LONGEVITY OF SINGLE-TOOTH ALL-CERAMIC CAD/CAM RESTORATIONS:

A META-ANALYSIS

by

Katherine L. Cheng
LT, DC, USN

A thesis submitted to the Faculty of the
Comprehensive Dentistry Graduate Program
Naval Postgraduate Dental School
Uniformed Services University of the Health Sciences
in partial fulfillment of the requirements of the degree of
Master of Science
in Oral Biology

June 2013

Naval Postgraduate Dental School
Uniformed Services University of the Health Sciences
Bethesda, Maryland

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Katherine L. Cheng
Lieutenant, Dental Corps, U.S. Navy

has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Oral Biology at the June 2013 graduation.

Thesis Committee:

Kim E. Diefenderfer, DMD, MS, MS
CAPT, Research Department
Chairman

Joseph D. Molinaro, DMD, MS
CAPT, Comprehensive Dentistry Department

Scott Kooistra, DDS, MS
CAPT, Operative Dentistry Department

Glen A. Munro, DDS, MBA
Dean
Naval Postgraduate Dental School

The author hereby certifies that the use of any copyrighted material in the thesis manuscript titled:

Longevity of Single-tooth All-ceramic CAD/CAM Restorations: A Meta-Analysis

is appropriately acknowledged and, beyond brief excerpts, is with the permission of the copyright owner.

Katherine L. Cheng

Katherine L. Cheng
Comprehensive Dentistry Graduate Program
Naval Postgraduate Dental School
21 JUL 13

NAVAL POSTGRADUATE DENTAL SCHOOL
KATHERINE L. CHENG

2013

ABSTRACT

LONGEVITY OF SINGLE-TOOTH ALL-CERAMIC CAD/CAM RESTORATIONS:

A META-ANALYSIS

KATHERINE L. CHENG
MS, COMPREHENSIVE DENTISTRY DEPARTMENT, 2013

Thesis directed by: CAPT Kim E. Diefenderfer, DC, USN
Professor, Dental Research Department
Naval Postgraduate Dental School

Introduction: Dental CAD/CAM technology has been available for over 25 years for the fabrication of inlays/onlays, crowns, endocrowns, and veneers. However, very few long-term studies have evaluated the longevity of these restorations. The primary advantage to CAD/CAM fabrication of restorations is the ability to produce a ceramic restoration in one appointment without the need for a laboratory. Areas of concern with these restorations include fracture potential, marginal integrity, and aggressive preparation to allow for milling of the restoration. Most studies conducted have reported only 2-3 years of data, following a relatively small numbers of restorations. To the author's knowledge, only one study has reported a mean restoration exposure time of over 10 years.

Objective: To determine the longevity of single-tooth all-ceramic CAD/CAM-fabricated dental restorations.

Methods: An English language search from 1985 to 2012 was performed in two databases: PubMed and Embase. Using pre-established inclusion and exclusion criteria, all articles identified by the search strategy were reviewed by title, then by abstract, and then by full text reading. Data were assessed by two independent examiners. The primary outcome was the percent of intact restorations at the study conclusion (survival rate), with confidence intervals calculated using the exact binomial method. This survival rate was pooled by using the random effects method.

Results: The initial search identified 1,997 citations; 28 studies, which included 5,566 restorations, were analyzed. The pooled survival rate across all studies was 95.0% (95% CI 93.2%-96.8%). Studies with a mean follow-up of ≤ 5 years seem to have a higher survival (96.4%; 95% CI 94.4-98.5) than those of > 5 years (92.1%; 95% CI 88.5-95.8). Three trials (n=150) using lithium disilicate had nearly perfect survival (99.3%) over a mean duration of 2.3 years. There was little difference in survival by restoration type (inlays/onlays [94.4%] vs. others [95.6%]) or study design (retrospective [93.3%] vs. prospective [95.8%]).

Conclusions: The survival rate of single-tooth all-ceramic CAD/CAM restorations appears to be clinically acceptable and consistent with published data for conventionally fabricated ceramic restorations. Larger trials of longer than 5 years utilizing lithium disilicate should be performed to determine if its survival rate is indeed superior to other materials.

.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I: REVIEW OF THE LITERATURE

HISTORY

CAD/CAM (Computer Aided Design/Computer Assisted Manufacturing) software is used to design and manufacture many different products. Its first applications were in the automotive and aeronautical industries, and it is also used in shipbuilding and architectural design. Applications of this technology in the field of dentistry were first attempted by Drs. John Young and Bruce Altschuler in the United States, Francois Duret in France, and Werner Mörmann and Marco Brandestini in Switzerland (Liu & Essig, 2008). Young and Altschuler (1977) first introduced the idea of using optical instrumentation to develop an intraoral grid-surface mapping system. Dr. Duret's 1984 design of a series of systems that started with an optical impression in the mouth and fabrication of a crown by a milling machine was the beginning of CAD/CAM technology in the dental field. He called his design the Duret system, which was later marketed as the Sopha Bioconcept system. This system was very complex and costly and, therefore, never well accepted in the dental market (Miyazaki, Hotta, Kunii, Kuriyama, & Tamaki, 2009; Liu & Essig, 2008).

Mörmann and Bradestini, working at the University of Switzerland, developed the first commercially viable dental CAD/CAM system which they called CEREC (CERamic REConstruction) (Liu & Essig, 2008). Working with Dr. Alain Ferru, a software engineer, they designed a machine that used a camera in the patient's mouth to acquire data, which were then used to produce dental restorations. In addition to this, Mörmann designed the ceramic blocks that were milled inside the machine to produce the restoration. He is also credited with the development of Liquid Cerec, the titanium oxide powder that is sprayed over the teeth in the patient's mouth prior to imaging. Titanium oxide, original with the CEREC system, was required for the camera to accurately detect the entire surface of the cavity preparation (Mörmann, 2004).

From its inception, computerized technology was cumbersome and, above all, a novelty, requiring inordinate amounts of time to produce a clinically acceptable product. This limited its practical usefulness to the dental laboratory rather than the clinical practice setting, as time constraints precluded chairside implementation. As adjunctive techniques, software, and available materials improved over time, employing CAD/CAM in the dental practice setting became feasible. Thus, "chairside" CAD/CAM technology now affords the practitioner the ability to produce aesthetic, well-fitting prosthetic dental restorations on-site in a matter of hours (Miyazaki & colleagues, 2009).

CAD/CAM SYSTEM COMPONENTS

All dental CAD/CAM systems today consist of three primary components: a digitalization tool/scanner that transforms geometry into digital data that can be processed by a computer, software that processes data, and a production technology that transforms the data set into the desired product (Beuer, Schweiger & Edelhoof, 2008). Following cavity preparation, an image is made that draws data into a computer, and proprietary software is used to create a seal for the cavity preparation within the program, essentially creating a virtual restoration. The software then sends these data to a milling chamber where the dental restoration is carved out of a solid block of porcelain or resin composite. The resultant restoration can then be adjusted and bonded in place. If a porcelain restoration is milled, practitioners may complete it with stains and glazes. Some ceramic products require subsequent heat treatments to both beautify and strengthen the definitive restoration prior to bonding. Following acid etching of both the cavity preparation and the intaglio of the restoration (this microscopically increases surface area on both opposing surfaces), a resin composite luting agent is used to bond the restoration to the tooth, completing the process (Masek, 2001).

MATERIALS FOR CAD/CAM RESTORATIONS

Numerous resin composite and ceramic materials are available for CAD/CAM dental restorations. All materials are supplied as pre-made solid blocks. Resin composite materials include Paradigm MZ100 (3M ESPE) and two materials for provisionals, Vita CAD-Temp (Vident) and Telio CAD (Ivoclar Vivadent). The Paradigm MZ100 blocks are polymers containing zirconia-silica filler particles. They are 85% filled by weight. Vita CAD-Temp is a highly cross-linked, microfilled polymer and Telio CAD is a millable cross-linked polymethylmethacrylate block for temporary crowns and fixed partial dentures (Fasbinder, 2012).

Available ceramic materials include feldspathic porcelain, leucite-reinforced ceramic, partially stabilized (PS) alumina, leucite-glass, lithium disilicate-glass, glass-alumina-spinel, and glass-alumina-PS zirconia. Zirconia has a relatively high stiffness and good mechanical reliability (Griggs, 2007). Alumina has a high modulus of elasticity and high fracture toughness, but is not as translucent as other porcelains. Leucite-glass has a high flexural strength (almost twice that of feldspathic porcelain), as well as high compressive strength. Lithium-disilicate-glass has superior flexural strength and fracture toughness; however, it is more opaque than other types of porcelain (Craig and Powers, 2002).

