DATA CAPTURE STABILISING DEVICE
FOR THE CEREC CAD/CAM CHAIRSIDE CAMERA

Mick Iván de Sousa Muianga

Dissertation submitted to the Faculty of Health Sciences,

University of the Witwatersrand, Johannesburg,

in fulfillment of the requirements for the degree of

Master of Science in Dentistry

Johannesburg, 2009

DECLARATION

I, Mick Iván de Sousa Muianga declare that this dissertation is my own work. It is being submitted for the degree of Master of Science in Dentistry in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other University.

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Mick Iván de Sousa Muianga

19th day of October 2009

ABSTRACT

Problem. One of the sources of inaccuracy in utilising the CEREC Chairside CAD/CAM system has been the difficulty of accurately positioning the intraoral camera relative to the path of insertion of the preparation and restoration. The degree of inaccuracy produced by variations in the angulation of the camera relative to the path of insertion is not known.

Purpose. The purpose of this study was to first review the literature and history of CAD/CAM in dentistry, and the CEREC Chairside System in particular, and then to determine the errors that may result from changes in angulation of the camera in three dimensions. Further, to design a device which would help stabilise the camera to eliminate such errors.

Method and Materials. A prefabricated Aesthetic Base Gold (ABG) Model was used and mounted on an articulator in order to simulate changes in angulation of each of the three dimensional axes which cause variations in roll, pitch, and yaw in the positioning of the camera. Images were captured for angle variations of 0 °, 1 °, 3 °, 5 °, 10 °, 15 ° and 20 ° using the CEREC software on a crown preparation for tooth 24. The same software was used to make measurements on the resulting images to determine the mesio-distal, bucco-lingual orientation and the occlusal, internal shoulder and external shoulder dimensions. In addition, a quality assessment was carried out to observe any shadows, surface texture changes, margin discrepancies and ability to automatically complete the restoration with ease and accuracy. An intraoral stabilising device was designed that could be placed intraorally using polyvinyl siloxane putty. The ABG model was positioned to simulate quadrants 2 and 4 on crown preparation for tooth 24. Time to set up and place the device was recorded, and a Visual Analogue Scale was used to determine ease of use.

Results. Difficulties were encountered in measurements of images where there was an angle deviation of greater than 5 °, and so it was only possible to analyse the four angles of 0, 1, 3, and 5 °. A three-way ANOVA revealed expected significant differences between the different measurements (as they are measuring different things) but there were no other significant differences. Thus neither the four different angles nor the three different axes had any influence on the readings. There was also consistency across the measurements, for every combination of the levels of the three factors (angle, measurement and axis). The stabilising device proved quick and easy to set up and place the silicone putty (less than 20 seconds) and the average VAS score for using the device improved by 25.3% when using the device in the lower, and by 36.4% when using the device in the upper arch.

Conclusions. The angle of the camera relative to the path of insertion of the restoration should not exceed 3 ° for changes in Pitch, or 5 ° for changes in Roll and Yaw of the camera. The stability device designed during this study proved to be more convenient and accurate for data capture as it decreased the time of search and reduced both the internal and external factors which interfere with data capture.

ACKNOWLEDGEMENTS

First and foremost I would like to express sincere gratitude to Prof CP Owen for his tireless guidance for the completion of this dissertation. I would like to show appreciation to my parents Aldino Muianga, Carolina de Sousa Muianga, and my brothers Aldino (Dino) and Hugo who supported me throughout. I would like to also thank the University of the Witwatersrand, Department of Prosthodontics staff and Faculty of Oral Health Sciences for allowing me access to equipment and facilities of the hospital. In addition, I would like to thank the department of Chemistry for allowing use of their equipment for which the study would not have been possible. Lastly I would like to show my appreciation to Sirona Dental Systems (South Africa) and Dr DJ Fasbinder for permission to use their figures.

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CHAPTER 1. A REVIEW OF CAD/CAM IN DENTISTRY

1.1 CAD/CAM IN RESTORATIVE DENTISTRY

1.1.1 Introduction

Throughout the years dentistry has gone through numerous developments in knowledge, techniques and technology. Among many of the more recent challenges is the approach to making high quality restorations in a short space of time. In the present technologically inclined approach to treatment, this has led to the development of the Computer Aided Design and Computer Aided Manufacture (CAD/CAM) system. Dental CAD/CAM is the process by which the model of a prepared tooth is digitally scanned and these data are then used to generate a coping/restoration design (CAD) which in turn is used to generate a cutting path for manufacturing the coping/restoration (CAM).

Although CAD/CAM has been used in the aeronautical and design industries since the 1950s, in dentistry the earliest attempts were conducted in the 1970s by Bruce Altschuler (USA), Francois Duret (France),Werner Mörmann and Marco Brandestini (Switzerland). Young and Altschuster were the first to introduce the idea of using optical instrumentation to develop an intraoral grid surface mapping system in 1977 (Liu, 2005). The first successful commercial system was the CEREC (Sirona Dental Systems, Bensheim, Germany) developed by Mörmann and Brandestini in the early 1980s. An early system was that developed by Duret and known as the Sopha Bioconcept system (Sopha Bioconcept, Inc. Los Angeles, USA). It demonstrated the ability of CAD/CAM to generate single-unit, full-coverage restorations, in

1984. However, due to its complexity and cost, this system was unsuccessful in the dental market (Liu, 2005).

Since then many systems and materials have been developed, and these are listed in Table 1.

1.1.2 Dental CAD/CAM systems

Presently there are basically 2 forms of dental CAD/CAM, the **Inlab** and the **Chairside** (Table 1). In general the Inlab systems required cumbersome processes and a lot of time to manufacture even simple restorations, and this led to the development of the Chairside CAD/CAM systems of which there are currently only two known systems in the market (CEREC 3 by Sirona Dental Systems and the E4D by D4D Technologies, Texas, USA) the CEREC system is currently the only one which has been scientifically researched, so this review will predominantly concentrate on the CEREC system.

Table 1.1 List of CAD/CAM systems, vendors/manufacturers and type of materials used

Product	Vendor/Manufacturer	Restorations Produced	Materials Used
INLAB SYSTEMS			
Cercon	DeguDent GmbH	Crowns, 3-4 Unit Bridges	Zirconium Oxide
Cerec MC XL	Sirona Dental Systems	Inlays, Onlays, Crowns, Bridges, Copings	Zirconium Oxide,
Everest	Kavo Dental Corporation	Inlays, Onlays, Veneers, Single Crowns, 3-4 Unit Bridges	Zirconium Oxide, Titanium, Ceramic
inLab CAD/CAM System	Sirona Dental Systems	Inlays, Onlays, Veneers, Crowns, Multi-Unit Bridge Frameworks, Crown Copings	Zirconium Oxide, Alumina, Spinell (Magnesium Aluminum Oxide) , Feldspathic Ceramic
In-Visio® DP 3D Printer	3D Systems Corporation		Light Cured Resin
Lava	3M ESPE	Crowns, 3-4 Unit Bridges	Zirconium Oxide
Neo System	Cynovad	Crowns, Full Arches, Full-contour Bridges with Cantilever Pontics	Resin Based Material, 3D Designs sent to Cynovad for fabrication of: Zirconia, Titanium, Ivoclar Procad
Preci-Fit	Popp Dental Inc	Crowns, Bridges	Titanium, Zirconium Oxide
Procera® Forte	Nobel Biocare	Multi Unit Bridges & Full Arch Bridges, Copings, Abutments, Laminates,	Zirconia, Alumina, Titanium
Procera® Piccolo	Nobel Biocare	Bridges, Copings, Abutments, Laminates	Zirconia, Alumina, Titanium
Turbodent	U-Best Dental Technology Inc.	Crowns, Multi-Unit Bridges	Zirconia, Vita InCeram, Ivoclar ProCad, Titanium
WaxPro	Cynovad	Crowns, Single unit Bridges, Simple & Clinical Copings with Band, Anatomical Coping with Automatic Cosmetic Thickness, Copings with Bite Stop, Occlusal Contacts	Wax
CHAIRSIDE SYSTEMS			
Cerec 3	Sirona Dental Sytems	Inlays, Onlays, Veneers, Partial, Full Crowns	Zirconia Oxide, Aluminium Oxide, Ceramic, 3 Colour Ceramic, Resin
E4D Chairside CAD/CAM	D4D Technologies, L.L.C	Inlays, Onlays, Veneers, Crowns, Multi-Unit Bridge Frameworks, Copings	Zirconia, Ceramic, Composite

.

The procedures and sequences of Inlab and Chairside techniques are quite different; the time taken is also vastly different. The Chairside system takes at most 2 hours for completion from tooth preparation to final cementation/bonding, whereas the Inlab system can take up to several hours to days for the same process. Figures 1.1 and 1.2 summarise the main steps in the processes.

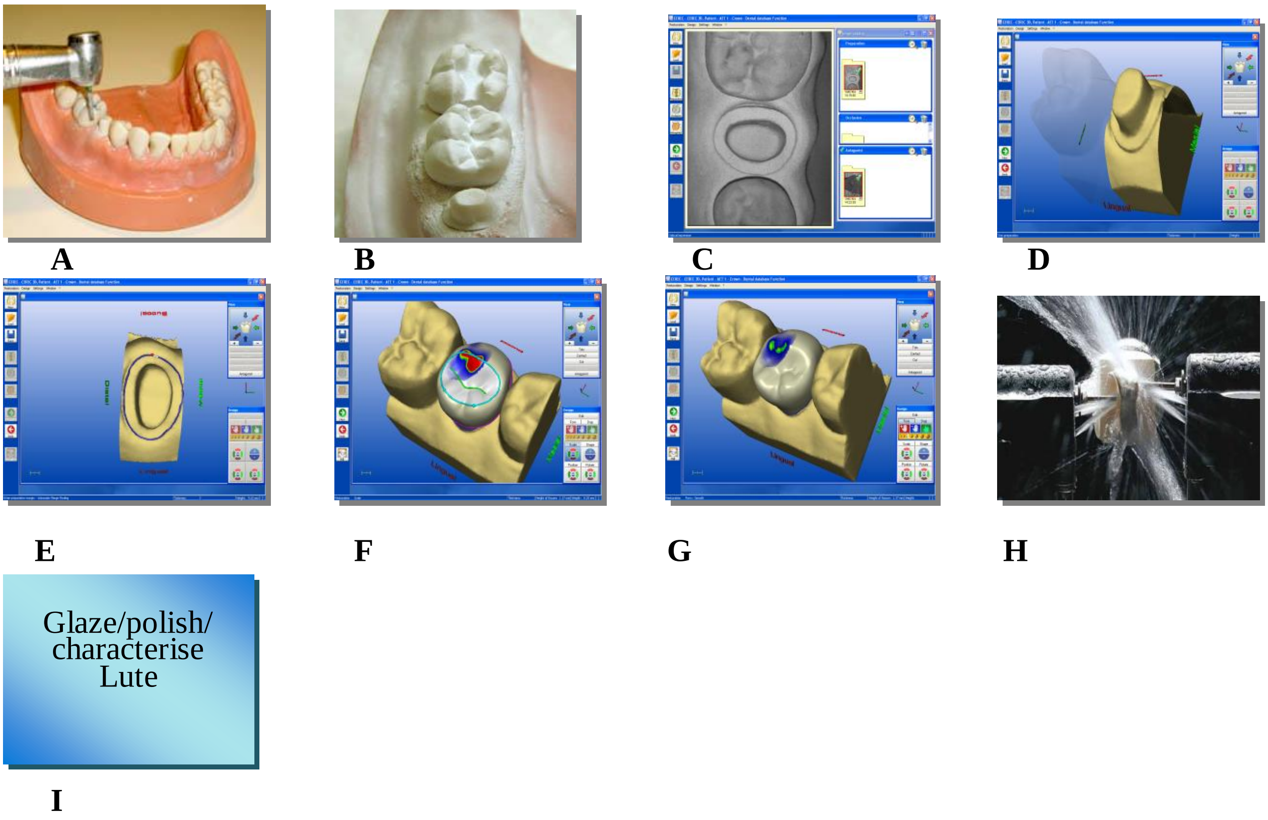


Fig 1.1 CEREC Chairside system **A.** Preparation **B.** Powdering/contrast medium for data capture by optic camera (white powder) **C.** Data capture **D-G.** Automatic 3D design sequence **H.** Milling **I.** Complete restoration. Time to completion 1-2 hours. (pictures used with permission-SIRONA)

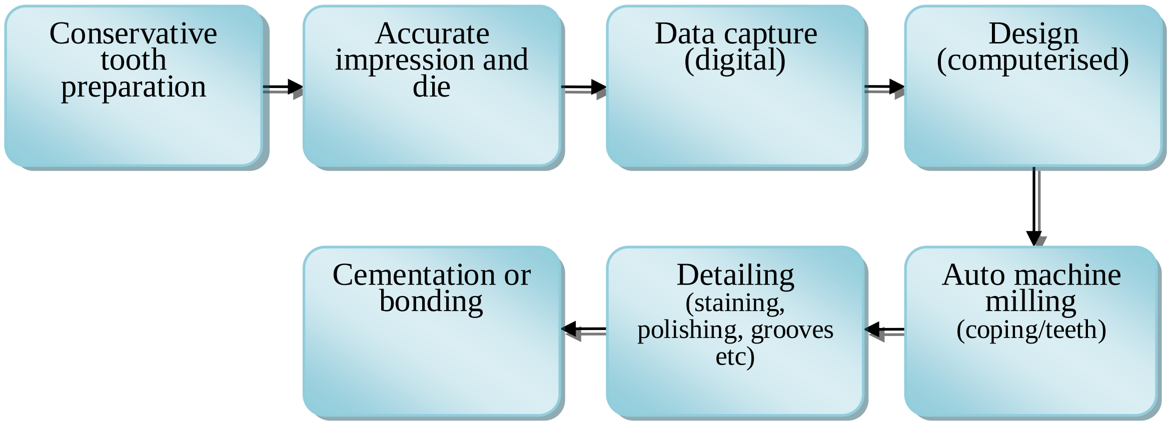


Fig 1.2 Inlab technique. General/Summarised CAD/CAM dental restoration production steps. Time to completion 2-4 days.

1.2 HISTORY OF CEREC CHAIRSIDE CAD/CAM

1.2.1 Introduction

In early 1980, Dr Werner H. Mörmann, one of the pioneers of Chairside dental CAD/CAM, foresaw the possibility of restoring posterior teeth with tooth-coloured material. At that time direct composite fillings were showing poor results because of polymerization shrinkage, thermal contraction, absorption of water, mechanical stress and dimensional changes in tooth structure which resulted in the formation of a marginal gap and consequently failure of the restoration (Staninec et al, 1986). On the basis of his own *in-vitro* and *in-vivo* studies with pressed and hot polymerized composite inlays, Mörmann developed the hypothesis that inlays made of porcelain could be inserted adhesively with resin-based composite as a luting agent (Mörmann, 2004). The concept of adhesive seal was confirmed later by *in-vitro* studies (Schmalz, Federlin and Reich, 1995) and *in-vivo* studies (Mörmann and Krejci, 1992; Bindl and Mörmann, 2003; Posselt and Kerschbaum, 2003). Mörmann developed the clinical concept of bonded ceramic inlays, at the same time raising the issue of the fast fabrication of ceramic restorations. He developed plans for an in-office CAD/CAM fabrication of ceramic restorations specifically to enable the dentist to complete one or multiple ceramic restorations in a single appointment (Mörmann, 2006). The term CEREC was defined from “CERamic REConstruction”.

1.2.2 Hardware

The challenge was to scan individual cavities directly in the mouth of the patient quickly and to use the data via computer to control a fast form-grinding machine (Mörmann, 2006). A data acquisition unit and the technical processes from designing to milling of dental restorations were then developed (Mörmann and Brandestini, 2006).

The initial concept (Figure 1.3) comprised a small mobile CAD/CAM unit integrating a computer, keyboard, trackball, foot pedal and optoelectronic mouth camera as input devices, a monitor and a machining compartment as output devices (Mörmann, 2006).

