specific reference points, which would make it possible to verify geometrical changes. However, the technical problems involved are not easily solved.

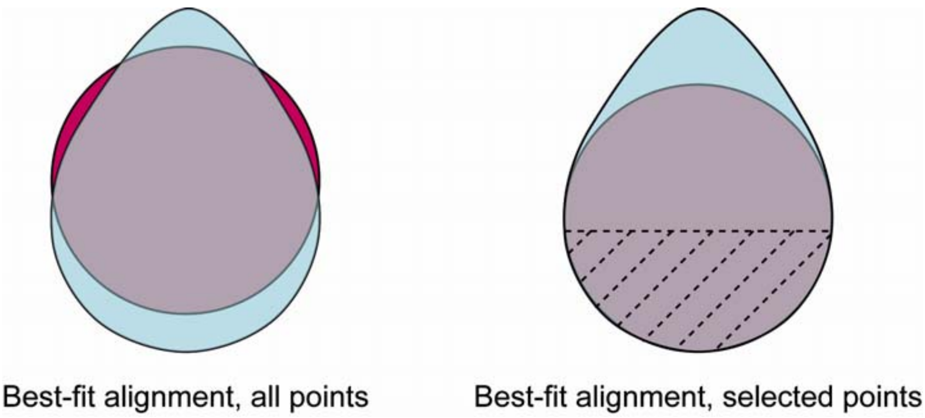

Figure 15. Illustration of the conceivable effects during the best-fit alignment process. All points used (left) and when selected points are used (right).

The internal and marginal fit of the final restoration might be adversely affected by the simplification of the manufacturing process. This could be clarified by evaluation of the precision of the produced restorations manufactured using CAM-files from intra-oral digitizations, digitized impressions and corresponding files from digitized stone replicas.

6 CONCLUSION

With respect to adequate data acquisition, the reliability of dental surface digitization devices differs. Touch-probe scanners show very high measurement certainty with high precision, but are not suitable for digitization of dental impressions. High quality data can be achieved directly from the digitized impression with the optical digitization device used in the thesis. The properties of the impression material need further modifications. The results indicated that the discrepancies noted were similar to those in digitized stone replicas. It is concluded that while the quality of the final restoration will probably be equal to that achieved by current CAD/CAM systems, elimination of the steps involved in making and digitizing stone replicas would improve laboratory efficiency and reduce sources of error in the manual handling.

Virtual three-dimensional analysis can be applied to differential quality analysis of the manufacturing process as well as to evaluation of different digitization methods. The method can be adapted for application to a wide range of interdisciplinary questions both *in vitro* and *in vivo*, such as estimation of geometrical variations in dental materials, virtual verification of dental drill-guided surgery, orthodontic and facial analysis and virtual occlusion and articulation.

7 SWEDISH SUMMARY

En ökad medvetenhet kring estetisk tandvård gör att efterfrågan på helkeramiska protetiska rekonstruktioner stiger, detta mycket på grund av dess likheter med den naturliga tanden och de biokompatibla egenskaperna. Passformen på en dental krona eller bro är viktig och påverkas av kvaliteten de olika stegen som ingår i tillverkningsprocessen, såsom preparationen av tanden, avtryckstagning, tillverkning av arbetsmodellen i gips, framställning av den protetiska rekonstruktionen, samt inpassning och justering vid den slutliga cementeringen. Vid användning av CAD/CAM system så är vissa steg automatiserade, vilket effektiviserar tillverkningen och ger bättre förutsättningar för kvalitetskontroll.

I avhandlingen har en tredimensionell virtuell analysmetod utvecklats och tillämpats på några av de olika steg som ingår framställningsprocessen av fast protetik. Det generella målet var att mäta de olika stegens inverkan på CAD-modellens exakthet.

Samtliga fyra delarbeten är *in vitro* studier, utförda i laboratoriemiljö. Tre olika dentala digitaliseringsutrustningar har använts, en optisk laserskanner och två kontaktskanners. Digitalisering av referensmodellerna resulterade i punktmoln, vilket användes som CAD-referensmodell (CRM). Respektive skanners tillförlitlighet utvärderades genom analys av repeterade skanningar. Virtuella punktmoln från skanningar av replikat och CRM matchades med ”best-fit alignment”. Möjligheten att digitalisera avtryck direkt i en optisk skanner undersöktes, genom att utvärdera exaktheten hos avtrycksreplikat och gipsreplikat. I det fjärde arbetet simulerades den kliniska situationen genom att använda en referensmodell i plast med tre preparationer för fullkronor, monterad med granntänder och antagonerande tänder i en ockludator.

Avtrycksmaterial kan inte digitaliseras genom kontaktskanning medan digitalisering med laserskanner ställer särskilda krav på avtrycksmaterialets optiska egenskaper. Resultatet från avhandlingen visar att det är möjligt att erhålla högkvalitativa data direkt från avtryck, då avvikelserna var i samma storleksordning som för digitaliserade gipsmodeller.

Genom att digitalisera avtryck erhålls en förkortning av tillverkningsprocessen vilket leder till att det manuella laboratoriearbetet reduceras, antalet möjliga felkällor minskar och slutligen effektiviserar det tandtekniskt arbetet. Resultatet indikerar att avtrycksavläsning kan vara en framgångsrik väg och där kvaliteten på den slutliga rekonstruktionen kan uppnå samma nivå som vid befintliga CAD/CAM system.

Avhandlingen ger en djupare förståelse över de specifika problemen som föreligger vid utvärdering av dentala CAD/CAM system. Den metodik som utarbetats i avhandlingen kommer att kunna bidra till den pågående processen om validering av dentala CAD/CAM system. Metodiken kan anpassas och användas för kvalitetskontroll av tillverkningssteg och vid utvärdering av olika digitaliseringssystem.

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