Ceramic blocks currently on the market include Vitablocs Mark II (Vident), which are feldspathic porcelain, IPS Empress CAD (Ivoclar Vivdaent)—evolved from ProCAD blocks—which are leucite-reinforced ceramic, Triluxe blocks (Vident), which are multicolored Vitablocs Mark II, RealLifeblock (Vident), also multicolored, CEREC blocs (Sirona Dental Systems), which feature a three-layered structure to provide varying translucencies in the final restoration, and IPS e.Max CAD (Ivoclar Vivadent), which is lithium disilicate-glass (Fasbinder, 2002, 2012).

In addition to the milling of full-contour, monolithic restorations, CAD/CAM technology also allows for the milling of high-strength, polycrystalline cores and frameworks. These relatively opaque materials, once processed, are then overlaid with either feldpathic or leucite-reinforced porcelain. High strength cores can be milled from aluminum oxide or zirconium oxide. Typically, these materials are milled in the "green state"—a softer, partially sintered state that allows for efficient milling. Cores and frameworks are fully sintered at extremely high temperatures following milling. During sintering, linear shrinkage of 20-25% occurs. Therefore, the green state cores and frames are milled in a 20-25% oversized state. Vident's original In-Ceram system utilized a slip-cast technique in which cores and frameworks were created from a slurry of either alumina, zirconia, or spinel. Following partial sintering, the extremely porous frameworks were infiltrated with lanthanum glass. Once infiltrated, the frameworks were overlaid with feldpathic porcelain. Vident now produces alumina, spinel, and zirconia blocks that are milled and subsequently infiltrated with glass. Commercially available blocks include In-Ceram Alumina, In-Ceram Spinell, and In-Ceram Zirconia, all of which are manufactured by Vident (Griggs, 2007). In-Ceram Spinell provides a more translucent core than In-Ceram Alumina, while In-Ceram Zirconia provides maximum strength cores (Fasbinder, 2002). The more translucent In-Ceram Spinell core has a lower mechanical strength (283 MPa) compared to In-Ceram Alumina (530 MPa) (Magne & Belser, 1997).

Most recently released is Lava Ultimate (3M ESPE), a material that integrates nanotechnology and ceramics. This block is made of silica and zirconia particles, as well as agglomerated nanoparticles of each that are all embedded in a highly cross-linked polymer matrix. The inclusion of nanoparticles offers the potential for easy contouring and creation of a high gloss surface finish with the purported ability to retain this high gloss finish over time. In vitro studies have indicated that this new material is resistant to toothbrush abrasion and retains the initial glossy surface finish, which tends to be a limitation of other CAD/CAM resin composite blocks (Fasbinder, 2012).

Milling can take place in the dental office, at a dental laboratory, or at a remote production center. The ability to fabricate restorations in the dental office eliminates the requirement of laboratory procedures (Beuer & colleagues, 2008). However, the option exists to have restorations milled at the laboratory, thus eliminating the time requirement of designing and modifying the restoration while the patient waits; this process decreases appointment time at delivery (Christensen, 2008).

ADVANTAGES OF CAD/CAM RESTORATIONS

The primary benefit of CAD/CAM technology in dentistry is the ability to fabricate indirect restorations in one appointment, thus eliminating the need for temporization since there is no extended waiting for laboratory fabrication of the permanent restoration. An alternative option to intraoral scanning of the prepared tooth is to make an impression of the cavity preparation and either send the impression to the laboratory for fabrication or to pour the impression in stone at the dental office and scan the stone cast. The latter is known as the “indirect technique” of fabrication. If a stone cast exists, it is easy to check the margin accuracy on the die prior to try-in. More commonly, however, the cavity preparation is directly imaged in the patient’s mouth, eliminating the need to make an impression. Thus, the time required for impression tray selection, material setting, and disinfection is eliminated.

Conventional laboratory procedures to fabricate porcelain restorations using a powder/liquid build-up firing process (Craig & Powers, 2002) are technique sensitive, and introduction of porosities into the ceramic restoration is an inherent disadvantage (Miyazaki & Hotta, 2011). Fracture toughness of conventional ceramic restorations is approximately 1.5 to 2.1 MPa $m^{1/2}$ with a compressive strength of approximately 150 MPa (Craig & Powers, 2002). These values preclude using the material for load-bearing molar restorations. Many of the previously described CAD/CAM ceramics have improved the mechanical properties over conventional porcelain. Pre-fabricated reinforced glass ceramic blocks can be milled using dental CAD/CAM, and the fracture toughness of these materials range from 1.5 to 3.0 MPa $m^{1/2}$ (Miyazaki & Hotta, 2011). Commercially fabricated blocks with stringent manufacturing controls have eliminated porosities and defects, and therefore, no porosities exist in milled CAD/CAM restorations. As with conventional restorations, finishing procedures, such as staining and glazing to enhance color matching and esthetics, are available (Miyazaki & Hotta, 2011).

Advantages of using resin composite blocks specifically designed for dental CAD/CAM include the ability to add to the surface, for example, if proximal contacts or a margin need to be adjusted. This can be accomplished by air abrading the surface of the restoration with 50 µm silicon dioxide and then bonding a hybrid resin composite to the abraded surface. An additional advantage includes the ease of intraoral polishing (Fasbinder, 2002). Another advantage specific to the resin composite block, Paradigm MZ100, is significantly less wear on opposing tooth structure when compared to two other ceramic materials (Vitablocs Mark II and ProCAD) and pressed ceramic (Empress 1) (Kunzelman, Jelen, Mehl, & Hickel, 2001).

DISADVANTAGES OF CAD/CAM RESTORATIONS

There are also disadvantages to the application of CAD/CAM technology in dentistry. The initial monetary investment for the equipment is significant. Systems currently on the market range from $25,000 to $120,000. Also, learning how to use the software properly can be time-consuming. Some applications are limited due to software and production procedures (Beuer & colleagues, 2008). As with any new technology, it takes time to learn how to use the software and the hardware. Although proficiency and clinical productivity increase with experience, practitioners should expect a rather steep initial learning curve. Most manufacturers generally provide one to two days of introductory training upon initial purchase and recommend attending at least one additional multi-day training course. As with any continuing education, this takes the practitioner out of the office, limiting earnings during that time. Another disadvantage cited in the literature, although no longer as significant, is that the original porcelain blocks were monochromatic. Because the blocks do not incorporate intrinsic staining, translucency, or opacity, it is not always possible to achieve an exact shade match (Freedman, Quinn, & O'Sullivan, 2007). Monochromatic blocks do, however, meet less demanding esthetic requirements, such as those for posterior restorations.

A relatively recent trend is the development of polychromatic blocks that can achieve a much more esthetic appearance in patients with difficult-to-match tooth shades (Tsotsos, 2001). Vident's RealLife block incorporates an internal "dome" of darker opaque ceramic covered with a "shell" of more translucent material. The block is designed to mimic the dentin and enamel regions of an anterior tooth. All glass-containing restorations can be custom stained after milling, but color changes following glazing have been reported (Crispin, Hewlett, & Seghi, 1991).

Marginal adaptation of CAD/CAM dental restorations has been a research focus since the technology was in its infancy. It has been suggested that poor marginal adaptation may influence the survivability of a restoration (Sjögren, 1995). A major concern with the early generation milled ceramic CEREC restorations was the ability to accurately fit the ceramic inlay to the cavity preparation. In her review of the developments in dental CAD/CAM systems, Rekow (1992) noted marginal gap as a known weakness of the CEREC system. In an *in vitro* study of Class II (MOD) CEREC 1 inlays, Inokoshi and colleagues (1992) reported interfacial values ranging from 0 to 235 μm. They reported mean marginal gap widths of 52 μm at the occlusal marginal ridge and an average value for both the mesiobuccal and mesiolingual box corners of 215 μm. These dimensions were considered to be the maximum achievable marginal accuracy for CAD/CAM inlays at the time (Gladys & colleagues, 1995).

In an *in vitro* study comparing the gingival marginal fit of two-surface inlays manufactured with CEREC 2 and CEREC 3, Estefan, Dussetschleger, Agosta and Reich (2003) found no statistically significant difference between the two versions. Gingival marginal gaps ranged from 42.8 to 58.6 µm for CEREC 2 and 39.1 to 52.2 µm for CEREC 3. Other studies have reported marginal gap size of CEREC 2 inlays as 80 ± 57 µm (Sturdevant, Bayne, & Heymann, 1999) and Everest (KaVo) full-coverage restorations as 79.43 ± 25.46 µm (Tan, Gratton, & Diaz-Arnold, 2008).