Fig 1.3 Evolution of CEREC hardware. **A.** 1985: the CEREC 1 prototype unit, the “lemon,” with Dr. Werner Mörmann (left) and Marco Brandestini, Dr. sc. techn.ETHZ. **B.** 1991: CEREC 1, as modified by Siemens (Munich, Germany) with E-drive and CEREC Operating System 2.0. **C.** 1994: CEREC 2, with an upgraded three-dimensional camera. **D.** 2000: CEREC 3, with split acquisition/design and machining units (With permission-SIRONA)

1.2.3 Scanning and Data capture (Input)

Initial developments focused on the possibility of making instantaneous three-dimensional measurements of tooth preparations with an intra-oral camera, as well as three-dimensional scanning of the preparation. As the scanner and camera needed to be one single instrument, this led to the use of a grid of parallel stripes under a parallax angle directed onto the preparation, using the principle of triangulation. To acquire the depth-dependent shift of the lines an area sensor (that is, a charge-coupled device [CCD] video chip) was used (at that time, high-tech parts such as these were subject to U.S. export control because they were being used for military purposes, but now this type of technology is common place and used most frequently in digital cameras).

In the spring of 1983, the measuring principle was refined and a grid of parallel black and “bright”-white stripes, each 250 µm wide was used on the optical bank; as a result the first optical impression of a cavity was obtained. Integrating the optical and electronic system into the small dimensions of a mouth camera required a major effort (Mörmann, 2006). A small camera and scanner with high visual clarity was difficult to achieve at that time (Mörmann, 2004, Mörmann and Brandestini, 2006).

The basic concept was for the dentist to be able to use the camera as any other dental instrument. The camera would be aligned according to the path of insertion of the preparation and stabilized by resting it on the patient’s teeth; the dentist would simultaneously watch the monitor for adjustments and trigger the process for data capture. This was based on the knowledge that the view of the preparation in the direction of the path of insertion enables all spatial information necessary for designing inlays or crowns so that it would be possible to acquire the image with a single scan. This process is called the "optical impression" (Mörmann 2006) and this procedure remains unchanged to date.

1.2.3.1 Milling (Output)

The first grinding trials on blocks made of feldspathic ceramic (Vita Zahn-fabrik, Bad Säckingen, Germany) showed that this material could be removed with a grinding wheel in a few minutes without damaging the rest of the bulk (Fig 1.4A).

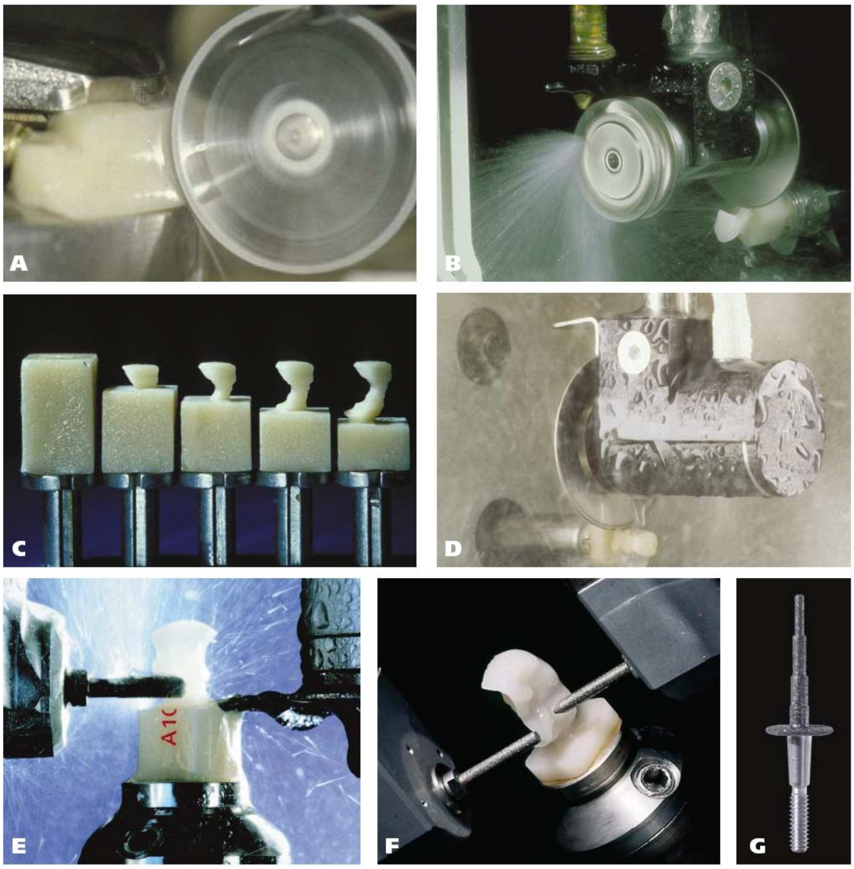


Fig 1.4 CEREC form-grinding evolution: feldspathic block ceramic. **A.** Basic grinding trial with diamond-coated wheel. **B.** CEREC 1: water turbine drive. **C.** CEREC 1: inlay emerging from a block. **D.** CEREC 1: E-drive. **E.** CEREC 2: cylindrical diamond bur and wheel. **F.** CEREC 3: cylindrical diamond and tapered burs. **G.** In 2006, a "step bur" replaced the cylinder diamond (With permission – SIRONA)

Proceeding from the grinding tests, the concept of grinding inlay bodies externally with a grinding wheel along the mesio-distal axis showed accuracy and reproducibility (Figures 1.4B and 1.4C). In this arrangement, it was possible to turn the ceramic block on the block carrier with a spindle and feed it against the grinding wheel, enabling the ceramic to be ground in a new contour at a different distance from the inlay axis at each feed step (Mörmann, 2006). This solution proved itself in a prototype arrangement in 1983, and was implemented in the same year in the CEREC 1 unit (Figures 1.4B, 1.4C and 1.4D). A CEREC team at Siemens (Munich, Germany), equipped the CEREC 2 with an additional cylinder diamond enabling the form-grinding of partial and full crowns (Figure 1.4E) (Mörmann and Schug, 1997; Mörmann, 2004). A compromise between grinding efficiency, instrument life and surface roughness of the ceramic had to be chosen and so the method of using a wheel and bur was chosen and used until the introduction of the CEREC 3 in 2000.

With the CEREC 3 the wheel was omitted and the two-bur-system was introduced (Figure 1.4F). The "step bur," which was introduced in 2006, reduced the diameter of the top one-third of the cylindrical bur to a small-diameter tip enabling improved form-grinding with reasonable bur life (Figure 1.4G) (Mörmann, 2006). With the CEREC 3 system an acquisition/design unit and the milling unit were separated into two independent units. Three-dimensional software (CEREC 3D) was also introduced in 2003 to make the preparation and design views on the monitor illustrative and more user friendly on both the office and the laboratory systems.

Since the introduction of the CEREC 3 in 2000, the last major upgrade was the 3D software in 2003, since then only slight upgrades have been made. The latest was in 2007 where the milling unit had the most noticeable features upgrade. It is claimed by Sirona that milling speed has increased by 60%, milling by the new MC XL machines can machine blocks up to a maximum size of 85 x 40 x 22 mm which is 100% larger than the previous ones. The diamond burs are now longer and deploy a 20 mm step bur to eliminate the risk of the bur jamming. With an increase in precision, the MC XL can also be equipped with a second set of motors and different diamond burs to cater for other types of ceramic material. This was introduced so that in the case of breakage of the burs during the milling process the machine can continue the milling operation (using the second motor) without any intervention by the user. A screen has been added so that all the operating steps are shown in plain text on the display and the milling chamber changes colour with each step so that the user may know the milling stage without having to approach the unit. Both MC XL milling machines are network-capable and can be accessed directly via LAN or WLAN (54MBps). It is also claimed that the new MC XL machines are only half as noisy as the previous CEREC 3 and inLab models. Most of these changes, although significant, were to a large extent cosmetic: shape, lighting, drawers, display screen and some push buttons to enable direct operation of certain functions were added. However, it is probably the software that makes the most difference, and in recent International Society for Computerized Dentistry (ISCD) forums it has been reported that milling is 3-5 minutes slower on the default milling function. As the upgrade is still recent and many users have not converted to the new machine there is no long-term reporting available yet.

Brandestini produced the first design for the CEREC 1 unit and for the intra-oral camera; he also built the associated computer and video board, as well as the entire CEREC 1 prototype unit (Mörmann, 2006). The CEREC 2 and 3 units, as well as the CEREC inLab and extraoral scanner (inEOS) were all developed by CEREC teams at Siemens and Sirona (Bensheim, Germany) (Table 1.2).

Table 1.2 Developments of CEREC® chairside system.

CEREC CAD/CAM Developments				
YEAR	**HARDWARE**	**SOFTWARE**	**RESTORATIONS**	**DEVELOPER**
1980	Basic concept	2D	1	Mörmann (University of Zurich) and Brandestini (Brandestini Instruments, Zurich)
1985	CEREC 1	2D	First chairside inlay	Mörmann and Brandestini (Brains, Zurich)
1988	CEREC 1	2D	1-3	Mörmann and Brandestini
1994	CEREC 2	2D	1-6	Siemens (Munich, Germany)
2000	CEREC 3 &	2D	1-6 and 3-unit bridge frames†	Sirona (Bensheim, Germany)
2001	CEREC inLab	2D	1-6 and 3- & 4-unit bridge frames† (inLab‡)	Sirona
2003	CEREC 3 & inLab	3D	1-6 and 3- & 4-unit bridge frames† (inLab‡)	Sirona
2005	CEREC 3 & inLab	3D	1-5 and 3-unit bridge frames†	Sirona
2006	CEREC 3 & inLab	3D	1-5 and 3-unit bridge frames	Sirona
2007	CEREC 3 CEREC & inLab MC XL Milling units	3D v3.00	1-5 and 3-unit bridge frames	Sirona

KEY
(1)Inlays, (2) onlays, (3) veneers, (4) partial crowns, (5) full crowns, (6) copings
*Sirona Dental Systems GmbH, Bensheim, Germany.
†Bridge frameworks fabricated in Europe only, on an experimental basis.
‡InLab only: Extended-range ceramic block spindle.

1.2.4 Software

Alain Ferru, a software engineer, designed the first software by using the anatomy of teeth, as well as the build-up of an inlay cavity in three planes: the cavity margins, the occlusion and the proximal contacts (Mörmann, 2006). The design algorithm was derived from the requirements to mark the cavity floor, enter the proximal contact lines, find the proximal and occlusal cavity margins, adapt the floor data and build up the proximal and occlusal surfaces. Using this information the CEREC 1 operating system was created. In order to simplify the process, the system was programmed so that it designed the occlusal surface of the ceramic inlays initially by means of the straight-line connection of opposing cavity margin points (Mörmann, 2006): it was up to the clinician to develop the occlusal anatomy and occlusal contacts manually, using a handpiece.

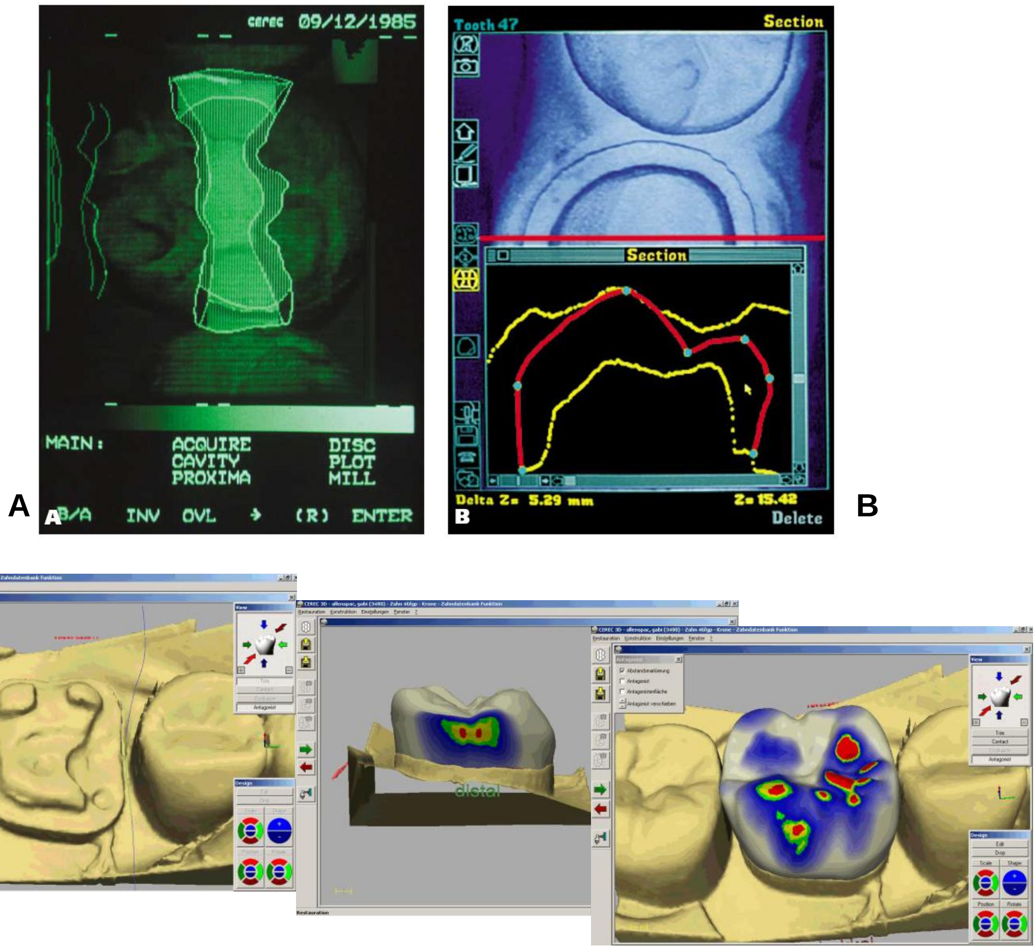


Fig 1.5 The evolution of CEREC software (Sirona Dental Systems GmbH, Bensheim, Germany). **A.** CEREC 1. **B.** CEREC 2. **C.** CEREC 3. (With permission-SIRONA)

The CEREC teams at Siemens and Sirona then continued the development of the associated software (Figure 1.5). The CEREC 2 software enabled the user to create full crowns, and it introduced the design of the occlusion in three modes: extrapolation, correlation and function. However, the design was still displayed two-dimensionally. The three-dimensional virtual display of the preparation, the antagonist and the functional registration became available with the introduction of the three-dimensional version of the software in 2003. The CEREC 3D software is more illustrative than the previous versions and makes the handling of the system comparatively easier. The 2005 and 2006 versions included the automatic adjustment of a selected digital full-crown anatomy to the individual preparation, to the proximal contacts and to the occlusion (a feature called the "antagonist tool"). The automatic "crown settling," "cusp settling" and "virtual grinding" functions provide the dentist with a method of controlling the vertical dimension of the restoration design before milling (Fasbinder, 2006).

In 2007 the software was upgraded to version 3.01 where it remains predominantly similar to its predecessor with the exception of the “Biogeneric design” function for inlays and onlays. This reconstructs the missing tooth’s tissue and adapts automatically to the adjacent teeth and the optical impression of the occlusal surface and tooth morphology registration, hence completing the restoration. The software has also been designed to reduce user input. For example, the margins can now be automatically detected and confirmed, but complete control can also be selected by opting for the Master mode which basically reverts to v2.8 functionality with just a few alterations.

1.2.5 Materials

1.2.5.1 Introduction

There are presently 4 ceramic options commonly used with both CEREC 3 and CEREC inLab laboratory-based systems. These include two types of feldspathic porcelain-based ceramics: Vitablocs Mark II and VITA Mark II Aesthetic Line (Vita Zahnfabrik, Bad Säckingen, Germany) and ProCAD (Ivoclar Vivadent, Schaan, Lichtenstein) blocks. A resin-based composite block called Paradigm MZ100 (3M ESPE, St. Paul, Minn.) is a factory-processed version of their Z100 Restorative (Giordano et al, 2006). Although these are the most common, Table 3 shows that there are many more materials available, many of which are newer introductions for which scientific research evidence is still lacking. In addition, some machines are compatible only with specific materials.

This section will review the performance of some of these systems as well as the claims made by the manufacturers.