The early published clinical studies revealed mean marginal gaps of 169 ± 48 µm when evaluating 120 Dicor inlays fabricated using CEREC 1 (O'Neal, Miracle, & Leinfelder, 1993). Mörmann, and Krejci (1992) found a mean marginal gap width of 191.6 µm ± 47.8 µm when studying eight CEREC MOD inlays five years *in situ*.

Lee, Park, Kim, and Kwon (2008) compared the marginal fit of copy milled (Procera) all-ceramic crowns and CEREC 3D machined all-ceramic crowns. Procera crown copings had a mean marginal discrepancy of 72.2 ± 7.0 µm; however, this value increased significantly, to 89.6 ± 9.5 µm, following firing of the outer layer of porcelain. CEREC 3D crowns exhibited a mean marginal gap of 94.4 ± 11.6 µm, statistically similar to that of Procera.

Because identifying and measuring marginal gap widths can be difficult, a definitive benchmark value for clinical acceptability has not been established (Baldissara, Baldissara, & Scotti, 1998; Jahangiri, Wahlers, & Hittelman, 2005).

CAVITY PREPARATION DESIGN

Using CAD/CAM technology to produce indirect dental restorations requires modifications to the conventional cavity preparation designs indicated for metal, ceramic, or resin composite. Tsitrou and van Noort (2008) evaluated minimal preparation designs for posterior CAD/CAM restorations to determine if the published values for conventional resin-bonded ceramic crowns were appropriate. Using first molar typodont teeth, crown preparations were made following published minimal guidelines of 0.6 mm of occlusal reduction, 0.4 mm of margin reduction, 0.5 mm of axial reduction, and a 6° vertical taper. Two different ceramic blocks (ProCAD and Vita Mark II) and one resin composite block (Paradigm MZ100) were selected, and the crowns were fabricated indirectly using CerecScan and CEREC 3D software. The resin composite (Paradigm MZ100) was the only material able to produce acceptable crowns based on the initially proposed minimal preparation design. Both ceramic materials produced crowns with excessive marginal chipping, fractures of the axial walls, and holes in the occlusal surface when applying the minimal preparation design. The authors published revised preparation designs for all three materials that included minimum occlusal reduction of 1.2 mm and axial reduction of 0.6 mm and 0.8 mm, respectively, for Vitablocs Mark II and ProCAD blocks.

Specific modifications to conventional cavity preparations for inlays, onlays, and crowns include semispherical cavity floors and rounded cavity shapes, including rounding of all edges inside the cavity instead of parallel-walled surfaces with sharp transitions to the cavity floor. A divergent angle of 6° to 10° is optimal, and occlusal reduction should be at least 1.5 mm in the area of the central fissure to allow for adequate ceramic thickness. These guidelines apply to preparations for all types of all-ceramic restorations, including conventionally fired, heat-pressed, and CAD/CAM materials.

By necessity, preparations for all-ceramic restorations must be more aggressive than for comparable metal restorations due to the requirement of ceramic thickness for adequate strength. The isthmus width should be no less than 2.5 mm, and the cavity walls should be a minimum of 1.5 to 2 mm in height. If the remaining cavity wall is less than 1.5 mm after proper occlusal reduction, reducing the wall is recommended, thus creating a partial crown. Proximal margins should be extended so that the preparation margins do not touch the neighboring tooth. This extension is indispensable for both conventional and optical impression making, as well as adhesive removal before and after curing. Beveled margins should be avoided in ceramic restorations so as not to compromise material strength in the area. Acute-angled bevels and feather edges are contraindicated (Ahlers & colleagues, 2009: Roberson, Heymann & Swift, 2002).

CURRENT DENTAL CAD/CAM SYSTEMS

Current CAD/CAM systems in dentistry include: CEREC (CEramic REConstruction) and CEREC Acquisition Center (AC) with Bluecam (Sirona Dental Systems), CEREC AC with Omnicam (Sirona), the E4D Dentist System (D4D Technologies), Lava Chairside Oral Scanner (COS) (3M ESPE), and iTero (Cadent, Inc.) (Puri, 2012). The CEREC ACs and E4D Dentist are chairside CAD/CAM, while Lava COS and iTero (Cadent) have only CAD features chairside; for these systems, data must be sent to a laboratory to mill the final restoration. CEREC InLab is the laboratory counterpart to CEREC AC (Poticny and Klim, 2010).

The E4D system, introduced in 2008, involves a laser with image stabilization for chairside scanning that connects to a milling unit in the office requiring both a water and an air source. Images cannot be sent to a laboratory for machining with this particular system. The cost of this system is approximately $116,000. The iTero system incorporates both a laser and a light emitting diode (LED) for image acquisition. A die is precision-milled in the laboratory based on a series of 21 images captured intraorally. The approximate cost for this system is $25,000, with an additional $25 operating fee for every use. The Lava COS captures images as a continuous video using an LED light source and a restoration is produced with stereo lithography in a laboratory. Approximate cost for this system is $26,900.

The CEREC system is the most popular CAD/CAM system and is now in its fourth major evolution, with the design software undergoing significant changes in the years since the technique was first introduced in 1986. CEREC 2 was introduced in 1994 with the ability to manufacture inlays, onlays, and veneers. CEREC 3 was introduced in 2000, and in 2003, a three-dimensional software version was released, CEREC 3D, allowing users to see a three-dimensional view of the tooth needing to be restored. CEREC 3D utilized an infrared scanner to capture digital images, and teeth required powdering with titanium oxide spray. In 2006, Sirona released BIOGENERIC, an additional version of the software that allowed the machine to accurately reconstruct missing tooth shapes and surfaces. In 2008, Sirona released the MCXL in-office milling unit that was capable of producing a restoration in four minutes. In 2009, Sirona released the CEREC Acquisition Center unit powered by Bluecam, an LED camera. This system costs approximately $120,000, but there is an option to purchase the scanner without the milling unit at a price of approximately $25,000. An updated version of the software, CEREC 4.0, was released in 2012. In August of 2012, Sirona unveiled its Omnicam, which is a color streaming camera that operates with the 4.0 software.

Using the CEREC system, a dentist or technician can choose from three major design approaches. The database design mode uses a library of tooth shapes that are stored on the computer to suggest the shape of the proposed restoration. Most commonly, a recording of the bite registration (the imprint of the opposing or antagonist tooth in a wax-like or rubbery material) is also added to the data the software can use when generating the proposal. The latest version of CEREC (CEREC AC) does not require a bite registration, but incorporates a "buccal bite" image to collect data about the patient's occlusal relationships. These data, together with a three-dimensional optical impression of the prepared tooth, establish the approximate zone within which the new restoration can exist. The proposed restoration is then modified to fit into this zone in an anatomically and functionally correct position. The dentist or technician can make corrections to this proposal and then send the final image to the milling unit for fabrication.

A second design approach is the correlation design technique. This technique requires two optical impressions: one of the preparation and one an intact occlusal surface. The second impression may be one of the tooth prior to restoration placement or of a wax-up that was completed to represent the ideal size and shape of the tooth and in harmony with the existing occlusion. The software superimposes both images on each other. This technique is useful when there are complex demands in the design of the occlusal morphology of the tooth to be restored.

The third approach is to use the function design technique. With this technique, the operator is once again using two optical impressions: one of the preparation and the other of a functionally generated pathway placed on the prepared tooth. The software superimposes these impressions, producing an image that serves as a guideline for designing the occlusal surface of the restoration (Reich, Wichmann, Rinne, & Shortall, 2004).

The first-generation CAD/CAM technology produced only single-surface inlays; fabrication of partial or full-cuspal coverage restorations was not possible. In 1990, software upgrades extended the capabilities of the machining process to enable fabrication of multi-surface inlays, as well as onlays. Further software enhancements in 1994 allowed for the fabrication of anterior veneer restorations; in addition, CEREC 2 featured a diamond-coated disk for cutting the restoration and a bur or cylinder that enabled milling of the occlusal surfaces of inlays and onlays. In 1997, new software enabled the fabrication of all-ceramic posterior crowns and crown copings, and in 1998, further enhancements allowed for the production of anterior crowns (Hehn, 2001). Today, the following restorations can be fabricated using CAD/CAM technology: veneers, inlays, onlays, single crowns, fixed denture prostheses (FDPs), endocrowns, partial coverage restorations, implant abutments, and frameworks for removable partial dentures.

LONGEVITY OF CAD/CAM RESTORATIONS

Compared to conventionally fabricated restorations, there are considerably fewer clinical studies of the longevity of CAD/CAM restorations. Most studies are of short duration (one to five years) and only a few have published results over 10 years. Although it is not possible to compare each of these studies directly, it is possible to draw relevant information about the study designs, materials and methods used, types of restorations fabricated, and the results of these studies to gain an understanding about how well CAD/CAM restorations function over time.

Evaluating 1,010 inlays and onlays placed in 299 patients in a private practice setting, Reiss and Walther (2000) found a survival rate of 90% after 10 years and 84.9% at 12 years. Survival was defined as retention of the restoration without the need for replacement during the observation period. All restorations were manufactured using the CEREC technique, bonded over the course of 39 months, and re-examined nine to 12 years after placement. The most frequent cause for failure was fracture of the restoration. A total of 81 failures occurred, including teeth in which restorations were replaced by a different provider for unknown reasons, endodontic complications, removal of the restoration due to prosthetic considerations, and recurrent caries.

Otto and Schneider (2008) reported an 88.7% success rate at up to 17 years (using Kaplan-Meier analysis) for CEREC inlays and onlays placed in Otto's private practice. Two hundred CEREC restorations were placed in 108 patients using the CEREC 1 CAD/CAM system and Vita Mark I feldspathic porcelain blocks between 1989 and 1991. The restorations were monitored for over 15 years, and the mean functional life of the restorations was 15 years 8 months. At 15 years, 187 restorations were available for follow-up. A total of 21 failures occurred, with the majority of the failures (62%) due to ceramic fracture. Other failures included tooth fracture (14%), caries, and endodontic problems.

In a retrospective study, Zimmer and colleagues (2008) reported the survival rates of 23 ceramic onlays and 203 inlays placed using CEREC 1 in a private practice between 1992 and 1994. A total of 23 failures were noted over the course of 10 years. Reasons for failure included seven instances of secondary caries, ten restorations lost, four restorations fractured, and two teeth fractured. Overall survival rate at 10 years was 85.7%.

Sjogren, Molin and Dijken (2004) compared CEREC restorations cemented with chemically cured and dual cured cements. At 10 years, 61 inlays in 25 patients were evaluated using modified USPHS criteria. The estimated survival rate after 10 years was 89% due to four inlay fractures, one cusp fracture, endodontic problems for one patient, and unresolved post-operative sensitivity for another. There was a statistically significant difference in survival by cement type, with 100% survival for chemically cured restorations, but only 77% survival for dual-cured restorations. The failure rate for the dual-cured restorations was thought to be caused by inadequate polymerization in some areas due to the thickness and/or shade of the ceramic.

Weidhahn, Kerschbaum and Fasbinder (2005) evaluated 617 porcelain laminate veneers in 260 patients for up to 9.5 years (mean = 4.7 ± 1.98 years). All restorations were fabricated using CEREC 1 and placed by a single practitioner. The authors reported a 97.8% survival rate. Reasons for failure were noted as porcelain surface defects requiring replacement, tooth fracture, and defective margins. In this study, the operator who placed the restorations was also the examiner through 9.5 years of follow-up.

SUMMARY

Traditional laboratory-processed indirect metal or ceramic dental restorations require a minimum of two or three appointments to complete. Because CAD/CAM all-ceramic restorations can be fabricated and delivered in a single appointment, they provide an expedient alternative to traditional techniques. However, CAD/CAM restorations are not a universal substitute for traditional indirect restorations. Furthermore, although CAD/CAM technology has existed in the field of dentistry for over 25 years, there have been relatively few well-controlled long-term clinical studies reported in the literature. There are a number of retrospective and prospective studies of short duration (two to five years) but only a few reporting results for 10 or more years. As a result, the clinical longevity of CAD/CAM restorations is not well established. Moreover, a search of the Cochrane Database of Systematic Reviews revealed only one such study of CAD/CAM restorations. Wittneben, Wright, Weber and Gallucci (2009) evaluated 16 studies reporting on the survival of 1,957 CAD/CAM single-tooth restorations. The mean exposure time was 7.9 years. The estimated failure rate was 1.75% per year, and the estimated total survival rate after five years was 91.6%.

A hand search of the literature revealed an additional systematic review published by Martin and Jedynakiewicz (1999). In a review of 15 studies (N = 2,862 restorations), the authors found a mean survival rate for CEREC inlays of 97.4% over 4.2 years.

Based on their review of the literature, Bader and Shugars (2009) suggested that, in general, 90% of posterior crowns will survive five years, and 50% to 80% will survive 15 to 20 years; however, compared to metal and metal-ceramic crowns, all-ceramic crowns (not exclusively CAD/CAM) have the poorest survival rates. We found only three studies directly comparing single-tooth all-ceramic CAD/CAM restorations to conventionally fabricated restorations. Two studies involved all-ceramic restorations (Cehreli, Kökat & Akça, 2009; Guess, Strub, Steinhart, Wolkewitz & Stappert, 2009) and one study involved gold restorations (Encke, Heydecke, Wolkewitz & Strub, 2009).

Our search revealed only two systematic reviews and no meta-analyses on the longevity of single-tooth all-ceramic CAD/CAM restorations in the dental literature. As this technology continues to expand, it is imperative to gain understanding from the literature about the long-term reliability of these restorations compared to conventional fabrication methods so that we can make the best clinical decisions for our patients. Therefore, the purpose of this study is to conduct a meta-analysis of published clinical studies involving CAD/CAM all-ceramic single-tooth restorations to determine the long-term survival rate of these restorations. The information obtained from this meta-analysis may assist with both clinical and organizational decision making regarding the utility of CAD/CAM restorations, as compared to a number of available alternatives.

CHAPTER II: MATERIALS AND METHODS

Meta-analysis Search Design and Article Selection

A search of the relevant English language literature (PubMed and EMBASE databases) published between June 1985 and August 2012 was conducted by two independent examiners (KLC, KED) using variations of the following key terms: (1) "CAD/CAM and dental," (2) "CAD-CAM and dental," (3) "CADCAM and dental," (4) "CAD CAM and dental," (5) "CAD CAM and dentistry," (6) "CAD CAM and dental restorations," (7) "CAD CAM and dental restorations and clinical." Our initial search identified 1,997 citations. Refining our search terms resulted in 381 journal articles (206 PubMed; 175 EMBASE) for further review. Comparing results from the two databases identified 120 duplicate publications. After eliminating the duplicates and applying several inclusion and exclusion criteria (Table 1), we subjected the articles to title and abstract reviews, followed by full text review, to select the final number of publications included in the meta-analysis.

Beginning with 261 non-duplicate publications, we eliminated 182 by title review and 43 by abstract review, leaving 36 articles for full text review. Two additional articles were found by a hand search of the available literature on dental CAD/CAM. Of the 38 articles reviewed in full, 28 met the specified inclusion criteria. All articles identified by the search strategy were reviewed independently and in duplicate by the same two examiners.

Table 1. Inclusion and exclusion criteria.

Inclusion Criteria	**Exclusion Criteria**
In vivo studies	*In vitro* studies
Written in English	Not written in English
CAD/CAM technology for fabrication of the restorations	No use of CAD/CAM technology for restoration fabrication
Single-tooth restorations (crowns, veneers, inlays, onlays, partial crowns, endocrowns)	Fixed dental prostheses, implant crowns, removable dental prostheses
Clinical trials	
Prospective studies	
Retrospective studies with patient recall	
Survival rates reported or calculable from provided data	Survival rates not reported or calculable
Study duration (follow-up) $\geq$ 2 years	Study duration (follow-up) $<$ 2 years

Data Collection

Data were assessed and abstracted by two independent examiners using a data abstraction form (Appendix A) developed specifically for this study. We recorded the following parameters for each study: 1) authors; 2) year of publication; 3) study design (prospective vs. retrospective); 4) type(s) of restoration(s) (inlay; onlay/partial crown; veneer; crown; endocrown); 5) coping type, if applicable (aluminum oxide, glass-alumina-spinell); 6) material type, to include veneering material type, if applicable (feldspathic porcelain, leucite, aluminum oxide, lithium disilicate, Dicor, zirconia, fluorapatite glass-ceramic, Syntagon porcelain); 7) location of restorations (anterior or posterior); 8) number of restorations; 9) total exposure time; 10) mean exposure time; 11) survival rate of restorations; 12) number of failed restorations. If not reported directly, total and mean exposure times and survival rates were calculated from data provided within the studies.