1. **Table 1.3** Restorative materials commonly used with dental CAD/CAM systems

Restorative Materials Commonly used for Dental CAD/CAM Systems

ITEM	MATERIAL	MANUFACTURER / VENDOR	CAD/CAM SYSTEM	CLINICAL / LAB
CEREC Blocs	Feldspathic Ceramic	Sirona Dental Sys.	CEREC	Both
Cercon Smart ceramics®	Zirconia based ceramic	DeguDent GmbH	Cercon	Lab
Dicor MGC	Fluormica ceramic (Glass ceramic)	Dentsply Int.	CEREC	Both
inCoris ZI	Zirconia	Sirona Dental Sys.	CEREC	Lab
inCoris AL	Zirconium oxide + Aluminium Oxide	Sirona Dental Sys.	CEREC	Lab
IPS Empress CAD	Leucite-Reinforced Glass Ceramic	Ivoclar Vivadent Inc.	CEREC, Everest,	Both
IPS Empress CAD Multi	Leucite-Reinforced Glass Ceramic	Ivoclar Vivadent Inc.	CEREC, Everest	Both
IPS e.Max ZirCAD	Zirconia	Ivoclar Vivadent Inc.	CEREC	Lab
IPS e.Max CAD	Glass Ceramic	Ivoclar Vivadent Inc.	CEREC, Lava	Both
KaVo Everest Zirconium	Zirconia	KaVo	Everest	Lab
Lava™ Crowns and Bridges	Zirconia	3M ESPE	Lava	Lab
Paradigm™ MZ100	Composite	3M ESPE	CEREC	Both
ProCAD	Leucite-Reinforced Glass Ceramic	Ivoclar Vivadent Inc.	CEREC, Turbodent	Lab
Procera	Zirconium oxide (partially sintered)	Nobel Biocare	Everest	Lab
TDS–Titanium	Titanium	U-Best Dental Technology Inc.	Turbodent	Lab
Vita CAD-Waxx	Acrylate Polymer	Vident	CEREC	Lab
Vita In-Ceram Zirconia	Zirconia	Vident	CEREC, Turbodent	Lab
Vita InCeram 2000 AL	Zirconium oxide + Aluminium Oxide	Vident	CEREC	Lab
Vita InCeram Alumina	Aluminous Porcelain	Vident	CEREC, Turbodent	Lab
Vita InCeram Spinell	Magnesium Oxide	Vident	CEREC	Lab
Vita Mark II Aesthetic	Feldspathic ceramic	Vident	CEREC	Both
Vita YZ InVizion	Yttria Stabilized Zirconia (Y-TZP)	Vident	CEREC, Turbodent	Lab
VITABLOC Aesthetic Line	Feldspathic ceramic	Vident	CEREC	Both
VITABLOC TriLuxe	Feldspathic ceramic	Vident	CEREC	Both

Ceramics, including those used in dentistry, have interesting performance characteristics. In an *in-vitro* study, Zhang and Lawn (2004) found that ceramics lose strength when subjected to repeated loading such as normal occlusal contact, even when highly polished. After more than 1 million cycles (approximately five years of clinical function), both alumina- and zirconia-based veneered structures lost 50% of their strength.

Damage caused by sandblasting, chairside adjustments with a bur or even during the CAD/CAM fabrication process can reduce the restoration's strength and compromise life expectancy. For some materials, researchers have recorded as much as a 30% reduction in strength after sandblasting (Zhang et al, 2004). This information is especially important for posterior restorations, which are subject to the highest stresses in the mouth.

Alternative materials that can provide excellent bond strength without sandblasting were explored by Mörmann and colleagues, (Mörmann et al, 1991). For alumina and zirconia cores, bond strengths equal to those on particle-abraded surfaces were achieved by using metal primers on "as-received" etched surfaces in combination with adhesive cement formulations such as Panavia 21 (Kuraray America, New York City, USA) and RelyX Unicem (3M ESPE, St. Paul, Minn.) (Dias De Souza et al. Effect of metal primers on cement bonds to fully-sintered zirconia (abstract 324); http://iadr.confex.com/iadr/2006Orld/techprogram/abstract_75149.htm - accessed 24/03/2007). It was also noted that the performance of ceramics can be compromised by a mismatch between the coefficients of thermal expansion of core and veneer materials. While this is not an issue for in-office–produced monolithic materials, it can play an important role in crown and bridge survival (Filser et al, 1997). This may also be a major factor in porcelain chipping, which has been reported for zirconia-based layered crowns (Rekow, 2006).

1.2.5.2 Longevity

A systematic review of the clinical performance of intra-coronal CEREC restorations luted with an adhesive composite technique (Martin and Jedynakiewicz, 1999) focused on survival rate and factors causing failure. Twenty-nine clinical reports were initially identified and systematic analysis reduced the review to 15 studies. The mean survival rate was 97.4% over a period of 4.2 years. The predominant reasons for failure were fracture of the ceramic, fracture of the supporting tooth, postoperative hypersensitivity, and wear of the interface lute. The conclusions were that machinable ceramics, as used by the CEREC system provided a high success rate over a period within 5 years; these restorations were colour stable and wear was clinically acceptable. It was observed that wear of the luting composite on the occlusal surfaces led to sub-margination, since the luting gaps are filled with composite and composite is not as wear resistant as ceramic. Hence ceramic fracture, wear at the interface and post-operative hypersensitivity remain problems which require further investigation.

A 2 year evaluation by Bindl and Mörmann (1999) on the survival rate and the clinical quality of CAD/CAM endo-crowns on posterior teeth which had complete loss of coronal hard tissues, showed that the service time of the 19 endo-crowns studied was 14 to 35.5 (mean 26, SD ±6) months. Only one molar endo-crown failed after 28 months because of recurrent caries.

Hickel and Manhart (2001) stated that longevity of dental restorations is dependent upon many different factors that are related to materials, the patient and the dentist; they reviewed the literature of the previous decade on the longevity of restorations in stress-bearing posterior cavities and assessed possible reasons for failure. Having reviewed longitudinal, controlled clinical and retrospective cross-sectional studies only the clinical performance of restorations in permanent teeth was included. Longevity and annual failure rates of amalgam, direct composite restorations, glass ionomers and derivative products, composite and ceramic inlays, and cast gold restorations were determined for Class I and II cavities. Results showed that annual failure rates after 11 years in posterior stress-bearing restorations were 0-7% for amalgam restorations, 0-9% for direct composites, 1.4-14.4% for glass ionomers and derivatives, 0-11.8% for composite inlays, 0-7.5% for ceramic restoration, 0-4.4% for CAD/CAM ceramic restorations and 0% to 5.9% for cast gold inlays and onlays. The principal reasons for failure were secondary caries, fracture, marginal deficiencies, wear, and postoperative sensitivity. The authors stated that a distinction should be made between factors causing early failure and those that are responsible for restoration loss after several years of service, but their analyses did not make this distinction.

Posselt and Kerschbaum (2003) carried out a study of 2328 Cerec inlays which were placed in 794 patients. The clinical performance of the restorations was evaluated and a Kaplan-Meier analysis to asses survival rates revealed a move of 95.5% after 9 years; 35 restorations were judged as failures mostly due to tooth extractions. In a clinical follow-up of the same study using light-microscopic examination of 44 randomly selected restorations, an average composite joint (space between restoration and natural tooth where composite resin was used to fill the space and lute both surfaces) width of 236.3 µm was found. In the same study marginal fit (the fit along the margins of the restoration, how closely and how well the restoration moulded to the prepared tooth) was investigated and 45.1% of the restorations exhibited clinically acceptable margins, and 47.4% of the investigated joint sections (the areas where joints where made between the restoration and natural tooth) showed underfilled margins. Otto and De Nisco (2002) examined the performance of 187 CEREC-1 CAD/CAM restorations made of Vita MK I feldspathic ceramic for inlays and onlays in terms of clinical quality over a functional period of 10 years; they found a failure rate of 8% and a drop of the survival rate to 90.4% after 10 years of clinical service.

Longevity in CAD/CAM restorations is a complex issue as survival is dependent directly and/or indirectly on various factors which include the quality of material itself, its thickness, fit, strength, bonding/cementing material, the user (intra-oral environment, forces, habits etc), and other factors which could cause restoration damage. Hansen (2003) stated the importance of design, preparation of the cavity and the milling of the restoration in determining longevity of a restoration. In order to better comprehend the basis and reasons for longevity, one must consider and interlink the topics described in this paper and not just consider the survivability solely as longevity of a restoration.

1.2.5.3 Strength

It is difficult to produce exceptional strength through traditional layering means. CAD/CAM materials are different in that they are industrially manufactured under controlled conditions and are pre-sintered. This ensures that the ceramic blocks have consistent particle size, porosity, and strength throughout. This inherent strength has been the subject of a number of investigations.

Chen et al (1999) conducted an *in-vitro* study to determine the fracture strength of Vita Mark II, ProCAD and IPS Empress. Forty crowns of each material were manufactured with either a polished or an oven-glazed surface finish. Results showed that ProCAD crowns fractured at a significantly higher load level than Vita Mark II and the fracture strength of Empress crowns was higher than those of Vita Mark II crowns, meaning the difference between Vita Mk II-IPS Empress and ProCad-IPS Empress was not statistically significant, however the difference between Vita Mk II-ProCad was significant. They concluded that oven-glazing the ProCAD crowns resulted in significantly higher strength and higher resistance to cyclic loading than surface polishing.

In a study to test the hypothesis that industrially manufactured ceramic materials, such as Vita Mark II and Zirconia-TZP have a smaller range of fracture strength variation, and therefore greater structural reliability than laboratory-processed dental ceramics, Tinschert et al (2000) used a four-point bend test to determine the flexure strength of 30 bar specimens per material. Their results showed significant statistical differences and concluded that the industrially prepared ceramics were more structurally reliable materials, but cautioned that CAD-CAM procedures may induce surface and subsurface flaws which may affect their strength.

Bremer and Geurtsen (2001) determined the fracture resistance of teeth following treatment with various types of adhesive restorations in caries-free, extracted human molars. The materials used were; CEREC inlays, IPS Empress ceramic inlays, Arabesk (Voco, Germany) and Charisma-F (Heraeus Kulzer, Wehrheim, Germany) resin-based composite (RBC). The control group comprised 10 sound, non-restored molars. All 50 teeth were loaded occlusally until fracture using a tensile testing machine. The results showed that there was no significant difference between the mean values of the sound teeth (2,102 N) and the teeth with the CEREC ceramic inlays (2,139 N).

The cerec.net (http://www.cerec.net/forums/index.php; http://www.cerec.net – accessed 17/04/2009) - a non peer-reviewed free discussion board for users and information seekers on the CEREC system - advises that as strength is dependent on the type of material used; the choice will therefore be dependent on the clinician on which material to use. In addition to this, anecdotal claims state that during glazing at 1500 ℃ for 5 minutes the melting surface ceramic enters the micro-cracks which may have been produced during milling of the restoration, thus fusing and closing up the cracks and therefore increasing the strength. As there are various conflicting articles and studies on strength values of the different brands of CAD/CAM materials, Table 1.4 shows the flexural strength and fracture toughness ranges of some of these materials

Table 1.4 Strength values of different materials commonly used in restorative CAD/CAM restorations

Strength values of Materials used with Restorative CAD/CAM				
MATERIAL	COMPOSITION	FLEXURAL STRENGTH (MPa)	FRACTURE TOUGHNESS (MPa.m^{-2})	STUDY
Alumina	Alumina/Glass Infiltrate	236-600	3.1-4.61	Seghi and Sorensen 1995, Giordano et al 1995, Wagner and Chu 1996, Guazzato et al 2002, Chong et al 2002
	Spinell/Glass Infiltrate	325-410	2.4	Seghi et al 1995, Ironside and Swain 1998
Glass Ceramics	Zirconia: Y-TZP	900-1200	9-10	Christel et al 1989, Filser et al 2001, Suttor et al 2001
	Zirconia	620-985	4.0-9.0	Besimo et al 2001, Guazzato et al 2002, Piwowarczyk et al 2005
	Pre-made/HIP	140-220	2.0	Ironside and Swain1998
	Lab-cast	115-125	1.9	Ironside and Swain1998
Porcelains	Leucite	122-180	1.2	Seghi et al 1995
	Feldspathic	67-205	1.1-1.9	Drummond et al 2000
Tooth Structure	Enamel	65-75	2.33	Ironside and Swain 1998
	Dentine	16-20	2.5	Ironside and Swain 1998

1.2.5.4 Wear

CAD/CAM restorations claim to have among their qualities enamel-like wear characteristics. It is known that enamel wears at different rates against different restorative materials. There are very few studies on wear involving CAD/CAM manufactured materials and natural teeth, and few studies which can closely relate to clinical conditions, as almost all studies are carried out *in-vitro* on extracted teeth. In addition, other factors such as saliva constituents, the changing intra-oral environment, varied occlusal forces, etc., are presently impossible to imitate accurately. Nevertheless *in-vitro* tests do give an indication of *in-vivo* performance especially when attempts are made to replicate the natural oral environment (Söderlhom, 1991).

Krejci, Lutz and Reimer (1994) compared Dicor MGC, Vita Mk I porcelain, Vita Mk II V7R porcelain, and Vita Mk II Vita V7K porcelains. All ceramic materials except Dicor MGC wore less than previously measured controls, such as natural human enamel and amalgam. The wear of opposing enamel cusps was high with Dicor MGC and with Vita Mk I, only Vita Mk II V7R showed a total wear comparable to that of enamel, because of its moderate abrasivity against opposing enamel. The wear of the two luting composite resins (Dicor MGC, Vita Mk I porcelain) was measured at the end of the test. Both luting composite resins wore more than the ceramic inlays and surrounding enamel, leaving a shallow ditch around the restorations.

Al-Hiyasat et al (1998) carried out an *in-vitro* study comparing the wear of enamel against aluminous porcelain, bonded porcelain, low fusing hydrothermal ceramic, feldspathic machinable ceramic and cast gold. Fifty pairs of tooth-material specimens were tested in a dental wear machine, under a standard load (40 N), rate (80 cycles min-1) and for 25,000 cycles in distilled water. The amount of wear was determined by measuring the height loss of the tooth, and the depth of wear track of the restorative materials. The hydrothermal and machinable ceramics were significantly less abrasive and more resistant to wear than the conventional aluminous and bonded porcelains. Gold was the least abrasive material and most resistant to wear, although the difference in wear between the machinable ceramic and gold was not statistically significant.

Kunzelmann et al (2001) studied materials and antagonist wear of laboratory-processed IPS Empress ceramic, Vita Mark II, and the composite mill block material MZ100, by testing in an artificial wear simulator with human enamel as the antagonistic material. The material samples underwent 50 000 test cycles (1 cycle per second, 50 N) in distilled water. The wear of the material samples and of the opposing enamel was documented after 30 000 and 50 000 cycles, digitized, and evaluated with a 3D evaluation system. The material wear of MZ100 differed significantly from Vita Mark II only in terms of volume loss. Regarding height loss, MZ100 exhibited a significantly higher wear than all ceramic materials and a significantly smaller amount of enamel wear when compared with Empress and Vita Mark II. Despite the highest material wear, MZ100 had the lowest material wear rate, the lowest enamel wear rate, and the lowest total wear rate. The laboratory-processed IPS Empress material had a higher material wear rate than the CAD/CAM materials. MZ100 showed to be the least resistant to general wear volume, meaning that it may have more stable wear characteristics as it had the lowest wear rate, in contrast Vita Mark II and Empress seemed to wear rapidly then plateau i.e. they wore rapidly then wore at a gradual rate.

They found no statistically significant differences between the ceramic materials tested either in the amount of material or in the amount of antagonist wear. The study however did not give the exact reason for the plateau. It could be speculated that the enamel began to wear more rapidly as it thinned or the continuous friction hardened the material thus creating the plateau. *Wear Rate* is the amount of material lost in a given period of time; *Total Wear* is the total amount of material lost over from beginning to end. MZ100 wore at a constant gradual rate, however; in total it wore more rapidly than other materials. In addition; a material with a higher wear rate should have higher total wear; a material with least resistance should also have a general higher total wear, nevertheless the wear rate may not be necessarily higher as the particles could be more stable.