Statistical Analysis

For each study included in this meta-analysis, the primary outcome was the percent of intact restorations at the study conclusion (survival rate), with 95% confidence intervals calculated using the exact binomial method. Survival rates were pooled by using the random effects method. Heterogeneity was calculated using the I^2 statistic, which estimates the proportion of variability as a result of heterogeneity rather than chance (Higgins & Thompson, 2002; Higgins, Thompson, Deeks & Altman, 2003). Survival rates were compared by (1) study design, (2) restoration type, (3) restorative material, and (4) study duration. All statistical analyses were performed using STATA 11.0 statistical software (StataCorp LP, College Station, TX), with all significance levels set at $\alpha = 0.05$.

CHAPTER III: RESULTS

From our initial search of 1,997 citations, 28 studies, which included 5,566 restorations, met our inclusion criteria. Twenty-two studies (78.6%) were prospective in design; six (21.4%) were retrospective. The majority of the restorations (84%) were limited to posterior teeth (premolars and molars). Only one study (N = 36) included only anterior teeth and comprised less than 1% of the total number of restorations analyzed. Four studies evaluated both anterior and posterior teeth, comprising 15% of the total number of restorations.

Table 2 (following page) lists the 28 studies included in the meta-analysis, along with the mean exposure time in years, restoration type, coping type (if applicable), material type (along with the veneering material if a coping was used), total and mean exposure times, calculated success rate, and the number of failures reported.

The median length of follow-up was three years (range 1.8 - 15 years). The pooled survival rate across all studies was excellent, as 95% (95% CI 93% - 97%) of the restorations were still intact at the study's conclusion. There was, however, a high degree of heterogeneity (I^2 = 77%). Subgroup analysis showed some of this heterogeneity explained by length of follow-up: studies with five years or less of follow-up had a slightly higher survival rate [96% survival (95% CI 94% - 98%), I^2 = 38%] than studies that followed patients for more than five years [92% survival (95% CI 89% - 96%) I^2 = 93%] (Figure 1; Table 3). Comparing prospective versus retrospective studies yielded similar results. The survival rates were 96% (95% CI 94%-98%) among prospective studies and 93% (95% CI 89% - 97%) among retrospective studies.

Table 2. Clinical studies included in the meta-analysis. Summary of exposure time, restoration type, location, and survival rate. Studies listed by first author only.

Study	Year	Study Design	Restoration Type	Coping Type	Material/ Veneering Type	Location	N	Total Exposure Time (Y)	Mean Exposure Time (Y)	Survival Rate	Failures (N)
Bernhart	2010	Pro	E	0	F	Post	20	39	1.95	90.0%	2
Vanoorbeek	2010	Pro	C	Al	F	Ant/Post	104	305	2.93	97.1%	3
Berg	1997	Pro	I	0	F	Post	115	560	4.86	97.4%	3
Beuer	2010	Pro	C	Z	Gc	Ant/Post	50	150	3	100.0%	0
Denissen	2000	Pro	O	Al	Sy	Post	9	18	2	100.0%	0
Denissen	2000	Pro	O	F	Al	Post	9	18	2	100.0%	0
Wrbas	2007	Pro	I	0	F	Post	60	113	1.88	93.3%	4
Wiedhahn	2005	Retro	V	0	F	Ant/Post	617	4,741	7.68	94.3%	35
Reich	2010	Pro	C	0	LD	Post	39	76	1.95	97.4%	1
Posselt	2003	Retro	I	0	F	Post	2,328	20,637	8.86	98.4%	35
Fasbinder	2010	Pro	C	0	LD	Post	61	122	2	100.0%	0
Isenberg	1992	Pro	I/O	0	F, D	Post	121	347	2.87	94.2%	7

Study	Year	Study Design	Restoration Type	Coping Type	Material/ Veneering Type	Location	N	Total Exposure Time (Y)	Mean Exposure Time (Y)	Survival Rate	Failures (N)
Heymann	1996	Pro	I	0	D	Post	42	168	4	100.0%	0
Mormann	1992	Retro	I	0	F	Post	8	40	5	100.0%	0
Bindl	1999	Pro	E	S	Al	Post	3	7	2.33	100.0%	0
Bindl	1999	Pro	E	0	F	Post	13	23	1.77	92.30%	1
Bindl	1999	Pro	E	Al	Al	Post	3	7	2.33	100.00%	0
Thordrup	1999	Pro	I	0	F	Post	15	41	2.73	86.7%	2
Molin	2000	Pro	I	0	F	Post	20	93	4.65	90.0%	2
Pallessen	2000	Pro	I	0	F, D	Post	32	245	7.66	90.6%	3
Bindl	2002	Pro	C	S	F	Post	19	58	3.05	100.0%	0
Bindl	2002	Pro	C	Al	F	Post	24	84	3.5	91.7%	2
Bindl	2004	Pro	C	0	F	Ant	18	64	3.56	94.4%	1
Bindl	2004	Pro	C	S	F	Ant	18	67	3.72	91.7%	1
Reich	2004	Pro	O, C, E, V	0	F	Ant/Post	58	174	3	96.6%	2

Study	Year	Study Design	Restoration Type	Coping Type	Material/ Veneering Type	Location	N	Total Exposure Time (Y)	Mean Exposure Time (Y)	Survival Rate	Failures (N)
Sjogren	2004	Pro	I	0	F	Post	61	578	9.48	89.0%	7
Bindl	2005	Pro	C	0	F	Post	208	816	3.92	84.6%	32
Thordrup	2006	Pro	I	0	Not spec.	Post	15	143	9.53	80.0%	3
Otto	2008	Retro	I/O	0	F	Post	187	2,798	14.96	88.8%	21
Zimmer	2008	Retro	I/O	0	F, D	Post	226	2,085	9.23	89.8%	23
Reiss	2000	Retro	I/O	0	F	Post	1,010	9,934	9.84	92.0%	81
Federlin	2006	Pro	O	0	F	Post	29	56	1.93	96.6%	1
Guess	2009	Pro	O	0	Le	Post	24	70	2.92	95.8%	1

Study Design	Prospective (Pro) or Retrospective (Retro)
Restoration Type	Inlay (I), Onlay/Partial Crown (O), Veneer (V), Crown (C), Endocrown (E)
Material Type	Feldspathic Porcelain (F), Leucite (Le), Aluminum Oxide (Al) Lithium Disilicate (LD), InCeram Spinell (S), Dicor (D), Zirconia (Z), Fluorapatite glass-ceramic (Gc), Syntagon Porcelain (Sy)
Coping Type	Aluminum Oxide (Al), InCeram Spinell (S)
Location	Anterior (Ant) or Posterior (Post)

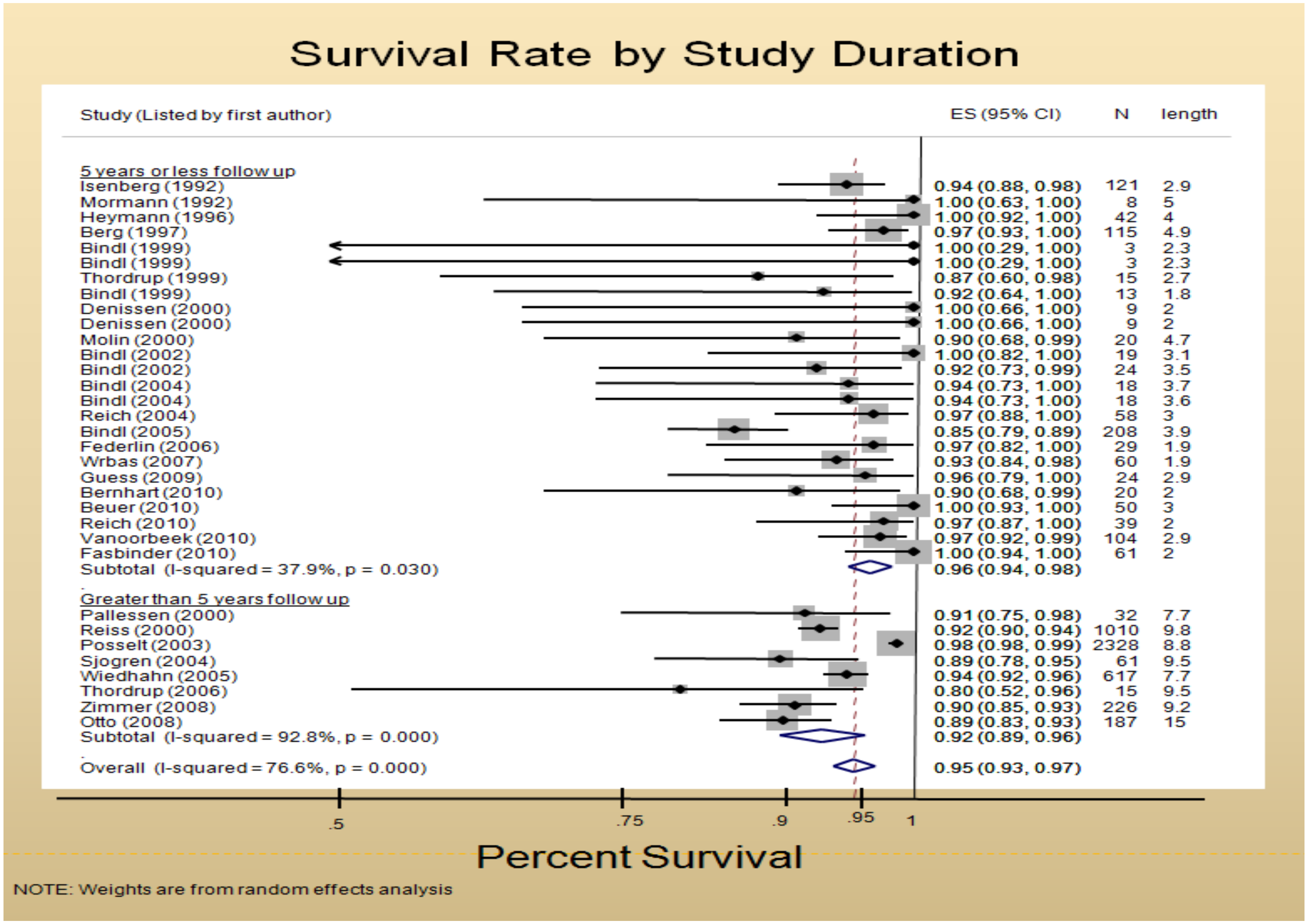

Figure 1. Forest plot. Survival rate by study duration (≤ 5 years or > 5 years).

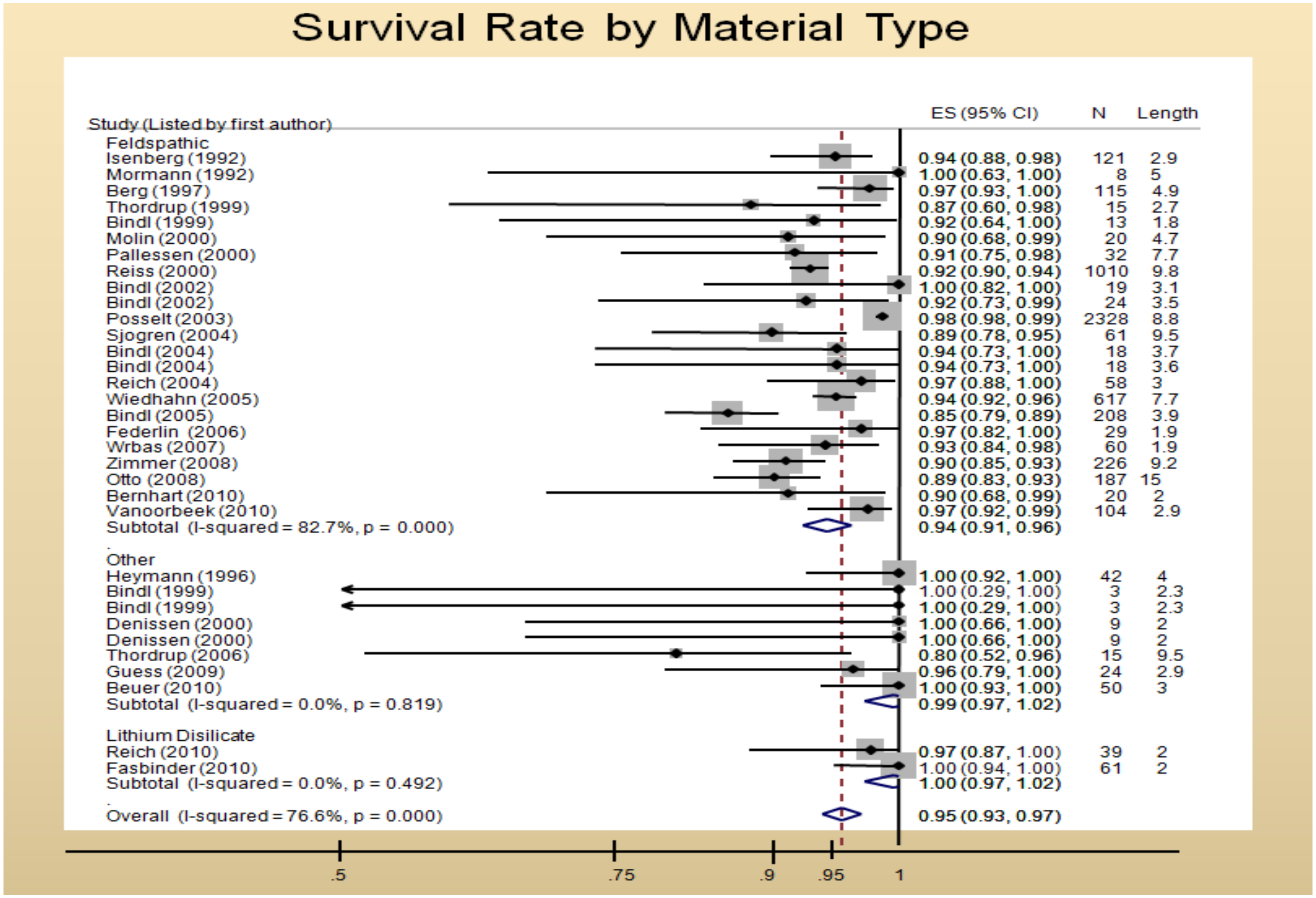

Figure 2. Forest plot. Survival rate of CAD/CAM restorations by material type.