The quality of these materials and their ability to mimic the wear characteristics of natural teeth have improved dramatically and continue to improve. Further studies are still required to identify the wear characteristics of the different restorative materials, as well as enamel and dentine *in-vivo,* in order to obtain a material similar to natural tooth wear.

1.2.6 Fit

Micro-leakage is defined as the clinically undetectable passage of fluids, bacteria, molecules or ions between a cavity wall and the restorative material (Kidd 1976) which in turn leads to failure of the restoration. Investigations had already shown that composite luting joints (the gap between the natural tooth and restoration) up to 500µm wide were impervious to micro-leakage (Bindl and Mörmann, 1999; Posselt and Kerschbaum, 2003). However, clinically acceptable gaps for ceramic restorations are considered by some to be 50-300µm (Audenino et al, 1999). In composites the seal degrades over time (Lundin and Noren, 1991) and this is dependent on factors such as nanoleakage (the leakage within the dentine margins of restorations), thermal contraction, polymerisation shrinkage, mechanical stress, absorption of fluids, and dimensional changes of the restorative material used, the luting agent and/or the natural tooth. It is therefore still relatively difficult to provide exact time-microleakage for luting joints. Theoretically, 50-100µm fitting accuracy *in-vitro* appeared to be achievable and later confirmed (Mörmann and Schug, 1997).

An *in-vitro* study by light and scanning electron microscopic analysis on the consistency of marginal fit of copy-milled all-ceramic crowns used Celay In-Ceram (Groten, Girthofer and Probster, 1997), and showed that the manufacturing steps after copy milling had no obvious influence on the external marginal gap width. In-Ceram, IPS Empress, and Procera crowns were compared in another *in-vitro* study of marginal fit (Sulaiman et al, 1997). The results showed that all crown systems were significantly different from each other. In-Ceram exhibited the greatest marginal discrepancy (16 µm), followed by Procera (83 µm), and IPS Empress (63 µm). The facial and lingual margins exhibited significantly larger marginal discrepancies than the mesial and distal margins. There were, however, no significant differences between the various stages of the crown fabrication (core fabrication, porcelain veneering, and glazing). The authors stated that the explanation for the lack of agreement on fit studies may be variations in the methods used by various investigators studying marginal accuracy. They suggested that the cause could be the use of different measuring instruments, sample size and the number of measurement areas per specimen may also have contributed to these variations.

Estafan et al (2003) evaluated fit at the gingival margin of inlay restorations milled by the CEREC 2 and CEREC 3. Results showed than although CEREC 3 milled inlays were more accurate than the CEREC 2, both were within the ADA specifications of 50 µm (initially it was difficult to obtain <100 µm, but with developments in technology and precision it became possible to obtain <50 µm fit, therefore ADA made their specifications at 50 µm which was considered enough to ensure decreased microleakage). Nakamura et al (2003) examined the effects of the occlusal convergence angle of abutments and the computer's luting space setting on the marginal and internal fit of CEREC 3 all-ceramic crowns. The luting space is due to powdering and milling inaccuracies which could occur if the setting is not compensated for. If it is over compensated, this could be exacerbated when the restoration is subjected to angular forces leading to eventual distortion of the restorations margin. The results showed that when the luting space was set to 30 µm, the marginal gaps ranged from 53-67 µm and were not affected by the occlusal convergence angle of the abutment. The internal gaps were within a range of 116-162 µm and tended to decrease as the occlusal convergence angle of the abutment decreased. The conclusions were therefore that crowns with clinically acceptable fit could be fabricated on the CEREC 3 system, regardless of the occlusal convergence angle of the abutment.

The different effects of the hardware and software on the quality of CAD/CAM all-ceramic production was investigated by Bindl and Mörmann (2003) in a cross sectional study of 818 partial crowns placed adhesively in 496 patients between 1993 and 1997 using CEREC 1 and CEREC 2 units (groups 1 and 2) as well as CEREC 2 with wall-spacing software (the upgraded software) (group 3). From each group, 25 randomly selected partial crowns were evaluated; of these, 12 were randomly selected in each group and the rest were not used (the article does not account for them, we therefore do not know what was done with the excluded restorations). Replicas, including gingivoproximal margins of the restorations, were taken using a putty wash impression technique and custom metal trays and examined in a scanning electron microscope for marginal interfacial width and for continuous margin adaptation. The mean interfacial width of group 1 (308 +/- 95 µm) was significantly larger than that of groups

2 (243 +/- 48 µm) and 3 (207 +/- 63 µm). Continuous margin adaptation at the tooth-luting composite and luting composite-restoration interfaces showed only minor differences in groups 1 (94.5 +/- 8% and 95.5 +/- 2%), 2 (98.1 +/- 1% and 97.5 +/- 1.4%) and 3 (96.8 +/- 3% and 96.8 +/- 2%); the conclusion was that the luting composite when appropriately prepared to tooth and restoration surfaces bonded well and therefore the technique is important in achieving a clinically acceptable lute interface. Pooled clinical rating was 97% for all groups which indicated a generally acceptable restoration quality; improvements in software and hardware were considered to have led to the increased precision in CEREC 2.

Balkaya, Cinar and Pamuk (2005) conducted a study to determine if fit was affected by porcelain and glaze firing cycles for 3 types of all-ceramic crowns: conventional In-Ceram, copy-milled In-Ceram, and copy-milled feldspathic crowns. The results indicated that the porcelain firing cycle from the addition of porcelain to the copings caused a significant change in marginal fit, except for the fit in the horizontal plane of the conventional In-Ceram crowns. However, no further significant changes occurred in any of the crowns after the glaze firing cycle. Significantly, the conventional and copy-milled In-Ceram crowns demonstrated medial deformations at the labial and palatal surfaces after the porcelain firing cycle that might result in occlusal displacement of the crown. The glaze firing cycle is a short high temperature firing cycle which only melts the surface, whereas the porcelain firing cycle is longer and also melts the core surface.

Some theories and research on marginal gaps and leakage can either be accepted or discarded due to the various factors and contradictions in dental adhesive research (Söderlhom, 1991), micro-leakage and nano-leakage appear to be presently impossible to overcome; therefore the theory that 500 µm is resistant to micro-leakage although possible in the short term, will eventually fail. Moreover there are too many variables, factors, theories, suggestions and contradictions to establish a single conclusion on micro-leakage/nano-leakage prevention and its ideal marginal gap, luting distance and material. From the statements above it is clear that fit and micro-leakage are directly related, a preparation with poor fit results in gaps between the material itself and the tooth thus an obvious increase in the probability of micro-leakage and eventual failure of the restoration.

1.2.7 Luting

1.2.7.1 Luting agents

There are basically 6 types of luting materials for ceramic restorations: Zinc phosphates; Poly-carboxylate; Glass ionomer; Resin reinforced ionomer; Composite, and Adhesive resin; however, adhesive resins have become a favourite due to their characteristics, and convenience. There are presently (at the time of writing) 71 brands of adhesive resin materials and this number is increasing.

Rosenstiel, Land and Crispin (1998) reviewed the factors that influence success when considering a luting agent: (1) biocompatibility, (2) caries/plaque inhibition, (3) microleakage, (4) strength and other mechanical properties, (5) solubility, (6) water sorption, (7) adhesion, (8) setting stresses, (9) wear resistance, (10) colour stability, (11) radiopacity, (12) film thickness or viscosity and (13) working and setting times. In their review, they included guidelines on manipulation which included: (1) temporary cement removal, (2) smear layer removal, (3) powder/liquid ratio, (4) mixing temperature and speed, (5) seating force and vibration, and (6) moisture control which influence the precision and quality of ultimate placement of the restoration. The authors unfortunately did not provide any guidelines for ceramic restorations and luting agents.

The system for luting a ceramic restoration was the “three step/conventional system” of etching, priming and bonding. It has been shown that this system is susceptible to contamination of the bonding surfaces, the “two step/self etch/single bottle system” eliminated one step (etch-prime); nonetheless the contamination problem still exists. The most recent introduction is the “all-in-one system” which incorporates all the steps (etch, prime and bond) in one single step; however, there are no long-term clinical data to demonstrate effectiveness. Although a considerable amount of work is being carried out on these luting materials, early studies are showing variability (Tyas and Burrow, 2004).

Additives such as desensitisers, nanofillers or antibacterial monomers, may also contribute to enhance the performance of self-etching enamel–dentin adhesives and their long term success (Moszner, Salz and Zimmermann 2005). Martin and Jedynakiewicz (1999) conducted a systematic review of clinical trials seeking to identify the clinical performance of intra-coronal CEREC restorations luted with an adhesive composite technique; they observed that although machinable ceramics as used by the CEREC system provide a useful restoration with a high success rate; ceramic fracture, wear at the interface and post-operative hypersensitivity remain problems which require further investigation.

1.2.7.2 Post-operative sensitivity

Adhesive cementation and bonding involves several clinical choices involving the etching process, bonding agent, and luting agent. Selection of the adhesive luting agent is often based on operator preference but should be on a comparison of physical properties and evidence based clinical studies. Several studies (O'Neal, Miracle and Leinfelder, 1993; Kawai, Isenberg and Leinfelder, 1993; Shinkai et al, 1995) indicate that micro-filled resin luting agents offer the best resistance to marginal wear. Fasbinder (2005) stated that Total Etch concept with a self-priming adhesive such as Excite (Ivoclar Vivadent), Single Bond (3M ESPE), or Prime and Bond NT (Dentsply Caulk) may be an option for clinically acceptable bonding and decreased sensitivity. However, one study (Zohairy et al, 2002) has demonstrated that the use of a bonding agent has a negative influence on bond strength longevity, possibly due to hydrolytic instability of the bonding agent and can result in post-operative sensitivity. Although only anecdotal user reports, data from 8 different CRA reports conducted over 11 years were compiled and showed that approximately 45 restorations for each of 31 material brands had been placed by about 20 different dentists, CEREC inlay/onlay restorations machined from Vita Mark II feldspathic porcelain reported to show no post-operative sensitivity (CRA Newsletter. Post-operative sensitivity related to type of restoration and material. CRA 1999; 23: 2). In reality to the above findings, there are various factors which could increase or decrease post-operative sensitivity. Fasbinder (Adhesive Cementation: The Overlooked Key to Success. ViDent Bloc Talk 2007; 1: 7-8) reported that adhesive cementation determines post-operative sensitivity and may very well be the key to ensuring longevity and success of these restorations.

Attar, Tam and McComb (2003) found that post-cementation sensitivity associated with the use of resin cements has been attributed to microleakage rather than to cement acidity and that the sensitivity was more related to contraction of the cements. However; Unemori et al (2001) suggested that with self etching and bonding that post-operative sensitivity was little related to the materials. Perdigão, Geraldeli and Hodges (2003) in their study comparing self etch and total-etch concluded that post-operative sensitivity was different with different bonding materials. In all studies it was evident that technique and micro leakage were major factors in sensitivity, and almost all concluded that further studies are still required to determine what the ultimate cause of post-cementation sensitivity is and what should be done to prevent it.

1.2.8 Aesthetics

Aesthetic satisfaction is independent and subjective and therefore difficult to measure. Reich and Hornberger (2002) examined the effect of multishaded blocks on the aesthetic appearance of all-ceramic CEREC crowns and compared these with single-shaded and stained restorations. Ten subjects were included in this study and for each subject 6 different crowns were milled using the CEREC machine from CEREC Vitablocs Mark II in classic colours; Vitablocs Mark II in 3D-Master colours; Vitablocs Mark II in either classic or 3D-Master colours, with additional staining; Megadenta Bloxx multishaded; Mark II experimental multilayer; and an experimental multilayer leucite ceramic. Three independent examiners assessed the aesthetic appearance of the crowns, but concluded that, within the limitations of the study, the results provided no evidence that multicoloured machinable ceramics improve the aesthetics of all-ceramic crowns.

One study by Herrguth, Wichmann and Reich (2005) examined whether crowns fabricated from machinable blocks could compete with the aesthetics of restorations obtained by an individual layering technique. Two crowns were provided for each of 14 patients: one crown was made with the Cerogold system, the other produced in a CEREC machine and was stained. Three independent examiners assessed the aesthetic appearance and the mean values were analysed. The results showed that regardless of the fabrication method the crowns were aesthetically acceptable in all 14 patients; the mean values for the layering technique and for the machined restorations did not differ significantly.

In both of the above studies it was found that layering and non-layering makes little to no significant difference in aesthetics. Forums from CAD/CAM users have stated that one of the main concerns with CAD/CAM restorations is aesthetics. Some manufacturers and ISCD articles have stated that CAD/CAM technology, techniques and the materials used have been continuously improved over the past years as the current ceramics mimic natural translucency, brightness and shades providing life-like aesthetics (http://www.renishaw.info/en/621.aspx) – accessed 15/05/2007). They claim wear of ≤ 3 µm/year, low water absorption (resists staining) of 9-12 mg/mm^3; acceptable colour stability and favourable aesthetics (http://www.sirona.com/ecomaXL/index.php?site=SIRONA_COM_cerec_klinische_studien_aesthetik – accessed 15/05/2007). In addition they state that excellent polishing and clear glazing (without residual monomers) results in resistance to plaque retention.

In general CAD/CAM aesthetics have been well received. Fig 1.6 show the results of a CAD/CAM produced restoration by Fasbinder (2006), note the colour and blending with the natural tooth. However, to achieve acceptable results the colour and bonding must be carefully matched and the restoration placed carefully.

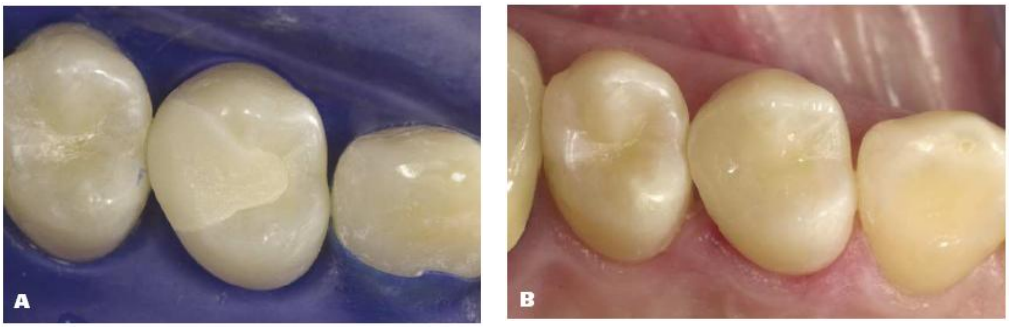


Fig 1.6 **A.** CAD/CAM produced inlay try-in (ProCAD-Ivoclair Vivadent) **B.** Inlay cemented and polished. Fasbinder 2006 (With permission)

1.2.9 Convenience *(Time)*

The only report found was that of Phillips (2005) who conducted a study at the University of Southern California School of Dentistry where students were given a brief resource session on the dynamics and application of the Correlation mode of the Cerec 3 and were then instructed to complete and bond a restoration on an extracted tooth within predetermined time constraints. The time-frame goals were: preparation and optical impression, 1 hour; design and mill a CEREC-fabricated restoration, 45 minutes; adjust and polish, 15 minutes; stain and glaze, 30 minutes; bond and debride, 30 minutes. Typically, the time a dental student will spend on a given clinical task is equal to the time allotted for that task, but all students did finish within the time frame. In clinical conditions the actual completion time is greatly reduced and no more than 3 hours are usually spent on a single restoration. Unfortunately there are no scientific studies on this aspect, and so it is not known what the average time to completion for any CAD/CAM procedure actually is.

1.2.10 Benefits of Dental CAD/CAM

Manufacturers, dentists and researchers have claimed the following advantages to CAD/CAM in restorative dentistry:

- Reduced production time for copings, frameworks and final restorations and thus increased productivity.
- Reproducible units, measurable results and consistency.
- Reduced learning time and curve for design and use of the machines, which are generally simple and user friendly.
- Freedom for creativity and flexibility in design and final production as changes can be made at any stage before milling and can allow for subtle correction after milling.
- Multiple works can be done simultaneously in one machine, a database of designed and manufactured restorations can also be readily available.
- Future production methods and upgrades can be made available rapidly.
- Waste is avoided as errors can be viewed and immediately corrected before milling.
- Ease of transfer of knowledge and sharing of work between clinicians, patients and laboratories on a global scale.
- Many restorative options are available: inlays, onlays, veneers, partial crowns, full crowns and multi-unit bridges.
- Many material options such as composite, ceramic, zirconia, alumina and titanium can all be used depending on the system being used and preference of user.
- Support and maintenance by the manufacturer/vendor.
- Use of materials which are not radiopaque (except for titanium).