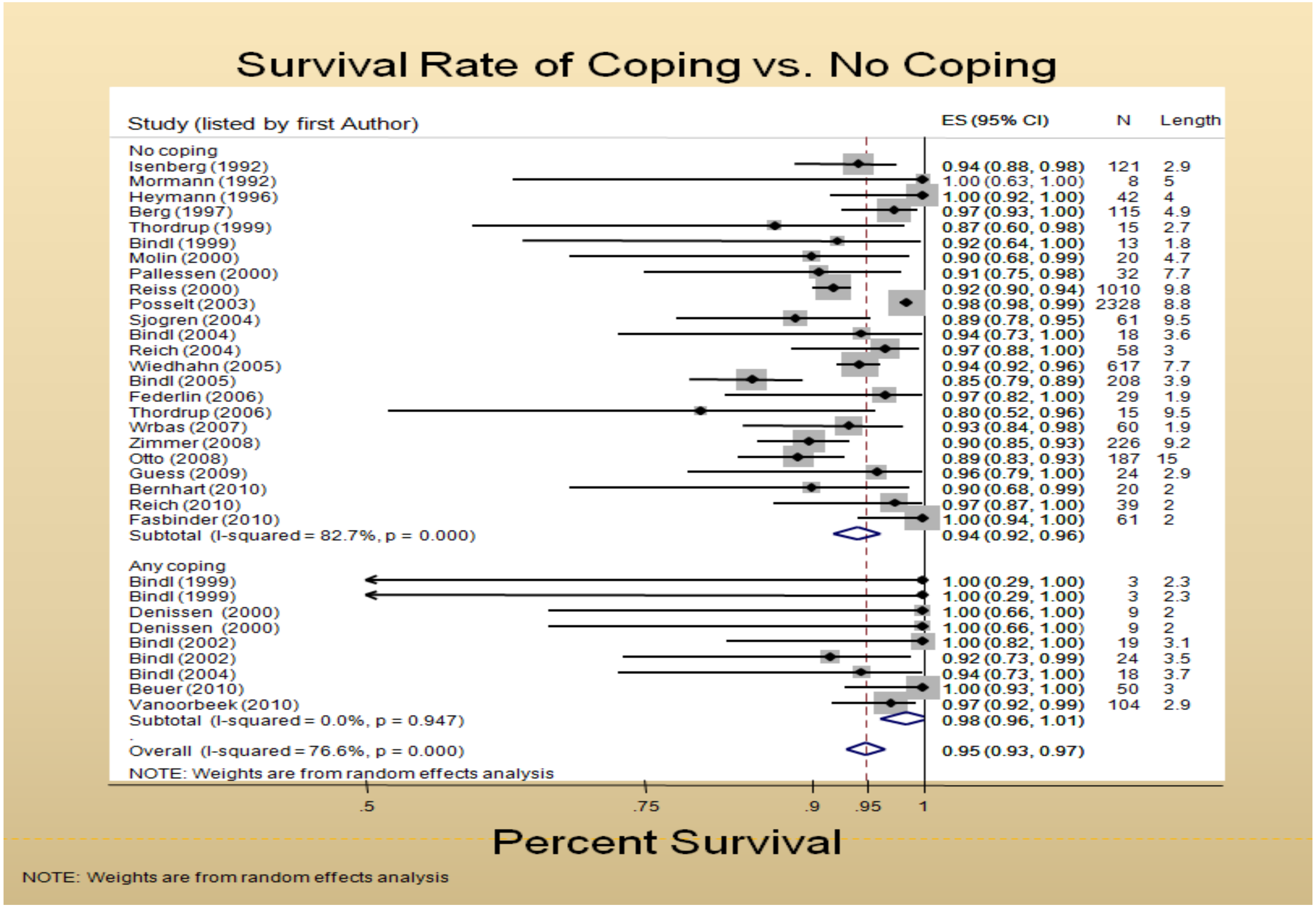

Figure 3. Forest plot. Survival rate of CAD/CAM restorations by coping vs. no coping.

Comparing restoration survival by material type (Figure 2; Table 3), the two studies of lithium disilicate had a survival of 99.6%, (95% CI 97% - 100%, mean number of subjects per study 50), feldspathic 94% (95% CI 91% - 96%, 23 studies, mean subjects = 231), all others 99.5% (95% CI 97% -1 00%, eight studies, n = 19).

The 18 studies of inlays and/or onlays (94.4% survival) were nearly identical to the 15 studies using crowns, veneers, and endocrowns (95.8%).

Lastly, the studies involving copings had greater survival rates (99% [95% CI 96% - 100%]) than those without copings (94% [95%CI 92% - 96%]), but these coping studies were generally small (nine studies, mean number of subjects 27) and of short duration (longest follow up was 3.7 years) (Figure 3; Table 3).

Table 3. Survival of CAD/CAM restorations by study duration, study design, material, restoration type, and coping vs. no coping.

Analysis	Survival Rate	95% Confidence Interval	Heterogeneity (I^2)	Studies (N)	Restorations (N)	Weight (%)
Study Duration						
≤ 5 years	96.4%	0.944 - 0.985	54.2%	20	1,090	65.5
> 5 years	92.1%	0.885 - 0.958	92.8%	8	4,476	34.5
Study Design						
Prospective	95.8%	0.937 - 0.978	56.9%	22	1,113	69.7
Retrospective	93.3%	0.894 - 0.971	94.4%	6	4,453	30.3
Material						
Lithium disilicate	99.8%	0.979 - 1.02	0%	2	100	19.7
Feldspathic	93.7%	0.916 - 0.959	84.4%	21	5,311	77.2
Other	92.6%	0.736 - 1.12	63.2%	6	155	3.1
Restoration Type						
Inlay/Onlay	94.1%	0.92 - 0.97	81.8%	18	4,311	
Other	95.8%	0.93 - 0.98	61.8%	15	1,255	
Coping vs. No Coping						
Coping	98.5%	0.96 - 1.01	0%	6	239	
No Coping	94.1%	0.92 - 0.96	82.7%	24	5,327	

CHAPTER IV: DISCUSSION

The trend toward evidence-based dentistry is ever growing. Searching electronic databases and reading peer-reviewed journals are the most popular and efficient methods to gain knowledge in all areas of dentistry today; however, a challenge to adopting evidence-based practices is the lack of information in many subject areas. One particular area is the use of CAD/CAM. We sought to answer the question, “What is the longevity of single-tooth, all-ceramic CAD/CAM-fabricated dental restorations?” While our search identified nearly 2,000 articles pertaining to CAD/CAM use in dentistry, only 38 clinical trials were found, 28 of which met our rather broad inclusion criteria.

Based on our analysis of 5,566 CAD/CAM restorations, the overall survival rate at 5 years was 95%, but with a high degree of heterogeneity. Lithium disilicate restorations showed a 99.6% survival rate, but only two studies were identified, and both were of short duration (< 5 years). Survival rates comparing inlays/onlays to other restorations types were nearly identical; studies involving copings showed a survival rate of 99%, but reported a limited number of restorations and were of short duration.

Using statistical methods for survival analysis, survival time is defined as the time between a predefined starting event and a terminal event. Survival analysis can be achieved by producing statistical values and survival functions. The most commonly quoted statistics when performing a survival analysis are median survival time, survival rate after a certain number of years, (commonly quoted are five- and 10-year survival rates) and the cumulative survival rate as a function of time (Stoll, Sieweke, Pieper, Stachniss, & Schulte, 1993).

In order to conduct a systematic review and further meta-analysis, specific inclusion and exclusion criteria must be defined. In defining the criteria by which articles will be selected for review and analysis, it is imperative to choose criteria that pertain precisely to the question being asked, but that are not so restrictive as to eliminate all possible studies from consideration. When defining our inclusion criteria, we decided that all articles must be written in English to facilitate full comprehension and data abstraction, although we realized this restriction may exclude potentially valuable foreign-language publications.

We chose to limit our analysis to single-tooth restorations to ensure consistency. Our initial search revealed nine studies published on the use of dental CAD/CAM for fixed dental prostheses (FDPs), three studies of implant crowns, and one report on removable dental prosthesis (RDP) frameworks. However, restoration longevity varies substantially depending on restoration size and number of units involved. Therefore, comparing several dissimilar types of restorations could easily result in inaccurate conclusions. It was also for this reason that we chose to include only all-ceramic restorations.

One study (Fasbinder, 2005) evaluated the longevity of resin composite CAD/CAM restorations, and one clinical trial (Vanoorbeek, Vandamme, Lijnen, & Neart, 2010) compared resin composite CAD/CAM restorations to all-ceramic CAD/CAM restorations. In all, we found eight studies comparing all-ceramic CAD/CAM restorations to other types of restorations (resin composite CAD/CAM, or conventional metal, metal-ceramic, or all-ceramic). As more reports are published, the indications for, and value of, meta-analysis will increase.

There were two primary reasons for choosing clinical trials with a minimum follow-up time of at least two years. First, studies of less than two years duration tended to report 100% restoration retention and/or no differences among treatment groups, suggesting that two years may be insufficient to demonstrate long-term weaknesses or limitations in restorative materials or procedures. In other words, virtually any restoration or material may be likely to last two years. Therefore, we considered studies with follow-up of less than two years to be inapplicable for a meta-analysis on longevity. Second, of the 28 studies analyzed, 20 (71.4%) were of less than or equal to five years. Of those, nine studies (32.1%) were three to four years in duration, three (10.7%) were of six to nine years, and only five (18%) were of ten years or longer. Setting our minimum study duration at three years, rather than two years, would have excluded eight studies including 267 total restorations (30% of the articles and 5% of the restorations included in our analysis).

In addition to prospective studies, retrospective studies with patient follow-up were included. Prospective study designs are more ideal for longitudinal analysis, and our analysis included 22 prospective studies. However, excluding the retrospective studies would have eliminated 80% of the restorations from our analysis.

In order to abstract data about survival rates, it was imperative to have sufficient follow-up data. For studies in which survival rates were not reported directly, we calculated the total and mean exposure times and calculated the survival rates from the data provided within the studies. If the data were insufficient to enable these calculations, the studies were not included in the analysis.

It is equally important to define specific exclusion criteria. This aids in rejecting articles that do not fit the scope of the research question. Including such inappropriate studies may skew the data and result in inaccurate conclusions. It is for this reason that we excluded multi-tooth restorations and restorations fabricated using resin composite. Similarly, we excluded *in vitro* studies because they provide no data on restoration longevity. Case reports were also excluded, due to their typically small numbers of subjects and lack of specific follow-up data.