The following advantages have been stated specifically for the CEREC system:

- Different material options such as composite, ceramic and alumina can all be used depending on user preference.
- Milling time is between 8-20mins depending on size, hardness of material and method being used. Using the Fast-mill function can take less than 10 minutes for mill completion. Milling accuracy is now <30µm for fit and marginal integrity.
- Blending of block shades with tooth shade has improved aesthetics.
- Ceramic blocks are completely biocompatible and non-cytotoxic thus being extremely safe.
- Many restorative options are available: inlays, onlays, veneers, partial crowns, full crowns.
- The restorations can be repaired intraorally, if necessary with similar materials, have excellent bondability, and reduced wear to antagonistic natural enamel.
- Relative long life-time of CAD/CAM machines ensures clinical reliability.
- Obtaining the data of the prepared teeth/tooth only takes a few seconds.

1.3. CHALLENGES FOR CAD/CAM IN DENTISTRY

The following is a reflection on the CEREC 3D Chairside system, so most of the statements below reflect this system unless otherwise stated.

1.3.1 Cost

Costs of purchase, upgrade, maintenance, fees and learning still remain extremely high for all CAD/CAM systems. The estimated figure for the number of dentists using CAD/CAM worldwide is still not available, but it would be safe to assume that only those who can afford the purchase on the basis that their patients can afford the fees would imply that the majority of the world’s population would not benefit from this form of dentistry.

1.3.2 Data Capture/Input Device

- Powdering which is necessary for accurate picture visibility for the CEREC Chairside system is a great inconvenience and can lead to distortion and incorrect data capture if too little or too much powder is sprayed; flaking may also occur which leads to inaccurate data capture. In addition to this, the layer of powder creates a “gap” which should be compensated for. Although laser camera could do away with this problem, there have been unofficial reports that although smaller and more convenient to handle, the laser cameras remain unreliable, but there are no independent data to support either positive or negative claims.
- The CEREC Chairside camera size remains large and is difficult to capture posterior teeth especially on individuals with limited mouth opening. Slight changes in angulation in

each plane (pitch, roll, yaw) do take place as human hands are not static and physiological tremors do occur; this may lead to distortion and failed images. No single reliable stabilising device exists at present which would reduce or eliminate data capture stability problems.

- The input device does not have its own light source, which can lead to inaccurate data capture on darker, deeper and hard to reach areas. A light source might obviate the need for powdering as the powder is used to reflect and intensify the light entering the unit.
- Although the Inlab systems are comparatively more accurate in comparison to the Chairside system in obtaining the prepared tooth's data, the whole process (for the Inlab systems) to the end product remains tedious (impression taking, making casts and models etc) and increases cost, time, and the possibility of errors especially for multi-unit bridges.

1.3.3 Milling/Output

New reports by the cerec.net discussion board have revealed that the new CEREC 3D v3.0 software takes longer for calibration and milling. This is definitely a draw back as what is required is time reduction with better results. However, milling time can be reduced by using the Fast Mill function but the milled surface is rougher, and there have been reports that the general milling time has in fact increased by 5-8 minutes on default settings. Micro-cracks also do occur during milling which can lead to devastating fracture of restorations. Although the Chairside unit can capture whole arches, it cannot mill multi-unit bridges, so for bridges, conventional methods are still a better option.

1.3.4 Finalising

A controversy remains over the finishing procedures on glazing or polishing, as there is no conclusive evidence for using the one over the other. Giordano (Milling and Finishing Effects On Machinable Blocks. e-Newsletter ViDent Bloc Talk 2007; 1: 3-4) states that glazing and staining alone takes long for completion and if not done well can damage the milled product; but not glazing leaves behind micro-cracks made during milling; polishing could also exacerbate these cracks leading to eventual fracture. Fasbinder (Adhesive Cementation: The Overlooked Key to Success. e-Newsletter ViDent Bloc Talk 2007; 1: 7-8) also raised the question of cementing or bonding. Although there have been some suggestions little to no reliable research has been carried out. As the blocks are not all made of the same material (Zirconia, Porcelain, Composite etc) the materials are structurally different and should be handled differently, but there is still no consensus on this and it has been unofficially observed that most private users do not know the exact material of the blocks they use, nor how different procedures may affect the ultimate results.

Monopoly of the market may also have limited creativity, development and affordability. It would appear that patent issues and manufacturing costs have prevented the development of more Chairside systems.

1.4. CONCLUSIONS

Since the first inception of CAD/CAM in dentistry and over the last 20 years the CEREC Chairside system (the only chairside system available at present) has gone through multitudes of changes in hardware, software, materials and general knowledge of clinical aspects.

Restorative work has since been done with less effort, quickly and in certain cases in a single visit in the dental office.

Unfortunately much of the supporting data are anecdotal and contradictory. There is still a great deal of research required in this field in all its aspects. The extremely large amount of non-peer reviewed information available is easily accessible, but the scientific peer reviewed studies are difficult to obtain as they are either in libraries or in pay subscription journals. This means that anyone can gain easy access to questionable information while the valid information remains open to a few. The fact that the dental industry and especially high end technology such as CAD/CAM is extremely costly may also be a contributor to the lack of quality and quantity of reliable research as comparatively few institutions have the staff, skills, support, equipment, time and financial backing to conduct extensive studies to achieve competitive results.

There are a number of areas which have been observed requiring more studies and evidence-based information:

- There is lack of concise information on the history and developments of Restorative CAD/CAM.
- There is no standard for determining, measuring, and defining fit for restorations. *In-vivo* measurements still remain a challenge.
- Strength (fracture & flexural): although the most researched there are too many non-scientific articles and several of the scientific results are quite contradictory.

- Wear: An area with significant studies has also produced notable results on the amount and rate of wear for different materials inclusive of enamel and dentine, however the challenges are still in imitating the exact intra-oral environment, forces and wear pattern in relation to natural teeth and different restorative materials; this unfortunately is presently still impossible to do as the factors determining wear in general and predicting its outcome are wide and varied.
- Aesthetics: As an extremely subjective factor, it is challenging to carry out and measure, and as a result, the majority of information on this topic is non-scientific. The few scientific exceptions lead to more questions than answers, research should be carried out at a global level to obtain an estimate figure on what is aesthetically pleasing in relation to teeth shape, colour and smile. Measuring aesthetics and colour remain problematic, as there are still varied opinions on the best measuring system and to date a standard has not been developed. Until then, all the present methods pose numerous questions about their validity.
- Post-operative sensitivity: as with aesthetics this is difficult to measure objectively, and there are many compounding variables: timing, relationship with materials used and bonding/cementation, degree of sensitivity, age, gender, disposition, type of pain and so on.
- Over the past few years there have been many new materials and brands introduced, and almost all the information provided (especially for the newer materials and brands) is from manufacturers. This information must be considered biased until independent scientific studies provide evidence in corroboration. It might be useful to establish an independent site where manufacturers could put up their new materials and information,

and request institutions to investigate and update the findings. The drawback again is funding, where the largest contributors could be the manufacturers; hence again biased results may be published.

As most of the materials used for Inlab are similar to those used for Chairside the same applies however, the chairside system is unique and requires additional studies such as:

- Powdering: hopefully do away with this method by using a laser camera or having a self contained light source on the scanning device.
- Camera size: the shaft and body are presently too large and relatively heavy.
- Picture: a stabilizing device could help to avoid the problems with Angulation (pitch, roll and yaw) and physiological tremors.

We can still consider computerized Dentistry in its infancy and there is a lot of room for improvement and development. CAD/CAM has indeed facilitated the clinician’s work and brought merit to dentistry in that high quality restorations of varied materials are readily available in a single short visit using simple techniques. At the present pace of development we can be assured that science and technology will surpass what we may have only thought impossible a few years ago, as CAD/CAM has done in the past we can look forward to having a clearer view in the way we work today and in the future.

CHAPTER 2. AIMS AND OBJECTIVES

The review of the literature and history of CAD/CAM in general, and the CEREC Chairside System in particular, has revealed that there are areas of potential errors as in powdering, the preparation, and in positioning the camera. The picture seems to be one of the major problems especially when capturing complex preparations; the angle axis (roll, pitch and yaw) and height have always been a problem particularly when designing multiple restorations and/or multi-unit bridges.

As individuals, the CEREC users are subjected to physiological tremors and other external effects such as patient movement, which directly or indirectly influence the positioning of the camera thus the quality of the captured image. Only one study has measured the camera tilt error generated by clinicians for Class I and II preparations. It was found to be 1.98 ±1.17 degrees on average with some being more than 5 degrees (Parsell et al, 2000). This tilt error will affect the accuracy and fit of milled restorations. It takes time to appropriately positioning the camera head particularly when trying to capture more than one restoration or for multi-unit bridges. The problem of active triangulation in the CEREC system as a result of tilt increases the virtual occlusal-cervical height of the prepared tooth. Depth data from the subsequent shadow are therefore unreliable, so that the internal fit of CEREC crowns may be poor. Distal shadows also influence the thickness of the cement spaces after milling, particularly at the distal axial walls (Mou et al, 2002). Clinicians and researchers have called for improvements in optical textures, smaller errors in interior orientation parameters attributed to instability, and smaller errors in the relative orientation and the camera. Ideally, the use of a fixed camera lens system is expected to reduce these errors (Grenness, Osborn and Tyas, 2005).

There are presently no studies even by the manufacturers determining the errors that may occur with changes in axis angle of the camera and how this may affect the subsequent image and ultimately therefore the fit of the restoration. It should be possible to verify which axis change (roll, pitch or yaw) is most susceptible to angular changes and the extent to which these changes are significant to the final restorative result before designing and milling.

The clarity and speed of picture and data capture in the CEREC chairside system is primarily dependent on the stability of the camera head itself. There are presently 2 systems which act as supports but not as stabilizing devices, therefore they both still require a steady hand and no external or internal movements; in addition they do not guarantee roll, pitch or yaw for each different picture taken.

The two objectives of this study are therefore to:

1) Verify and determine the visual and angle threshold errors to changes in pitch, roll and yaw of the intraoral camera and their effects before milling.
2) Devise a system or instrument that can quickly and efficiently be used to stabilise the CEREC chairside camera head and in turn be used in combination with other systems so that data capture is effortless, convenient, unaffected by movement, accurate and suitable for a variety of restoration preparations.

CHAPTER 3. METHOD & MATERIALS

3.1 ANGLE ERROR THRESHOLDS

The CEREC chairside camera uses infrared light by transmitting and receiving it so that light differences create a picture (Kubard, 2000), and active triangulation is used to capture surface texture (Mou et al, 2002). The camera is large and difficult to manipulate and can be used in planar as well as three-dimensional axes, as shown in figure 3.1.

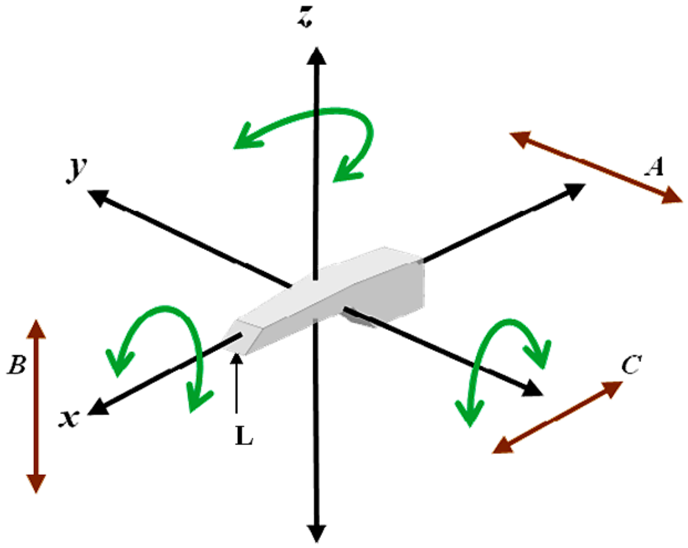


Fig. 3.1 The basic angulations and movements of the camera: ***x*** *= roll,* ***y*** *= pitch and* ***z*** *= yaw.* ***A*** *= body/left-right* ***B*** *= height/up-down* ***C*** *= front-back.* ***L*** *= Camera Lens*

Data was measured for angle error using the x, y, z axes; where x = roll, y = pitch and z = yaw. Threshold error margins were 0°, 1°, 3°, 5°, 10°, 15° and 20° for a full crown preparation on tooth 24 on a prefabricated Aesthetic Base Gold (ABG) Model which eliminated the need for powdering, as powdering would inevitably distort results (difference in thickness, clarity, layering, clumping etc as it is impossible to exactly powder equally each time an angle is modified). All studies were carried out under the same condition of temperature and humidity.

The model was fixed to the upper member of an articulator to which a protractor had been attached (figure 3.2). To measure angulation, the position of the articulator arm was varied and the angle verified using the protractor (figure 3.3). All instruments were fixed to a counter top; the articulator was clamped using a G-clamp. The intraoral camera was attached to a laboratory clamp (figures 3.4 to 3.6), and the camera height was adjusted so that the lens was no more than 1mm from the closest tooth surface at all times and angles. The default set up was the path of insertion angle.

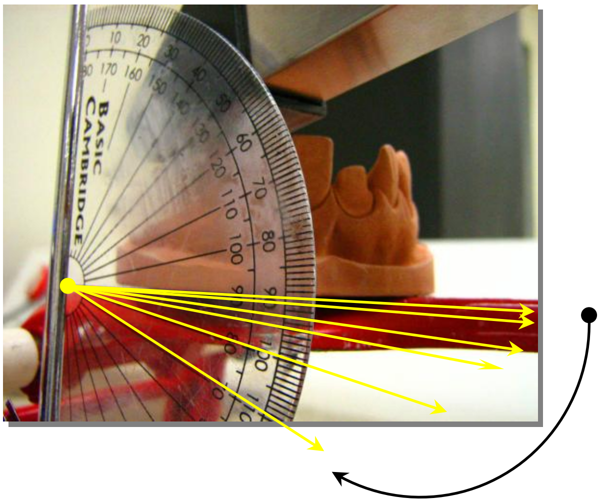


Fig 3.2 Direction of movement of articulator

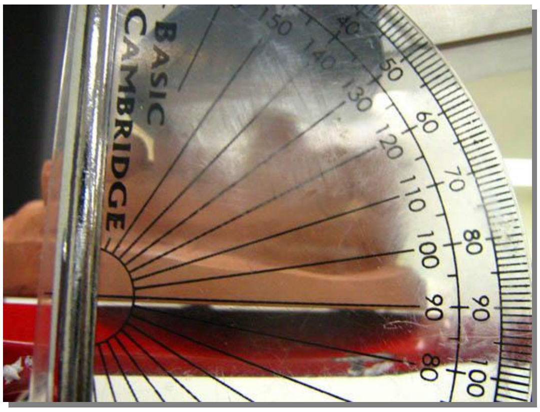


Fig 3.3 Accuracy of placement of model with protractor (note 90 °line-articulator and model)

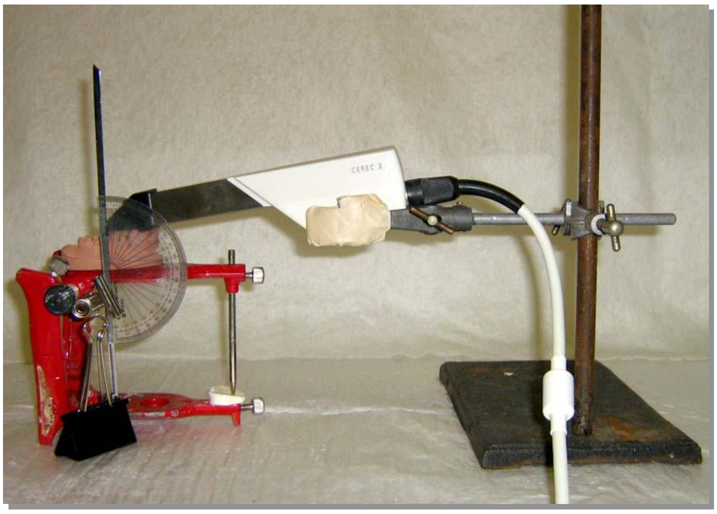


Fig 3.4 Set-up for Pitch

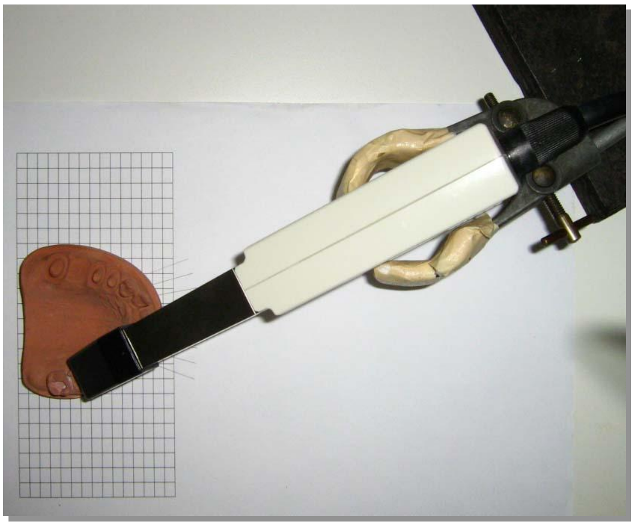


Fig 3.5 Set-up for Yaw

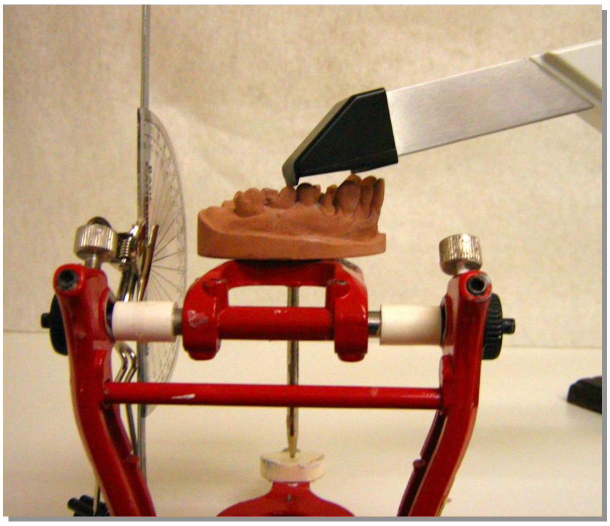


Fig 3.6 Set-up for Roll

Initial successful pilot studies for pitch, roll and yaw were made. Multiple images were taken and only the clearest were selected and used to avoid interlacing (merging) the pictures. The use of a single image would reveal the exact angle errors obtained: multiple pictures create interlacing which the CEREC system automatically corrects by diminishing some errors and angle deviations. This would make it impossible to identify the errors which the system cannot correct; therefore a single image is essential. For each image, angle errors, shadows, margin discrepancies, and surface texture were visually verified, as was the ability to complete a full restoration with minimal adjustments. Before commencement of measurements once data was captured, errors were verified to exclude differences due to angle change.

Pitch

Pitch was measured by moving the articulator downwards (figure 3.3), reproducing in effect, an upward tilt of the camera tail-end (distal). Clinically, a change in camera position whereby the anterior part is lifted upwards does not occur because of the stop on the anterior end of the camera.

Yaw

An angle grid was made and fixed to a flat surface (figures 3.5 and 3.7). The model was moved in a clockwise direction according to the grid angles by aligning pencilled marks on the mid-line of the model anteriorly and posteriorly; the model was moved over a single starting reference point over each angle.

Fig 3.7 The grid and defined angle lines for yaw.

Roll

To measure roll, the model was fixed to the articulator sideways (figures 3.6, 3.8 and 3.9). The upper arm of articulator was adjusted on a downward tilt which would in turn signify a buccal roll movement for the camera.

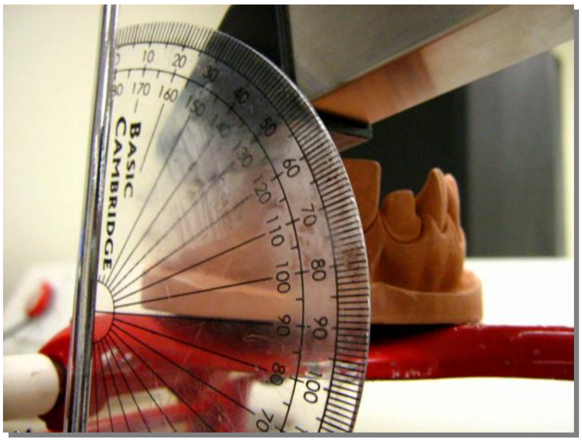


Fig 3.8 Positioning for angle for Roll

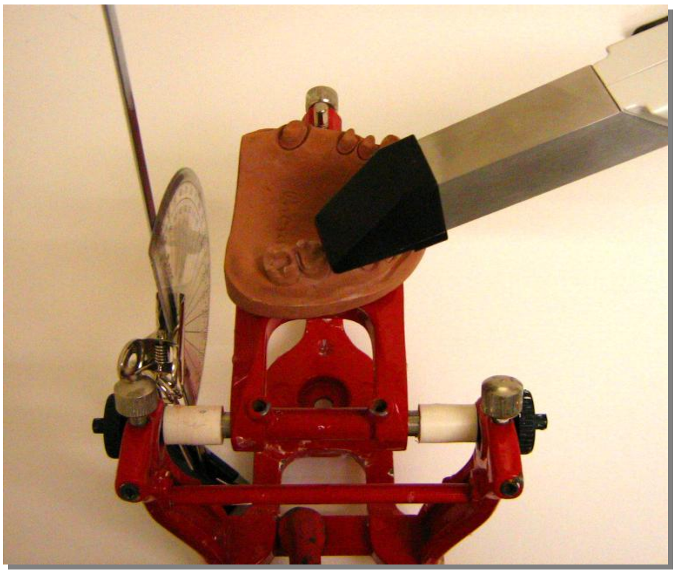


Fig 3.9 Roll position (measurement tool placed behind model)

3.2 IMAGE MEASUREMENTS

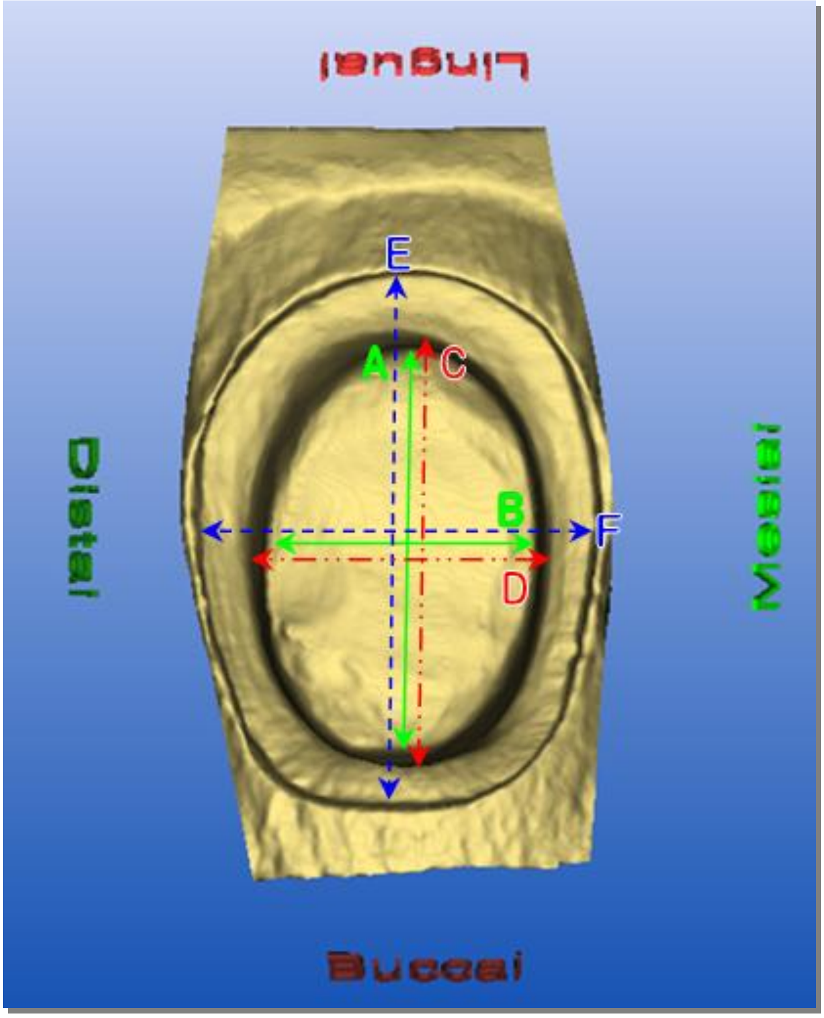
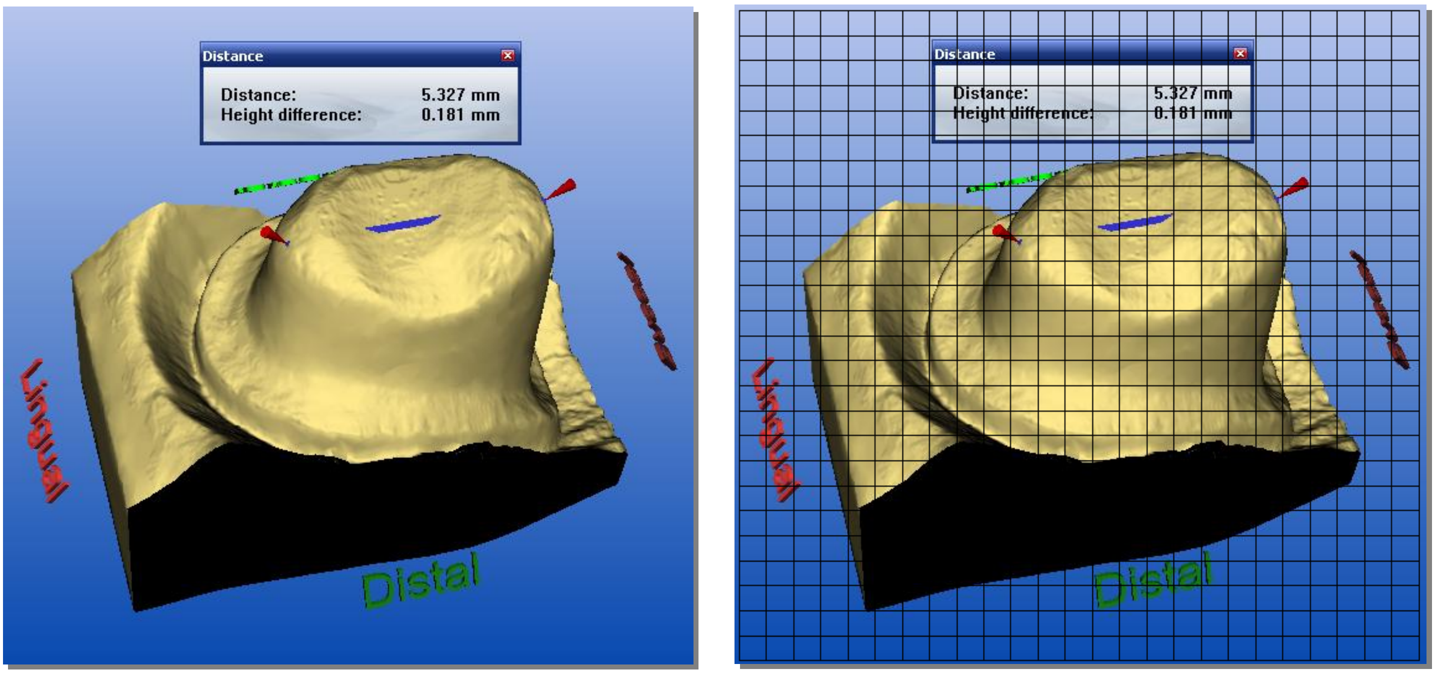


Fig 3.10 Measurements for angle difference: **A** = bucco-lingual occlusal **B** = mesio-distal occlusal **C** = bucco-lingual internal shoulder **D** = mesio-distal internal shoulder **E** = bucco-lingual external shoulder **F** = mesio-distal external shoulder. **E-C difference** = combined shoulder width of buccal and lingual shoulders; **F-D difference** = combined shoulder width of mesial and distal shoulders.

For all angles and variations, results were observed and measured for 0 °, 1 °, 3 °, 5 °, 10 °, 15 ° and 20 ° and measurements were made as shown in figure 3.10 for the occlusal, shoulder and margin dimensions. The Measurement tool in the CEREC software was used to measure the distances (figure 3.11). To increase consistency, a transparent reference grid was constructed and attached to the computer screen to allow for accurate and consistent positioning of the measuring points.

Maximum zoom was used for enhanced viewing, the height difference for the measuring points at 0 °was averaged and a leeway of ±0.01mm was allowed for each position, as it is impossible to achieve exactly coincident points when measuring to a thousandth of a millimetre. The study set-up was repeated three times and measurements taken repeatedly for each set-up.



Distance: 5.327 mm
Height difference: 0.181 mm

A **B**

Fig 3.11 An example of the use of the measurement tool **A**: Without Grid **B**. With Grid

3.3 IMAGE QUALITY ASSESSMENT

As none of these measurements have ever been made before, and it was not possible to predict what significant differences, if any, may emerge, it was felt important to have some form of qualitative measurement in order to assess the relative ease or difficulty encountered when making the images at different angulations. This would be important for the kind of stabilisation that might be required.

A five-point scale was therefore devised to assess the presence of shadows, the quality of the surface texture, margin discrepancies that may require adjustment, and the ability to automatically complete the restoration with ease and accuracy. The scale and key is shown in table 3.1.

Table 3.1 Key for qualitative assessment of images

	SCORE				
	0	**1**	**2**	**3**	**4**
SHADOWS	None	Minimal	Distinctive	Area behind line of angle is obscure	Area behind line of angle disappears
SURFACE TEXTURE	Smooth	Fairly rugged	Rugged	Evidently rugged with distortions	Extremely rugged
MARGIN DISCREPANCIES	Smooth and distinct	Smooth	Requiring minimal adjustments	Requiring major adjustments	Obscure, unable to design automatically
AUTOMATIC COMPLETION	Accurate	Accurate, requiring minimal adjustments	Requiring fairly extensive adjustments, but possible to complete	Impractical and inaccurate to complete	Impossible to complete accurately

3.4 ANALYSIS

Data were entered into the SAS© statistical package (v 9.1, SAS Institute Inc., USA). The study is balanced between three factors: the seven variations in angle, the three variations in axis, and the six measurements, with three replicates with each factor combination. It was therefore appropriate that a three-factor Analysis of Variance (ANOVA) be performed to test for possible interactions between the different factors. Two analyses were performed:

1. 3-way ANOVA, with three replicates per cell, performed on the measurements themselves

2. 3-way ANOVA performed on the standard deviations of the three replicates in each cell (a log transformation was performed on the standard deviations) to test whether the consistency of the readings is affected by any of the factors.

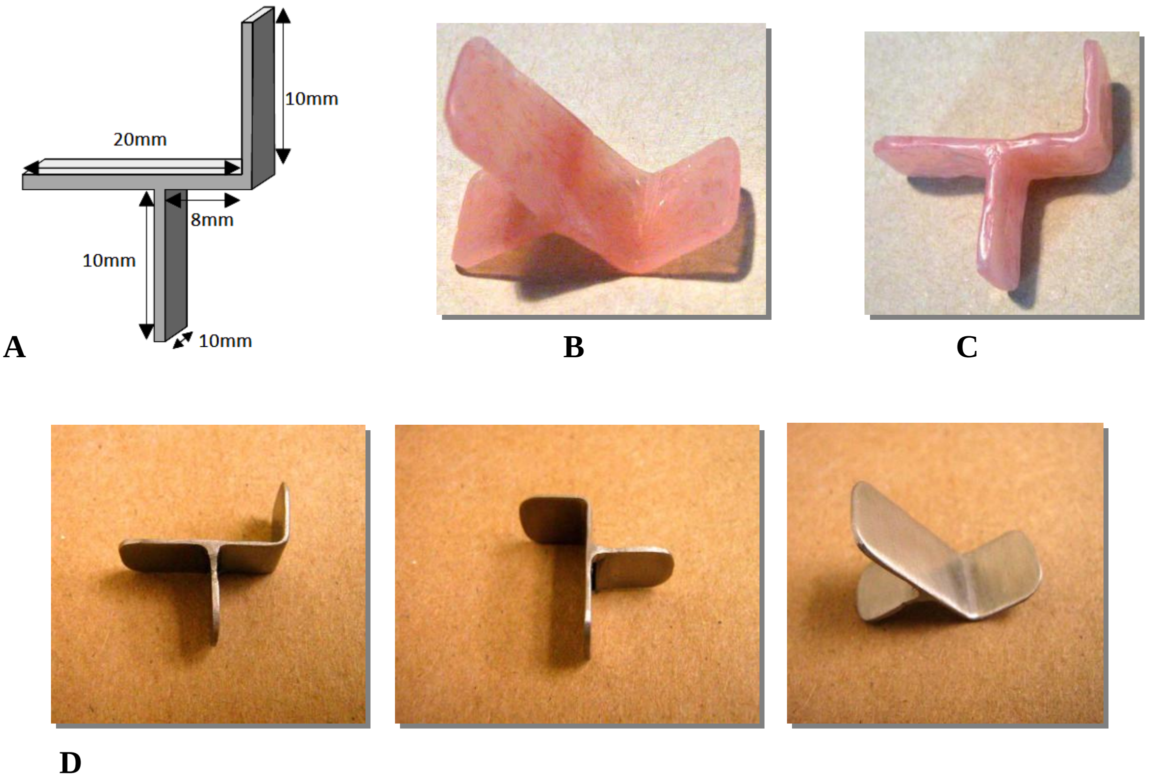
3.5 STABILITY DEVICE

3.5.1 Development of the device

Various devices which included hinged and clamp designs were produced using wax and tested in trials. The devices were either too intricate, costly to produce, large, would take long for placement and/or could not be used on all quadrants.

Further trials with typodonts proved that it was either impractical or impossible to guarantee a restriction of movements as they would inevitably need to change in order to adapt to the preparation path of insertion. Hence it was felt that if the camera could be stabilised prior to preparation, perpendicular to the occlusal surface, and in such a way that minor movements could still be made in order to take into account any preparation direction, this would solve many of the problems reported by clinicians, especially inexperienced ones. Studies using a wax prototype found that different angles and distances from every tooth would be necessary; consequently different designs were made and improved which would allow for stabilising and positioning the camera in different regions of the mouth. Placement would require a material which could contour to the site where the device was placed and later harden enough to be steady and remain in place, and polyvinyl siloxane impression putty proved to be ideal for this purpose.

As the device allows for a variety of placement combinations, pilot studies were first performed with the device made from modelling wax. It was subsequently produced using acrylic for strength and durability. The end product was to be made of stainless steel which automatically reduced its thickness while increasing durability, strength and the ability to be disinfected by various methods for re-use (figure 3.12). Acrylic could alternatively be used for cost effectiveness as it can be produced in auto-polymerising or light-cured material to the same overall dimensions: it would, though, have to be thicker for strength.



A B C D

Fig 3.12 **A**: final device design and dimensions; **B** and **C**: acrylic prototype version; **D**: stainless steel version.

3.5.2 Use of the device

In order to test the device the clinical situation was reproduced to enable a variety of users to experience the device and report on its convenience.

A prefabricated Aesthetic Base Gold (ABG) Model was again used to exclude powdering during repetitious data capture as the device would be continuously removed and placed for each trial. Two models were made using ABG. These were placed and fixed to an articulator (which in turn was fixed to a table using a G-clamp) for user comfort and convenience in holding the camera as well as to prevent the users from interfering with the positioning of the articulator and models. The full set-up was arranged and the device fixed in place using Coltène® lab putty. A crown was milled from the 24 tooth preparation; this was in order to verify if initial estimates of the unprepared tooth would lead to a close to accurate insertion angle after preparation. The insertion angle is expected to change from the initial position as it is impossible to prepare exactly as planned on an unprepared tooth: after preparation slight adjustments will be required to achieve an accurate insertion angle. The model was repositioned on the articulator to simulate quadrants 2 and 4 (figures 3.13 to 3.15).

Fig 3.13 Set-up of stabilising (acrylic) device with lab putty to simulate quadrants 2 and 4

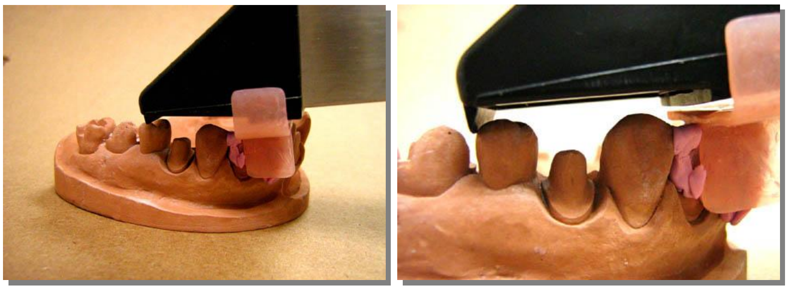


Fig 3.14 Camera positioned on device

Fig 3.15 Stainless steel device on model and articulator

Data capture was taken without and then with the device. Ease of Use was established by recording scores from 10 different users on a 100mm Visual Analogue Scale where 0 = easy and 100 = difficult.

3.5.3 Time for set-up

Time for Set-up was measured using a stop-watch and repeated ten times. Setting up the device involved positioning the putty appropriately, with the device on the desired area of the oral cavity and using the CEREC camera to ensure proper path of insertion. The results of ten repetitions were then averaged. Additionally, time for placing of putty on the device was also measured. Finally, both times were added to identify the overall time for putty placement and set-up which included data capture.

CHAPTER 4. RESULTS

4.1 ANGLE THRESHOLD ERROR: IMAGE MEASUREMENTS

Figure 4.1 shows three images from the ideal path of insertion, and figure 4.2 gives examples of the variations of pitch, roll and yaw for the different angles of measurement.

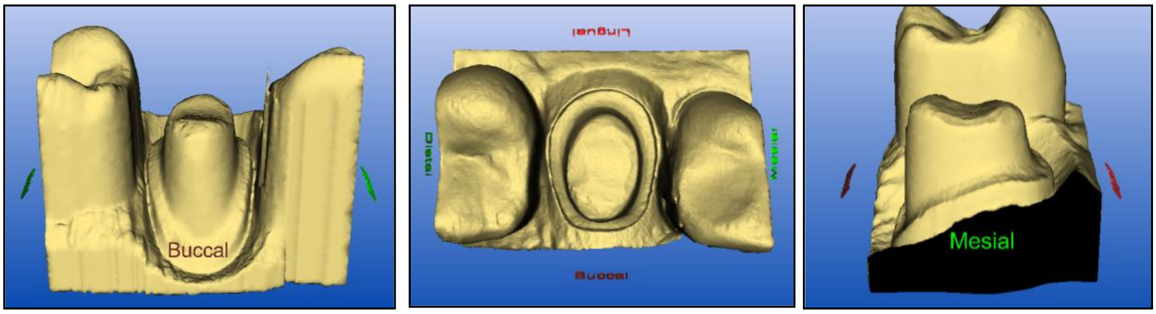


Fig 4.1 Images from a 0 °Path of insertion

It is clear even from a visual inspection of these images that after only a small increase in the angulation, errors are likely.

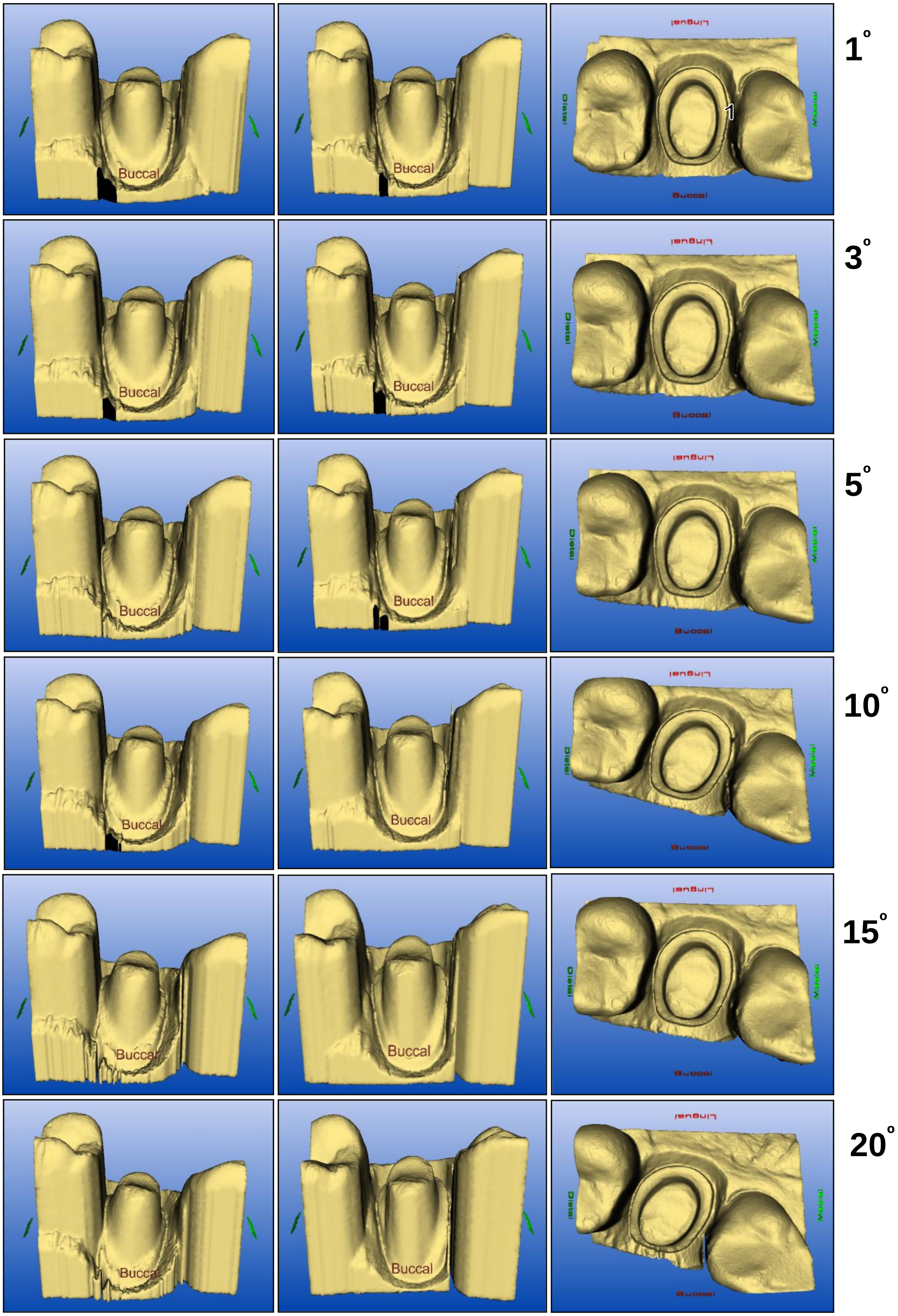


Fig 4.2 Visual effects of angle changes. Left column: Pitch, middle: Roll, right: Yaw.

Table 4.1 gives all the measurements obtained. Figures in red and with an asterisk represent measurements where difficulties or errors were encountered, but where it was still possible to make a measurement. However, that measurement would have been doubtful. The absence of a measurement means that it was impossible to make a measurement at all.

It can be seen that the results for the first four angles (0°, 1°, 3° and 5°) are complete, with only a few uncertain readings (all three replicates of the same reading) at 5°. At 10° and 15° all replicates of the same measurement are missing and there are many more uncertain readings, and at 20° there are a number of missing readings as well as uncertain ones. Therefore only the first four angles were included in the analysis, to give a balanced analysis which would be easier to interpret.

Table 4.1 Distance measurements with angle change at three different occasions (AET1, 2, 3). Red (asterix) figures represent uncertain measurements.

AET1					AET2					AET3				
		ROLL	**PITCH**	**YAW**			**ROLL**	**PITCH**	**YAW**			**ROLL**	**PITCH**	**YAW**
0 °	A	5.526	5.558	5.572	0 °	A	5.557	5.565	5.504	0 °	A	5.567	5.579	5.564
	B	3.759	3.76	3.757		B	3.768	3.772	3.736		B	3.748	3.855	3.799
	C	7.645	7.648	7.62		C	4.712	7.591	7.584		C	7.572	7.421	7.573
	D	4.744	4.773	4.757		D	4.712	4.694	4.755		D	4.707	4.621	4.69
	E	8.882	8.864	8.845		E	8.848	8.867	8.847		E	8.908	8.951	8.973
	F	5.824	5.889	5.814		F	5.875	5.812	5.847		F	5.912	5.887	5.851
1 °	A	5.526	5.55	5.539	1 °	A	5.548	5.575	5.584	1 °	A	5.623	5.562	5.537
	B	3.764	3.716	3.712		B	3.737	3.707	3.734		B	3.773	3.777	3.774
	C	7.761	7.614	7.685		C	7.599	7.655	7.565		C	7.629	7.536	7.57
	D	4.857	4.759	4.703		D	4.724	4.701	4.7		D	4.622	4.639	4.666
	E	8.891	8.878	8.85		E	8.896	8.819	8.89		E	8.879	8.879	8.958
	F	5.853	5.849	5.863		F	5.825	5.861	5.83		F	5.868	5.86	5.879
3 °	A	5.562	5.533	5.585	3 °	A	5.525	5.555	5.587	3 °	A	5.564	5.551	5.558
	B	3.768	3.721	3.766		B	3.767	3.707	3.747		B	3.747	3.742	3.767
	C	7.675	7.624	7.68		C	7.647	7.628	7.614		C	7.586	7.562	7.532
	D	4.755	4.765	4.775		D	4.741	4.768	4.7		D	4.709	4.759	4.696
	E	8.904	8.898	8.879		E	8.896	8.899	8.864		E	8.876	8.859	8.912
	F	5.89	5.836	5.87		F	5.852	5.876	5.819		F	5.939	5.947	5.829
5 °	A	5.57	5.533	5.539	5 °	A	5.655	5.571	5.591	5 °	A	5.569	5.549	5.559
	B	3.757	3.674	3.703		B	3.79	3.739	3.771		B	3.761	3.641	3.768
	C	7.643*	7.624	7.592		C	7.639*	7.51	7.484		C	7.58*	7.589	7.535
	D	4.779	4.765*	4710		D	4.633	4.798*	4.79		D	4.699	4.702*	4.745
	E	8.879	8.841	8.874		E	8.865	8.893	8.878		E	8.919	8.837	8.948
	F	5.835	5.89*	5.85		F	5.872	5.775*	5.805		F	5.912	5.918*	5.889
10 °	A	5.562*	5.542	5.609	10 °	A	5.562*	5.527	5.587	10 °	A	5.59*	5.539	5.602
	B	3.83*	3.62	3.735		B	3.82*	3.64	3.73		B	3.789*	3.733	3.718
	C	7.815*	7.718	7.592*		C	7.97*	7.665	7.586*		C	7.831*	7.612	7.708*
	D	4.792	4.956*	4.735		D	4.779	4.94*	4.777		D	4.643	4.858*	4.749
	E	8.949*	8.843	8.98*		E	8.918	8.817	8.867*		E	8.948*	8.893*	8.963*
	F	5.951		5.851		F	5.89		5.8		F	5.922		5.839
15 °	A	5.506*	5.538	5.571	15 °	A	5.507*	5.539	5.576	15 °	A	5.606*	5.528	5.554
	B	3.786*	3.513*	3.747		B	3.812*	3.67*	3.709		B	3.825*	3.666*	3.723
	C	8.127*	7.665	7.885*		C	8.122*	7.749	7.642*		C	8.179*	7.697	7.648*
	D	4.753	5.008*	4.755		D	4.637	4.984*	4.712		D	4.677	5.023*	4.73
	E	8.949*	8.89	8.98*		E	8.992	8.831*	8.872*		E	9.041*	8.886*	8.984*
	F	5.986		5.836		F	5.835		5.808		F	5.877*		5.824
20 °	A	5.5*	5.577	5.582	20 °	A	5.497*	5.569	5.574	20 °	A	5.528*	5.516	5.576
	B	3.755*	3.6	3.752		B	3.828*	3.615	3.703		B	3.766*	3.667	3.739
	C		7.656*	7.897*		C		7.797*	7.659*		C		7.618*	7.655*
	D	4.79		4.757		D	4.679		4.737		D	4.831		4.689
	E		8.913*	8.933*		E		8.961*	8.896*		E		8.947*	8.942*
	F	5.909*		5.836		F	5.978*		5.869		F	5.954*		5.864

Table 4.2 shows the results of the three-way analysis of variance performed on the measurements, and shows that, while there are highly significant differences between the different measurements – which are to be expected, since they are measuring different things – there are no other significant differences. Thus neither the four different angles nor the three different axes had any influence on the readings, as confirmed by the average values across the four different angles and across the three different axes.

Table 4.2 Analysis of variance on the measurements

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Degree	3	0.1289463	0.0429821	1.08	0.3585
Time	2	0.1206587	0.0603293	1.52	0.2222
Measurement	5	630.6421097	126.1284219	3176.05	<.0001
Axis	2	0.0313124	0.0156562	0.39	0.6749
Time*Axis	4	0.1680665	0.0420166	1.06	0.3794
Time*Measurement	10	0.5056418	0.0505642	1.27	0.2502
Degree*Time	6	0.259225	0.0432042	1.09	0.3722
Degree*Measurement	15	0.6935673	0.0462378	1.16	0.3055
Measurement*Axis	10	0.2826668	0.0282667	0.71	0.7124
Degree*Axis	6	0.280356	0.046726	1.18	0.3217

To test for consistency across the measurements, for every combination of the levels of the three factors (angle, measurement and axis) the standard deviation across the three replicates, AET1, AET2 and AET3 (i.e. the SD of these three values) was calculated and a three-way ANOVA was performed on the log transformation of these standard deviations. This is shown in Table 4.3.

Table 4.3 Three-way ANOVA results on the Log SDs of the three replicates

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Degree	3	4.06638661	1.3554622	2.58	0.0718
Axis	2	0.07216705	0.03608353	0.07	0.9337
Measurement	5	11.07833673	2.21566735	4.22	0.005
Measurement*Axis	10	7.39138212	0.73913821	1.41	0.224
Degree*Axis	6	1.01535814	0.16922636	0.32	0.92
Degree*Measurement	15	7.24031575	0.48268772	0.92	0.5532

The results are similar to those on the measurements themselves, with once again only the different measurements showing significant differences.

4.2 ANGLE THRESHOLD ERROR: IMAGE QUALITY ASSESSMENTS

Figure 4.4 shows the quality assessments for each of the measurements made using the key given in table 3.1. If the scores of 3 and 4 are considered to be such that an inaccurate restoration will result then scores of less than 9 would be acceptable.

Difficulties were first encountered at the 5 °angle, and only for axis variable of pitch. At 10 ° both roll and pitch caused difficulties, with pitch again creating the greatest difficulty. Most problems were encountered with the higher angulations.

Some selected images are shown after the table, to illustrate the difficulties encountered.

Table 4.4 Quality assessments of measurements

ROLL							PITCH							YAW						
		0	1	2	3	4			0	1	2	3	4			0	1	2	3	4
0°	Shadows	✓					0°	Shadows	✓					0°	Shadows	✓				
	Surface	✓						Surface	✓						Surface	✓				
	Margin	✓						Margin	✓						Margin	✓				
	CR	✓						CR	✓						CR	✓				
		0							0							0				
1°	Shadows		✓				1°	Shadows		✓				1°	Shadows	✓				
	Surface		✓					Surface	✓						Surface	✓				
	Margin	✓						Margin	✓						Margin	✓				
	CR	✓						CR	✓						CR	✓				
		2							1							0				
3°	Shadows		✓				3°	Shadows			✓			3°	Shadows	✓				
	Surface		✓					Surface		✓					Surface		✓			
	Margin	✓						Margin		✓					Margin	✓				
	CR	✓						CR			✓				CR	✓				
		2							6							1				
5°	Shadows			✓			5°	Shadows				✓		5°	Shadows	✓				
	Surface		✓					Surface				✓			Surface		✓			
	Margin		✓					Margin				✓			Margin	✓				
	CR		✓					CR				✓			CR		✓			
		5							12							2				
10°	Shadows				✓		10°	Shadows					✓	10°	Shadows		✓			
	Surface		✓					Surface				✓			Surface		✓			
	Margin				✓			Margin					✓		Margin	✓				
	CR				✓			CR					✓		CR		✓			
		10							15							3				
15°	Shadows					✓	15°	Shadows					✓	15°	Shadows		✓			
	Surface	✓						Surface					✓		Surface		✓			
	Margin					✓		Margin					✓		Margin		✓			
	CR					✓		CR					✓		CR				✓	
		12							16							6				
20°	Shadows					✓	20°	Shadows					✓	20°	Shadows				✓	
	Surface	✓						Surface					✓		Surface					✓
	Margin					✓		Margin					✓		Margin			✓		
	CR					✓		CR					✓		CR				✓	
		12							16							12				

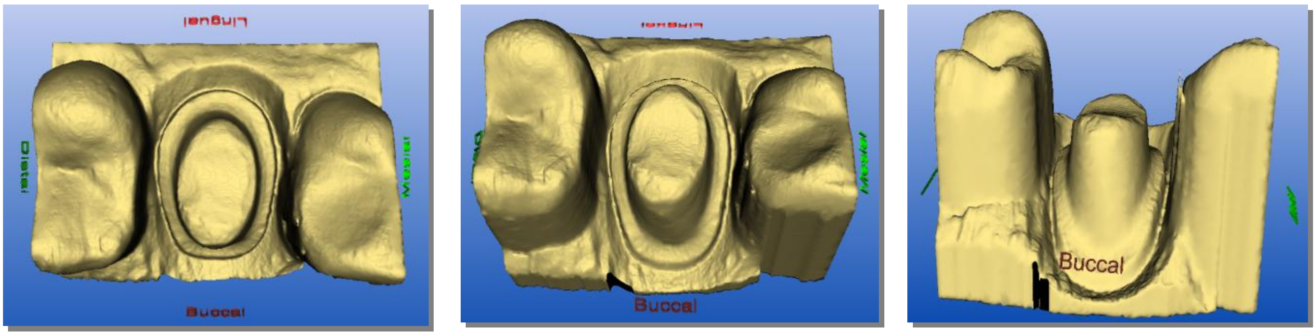


Fig 4.3 View of image at 0 °. Note the lack of shadows, the smooth surface and clear and distinct margin.

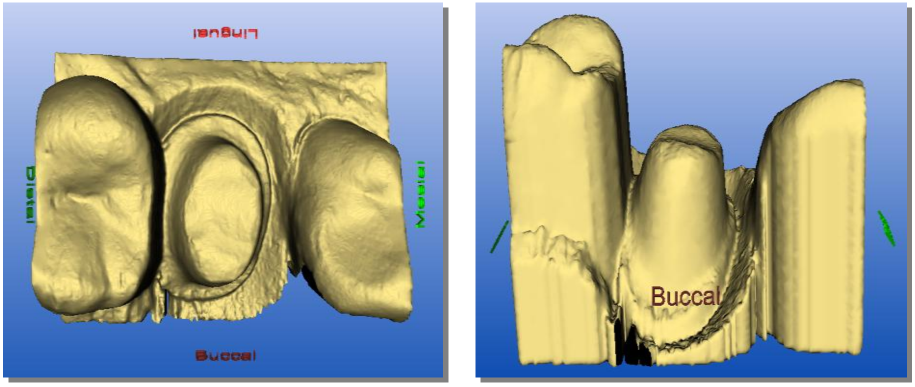


Fig 4.4 Images when Pitch is angled at 20 °

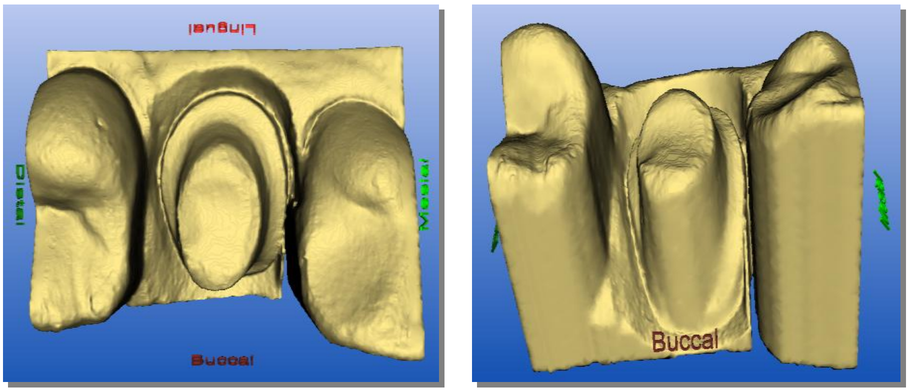


Fig 4.5 Images when Roll is angled at 20 °

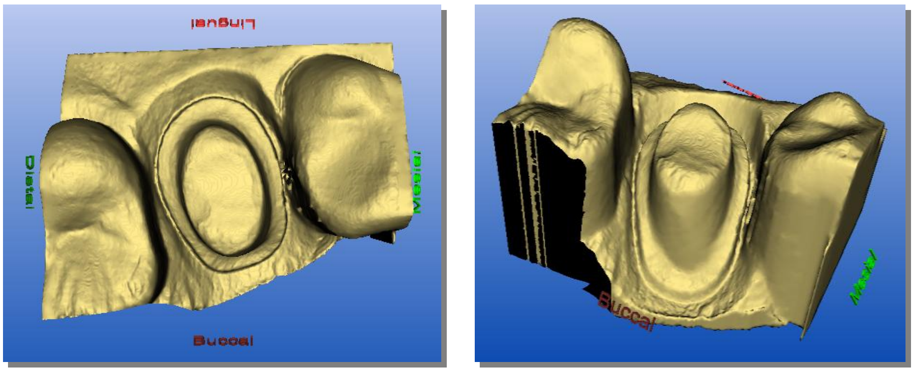


Fig 4.6 Images when Yaw is angled at 20 °

Regarding variations in Pitch, it was found that mesio-distal inaccuracies were most common. The effect of shadows affected the preparation as from 5 °, and at 10 °it was impossible to obtain margin measurements. At 20 °bucco-lingual measurements were extremely difficult to obtain due to both surface and shadow effects. A tilting effect of the abutment towards the shadowed area was also noted.

For variations in Roll, bucco-lingual inaccuracies were most evident from 10 °. Although possible to measure, the effects of shadows were evident also from 10 ° and at 15 ° it was extremely difficult to obtain internal shoulder measurements. At 20 ° both bucco-lingual and mesio-distal areas were dramatically affected, the former being impossible to obtain as shadows caused obscurity of the shoulder and margin.

As regards Yaw, bucco-lingual and distal inaccuracies were observed, however the overall shape of the restoration was not greatly affected, but a rather confusing twisting effect was observed although this did not interfere greatly with the production of a restoration. From 15 ° although possible to complete designing, the restoration required minor adjustments.

4.3 STABILITY DEVICE

4.3.1 Time taken to set-up and place putty

A stop-watch was used to measure the time taken to appropriately place the putty on the device and the time taken to appropriately place the device in a simulated clinical situation. The total time required averaged 21 seconds 433 milliseconds, but a rapid learning curve was observed during repetition. The time considerably reduced from an initial time of just over 28 seconds to just over 18 seconds. Setting time was not recorded as this will vary according to the material used clinically.

4.3.2 Ease of Use

The results for Ease of Use were tallied from 10 users, some familiar with the CEREC and others unfamiliar. The VAS scores in cms are shown in Table 4.5. Generally capturing data from the upper teeth was evidently more challenging whether the device was used or not, however not using it was substantially more difficult. Results showed that using the device proved easier to place and capture data. There was a 25.3% improvement in using the device in the lower, and a 36.4% improvement in using the device in the upper arch.

Table 4.5 Stability device ease of use - VAS assessment score (the lower the score the easier)

	Without Device		With Device	
ID #	**Lower**	**Upper**	**Lower**	**Upper**
1	9	73	2	31
2	74	83	17.5	29.5
3	60	50	80	80
4	24.5	61	12	45
5	50.5	79	40	14.5
6	60	62	30	25.5
7	44	83	17	21.5
8	50	60	20	30
9	73.5	80	22.5	18.5
10	50	53.5	1.5	25
Average	**49.6**	**68.5**	**24.3**	**32.1**

CHAPTER 5. DISCUSSION

The literature review revealed that the Cerec CAD/CAM system is a reliable one that has shown good clinical results, but that there are still some areas which give cause for concern in that they can affect the accuracy of the subsequent restoration. Much of the problem revolves around the capturing of the image because of the inherent difficulties, not least of which is the camera itself. It is bulky and difficult to manoeuvre, and subject to errors of angulation in three dimensions as well as to errors resulting from the natural tremors of the hand and arm.

This study set out to address the effect of deliberately introducing errors of angulation in order to ascertain the threshold beyond which an image would be inadequate and affect the restoration accuracy. It was found that for angles up to 5 °neither the average measurements, nor their variability, were affected by angles of 0, 1, 3 or 5 °, nor by changes in the three different axes. It would therefore seem that the measurements are robust against changes in the axes and angle of the camera, at least over the angles included in the analyses. However, beyond a change in angle of 5 °the difficulties encountered would almost certainly result in an inaccurate restoration. And even at 5 °, changes in the pitch of the camera will produce results that might also include some inaccuracies in the final restoration.

It was found that even though these angles created difficulty in manipulating the images to produce a restoration, it was still possible to do so, again up to a 5 °change, but certainly not at 10 °. These are, however, small angles to control without assistance, and hence the quest for a stabilising device was well justified.

It was somewhat surprising that it was the pitch that was affected the most as the author’s initial conjecture was that it would be changes in the axis producing the effect of yaw that would result in the greatest inaccuracies. It was curious to observe the distortions produced by changes in yaw, but again at 5 ºand less, these did not affect accuracy.

So to improve accuracy, measurements should preferably not deviate from the path of insertion of the restoration by more than 3 º. It is therefore imperative that data capture is carried out with as little movement and deviation from the path of insertion as possible. The stabilising device developed during this study should therefore prove to be of great value as it considerably improved the ability of the operator to maintain the camera steady. The clinical procedure would be to first position the camera using the stabilising device and polyvinyl siloxane putty, so that the camera is perpendicular to the proposed path of insertion of the restoration. Once the tooth is prepared, then only very minor changes in camera position would be required, almost certainly less than 5 º, to capture the final post-preparation path of insertion. Furthermore, the stabilising devise would also help eliminate natural hand tremors.

This study deliberately took only one image, but accuracy would be further improved by taking multiple images in a small range, which would allow the software to interlace the images into a final most accurate one. This aspect of both the camera and the software could be improved further, but however if this improves, there would still be a great advantage to the proper stabilisation of the camera prior to capture of the image.

Due to the rapid development of technologies, upon completion of this paper the CEREC AC chairside digital impression system powered by Bluecam was introduced; the system is however expensive and could be beyond the reach of potential new users and those wanting to upgrade. This may lead to potential new users being deterred and present users continuing with their systems. Thus, the stability device would be necessary until further studies have been carried out. The CEREC AC and other new technological advancements in the system should be reviewed on a separate study.

CHAPTER 6: CONCLUSIONS

When data capturing using the CEREC chairside camera, the angle of the camera relative to the path of insertion of the restoration should not exceed 3 ° for changes in Pitch, or 5 ° for changes in Roll and Yaw of the camera.

The stability device designed during this study proved to be more convenient and accurate for data capture as it decreased the time of search and reduced both the internal and external factors which interfere with data capture.

It is recommend that both *in vitro* and *in vivo* studies be undertaken to determine the clinical outcomes of using the stabilising device.

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