Meta-analysis is the comparison of summary results across a group of studies with common underlying characteristics (Cohen, 1992). Dr. Gene Glass, who coined the term meta-analysis, defined it as "the statistical analysis of a large collection of results from individual studies for the purpose of integrating findings" (Cohen, 1992). Originally intended for application to randomized controlled clinical trials in medicine, the purpose of meta-analysis is to summarize the available literature on a topic of interest. Meta-analysis has been used extensively in psychology and education since the mid-1970s. In medicine, it is used to analyze randomized clinical trials to gain a broader understanding of short-term, minimally populated studies. Such smaller scale studies may, individually, lack sufficient statistical power to demonstrate possible treatment effects; however, when combined with other similar studies, treatment effects may be illuminated.

To summarize findings across a number of studies, results must be quantified and standard systems for expressing outcomes must be used. Outcomes are expressed in terms of effect size, which is defined as the difference between the mean values of the treatment and control groups. A larger effect size indicates a more significant outcome than a smaller effect size (Cohen, 1992).

In a meta-analysis, two sets of analyses are generally conducted. An initial analysis describes the overall size and significance of the effect sizes for the entire pool of studies by averaging the effect size across studies. A graphic presentation of the effect sizes can easily show outliers that differ markedly from other studies. Outliers can then be studied in greater detail to determine the possible reasons for uniqueness. In a second set of analyses, the impact of specific characteristics on the magnitude of the effect sizes is assessed using multivariate techniques such as multiple regression analysis and analysis of variance (Cohen, 1992).

There are, however, limitations of meta-analysis as a quantitative review technique. Variations in study design (e.g., prospective versus retrospective, randomized controlled clinical trials versus case reports, length of follow-up) can make it difficult to categorize studies as similar. Specific to dentistry and the use of CAD/CAM, variations exist among types of machining equipment as well as the types of restorations placed and the location of those restorations in the mouth. However, these differences do not make direct comparisons impossible.

Because meta-analysis relies on the quantification of outcomes, studies reporting qualitative data, such as certain case studies, cannot be included. In the dental literature, a number of case studies have been published regarding CAD/CAM; however, we were unable to include these studies in our meta-analysis because they lacked sufficient sample size, did not report quantitative data, and/or did not specify the length of the study. For example, in a case study published by Mörmann and Bindl (2000), the authors reported their findings in a private practice setting while "test-driving" the CEREC 3 over a period of six months. The authors discussed two clinical cases, both involving a single restoration fabricated and placed in one appointment. No follow-up was indicated for either patient, and the authors did not mention at what point the restorations were placed during the six months that they were using the software.

It is challenging to conduct a truly randomized controlled clinical trial in dentistry. Although this is a viable option for dental teaching facilities, clinical studies with a randomized controlled design have been of limited duration, perhaps due to a provider population that changes frequently, lack of funding for required restorative materials and software updates inherent to CAD/CAM technology, time constraints in the educational clinical setting, and patient populations that tend to be transient.

In contrast, private practice settings may be more conducive to long-term clinical studies where there are typically only one or two practitioners. In this environment, however, true scientific methodology may be compromised. For example, randomization with regard to selection of restorative material or restoration type is not usually possible, as intraoral conditions often dictate these choices (e.g., metal vs. ceramic; inlay vs. onlay or crown). Moreover, when evaluating treatment outcomes, the practitioner cannot always be blinded regarding the type of restoration or material utilized because (1) dental materials and restorations are, in general, readily discernible due to their inherent differences in appearance, or (2) the practitioner placed the restorations. This raises the question of evaluator bias (intentional or unintentional).Despite its limitations, meta-analysis remains a very important research tool in the dental literature. Results from meta-analyses allow researchers to design future studies in needed areas and avoid pitfalls of previous research. The application of meta-analysis in clinical dentistry and dental education will not only provide better reviews of research, but also will elevate the standards for primary research in dentistry (Cohen, 1992).

Since its inception, dental CAD/CAM technology has undergone continuous refinement. The CAD/CAM systems used in early studies (i.e., those reporting results of over ten years in duration) often used software or hardware that has been upgraded in more recent publications. Nevertheless, the overall survival rates of these early studies are not significantly different from studies published using newer (i.e., more advanced) technology.

Marginal adaptation continues to be a subject of interest in the field of CAD/CAM dental technology. Technological improvements are evident in the reports in the literature. In an *in vitro* comparison of marginal gap produced with IPS Empress (a hot-pressing technique) and CEREC InLab ProCAD (a laboratory CAD/CAM technique), Keshvad & colleagues (2011) found a statistically significant difference between the two products. The mean marginal gaps of IPS Empress restorations (56 ± 18 µm) were greater than ProCAD restorations (36 ± 11 µm). Even though marginal gap studies are not conducted *in vivo*, they can provide valuable information on the technological advances when compared to the published data for the original CEREC restorations and those fabricated using CEREC 2. Most of the long-terms studies included in our meta-analysis evaluated CEREC restorations fabricated with the first version of the technology. Even with larger marginal gaps, these restorations have survived.

Although no direct comparisons can be made between the longevity of CAD/CAM and conventional restorations, it is still possible to indirectly compare outcomes. Granell-Ruiz and colleagues (2010) evaluated the longevity of porcelain laminate veneers using a heat-pressed ceramic (IPS Empress, Ivoclar) placed in anterior teeth up to eleven years. Of the 323 restorations followed, a total of 13 fractures (4%) and 29 debondings (9%) were noted. Restorations were classified into two categories: simple restorations, in which the preparation design was limited to the facial surface, and functionally designed restorations, in which the preparation involved the palatal aspect of the tooth. Kaplan-Meier estimation of the probability that 323 restorations would survive after 11 years was 94% in simple design restorations and 84.7% in functional design restorations. Wiedhahn, Kerschbaum, and Fasbinder (2005) reported a 94.3% survival rate of 617 CEREC veneers followed up to nine years.

In a study of 546 all-ceramic (In-Ceram) anterior and posterior crowns placed in a general practice, the reported success rate was 99.1% after six years. All restorations were placed by a single provider and followed by the same provider (Segal, 2001). In a retrospective study conducted in a university setting, 232 ceramic inlays and 55 partial ceramic crowns were followed for up to seven years. Ceramic materials included cast, pressed, and milled products [Dicor, IPS Empress, Mirage II, CEREC Vita-Mark I and Duceram LFC]. Results were as follows: 98% survival for ceramic inlays and 56% survival for partial crowns. It is interesting to note that none of the CEREC restorations (N = 33) failed (Felden, Schmalz, Federlin, & Hiller, 1998).

CHAPTER V: CONCLUSIONS

Based on our meta-analysis of 28 published clinical studies, we can conclude the following regarding the longevity of single-tooth CAD/CAM all-ceramic restorations:

1) Overall, the survival rate of single-tooth all-ceramic CAD/CAM fabricated dental restorations was excellent (95.1%). This is comparable to that of conventionally fabricated metal, metal-ceramic, and all-ceramic single-tooth restorations.

2) Lithium disilicate restorations had an excellent survival rate (99.6%) at two years.

3) Restorations fabricated as copings and veneered with dental porcelain (Alumina, Spinell, and Zirconia) had an excellent survival rate (99%) at two years.

Clinical implications of these results may warrant the purchase of an in-office CAD/CAM system or the increase in requests for laboratory-fabricated CAD/CAM restorations for patients requesting/requiring single-tooth all-ceramic restorations.

Although existing literature suggests that the longevity of CAD/CAM all-ceramic restorations is favorable, the lack of long-term clinical studies remains a concern. Research with higher levels of evidence than retrospective studies conducted in private practice dental offices is needed. Split-mouth randomized controlled clinical trials, although not always practical, should be conducted to truly evaluate the longevity of CAD/CAM dental restorations compared to conventionally fabricated restorations. These trials need to be of sufficient length (greater than five years) to more accurately assess clinical longevity.

Appendix A

DATA COLLECTION FORM

Title:____

Author(s): ____

Year of publication: ______
Journal:_________________________________

Type of study: ____

Number of examiners: ___________

Inclusion criteria: ____
____

Exclusion criteria: ____
____

CAD/CAM system/fabrication methods: _____________________________________

Type of restoration(s) studied: ____

Number of restorations in the study: ____

Location of restorations intraorally: ____

Luting agent(s) used: ____

Duration of the study: ___________________

Parameters for failure: ____

Reasons for failure noted: ____
____
____

Overall survival rate of restorations studied: _____________________

Additional notes:

REFERENCES

http://www.cereconline.com/cerec/faqs.html

Ahlers M, Morig G, Blunk U, Hajto J, Probster L, & Frankenberger R. (2009). Guidelines for the preparation of CAD/CAM ceramic inlays and partial crowns. *International Journal of Computerized Dentistry, 12* (4), 309-325.

Baldissara P, Baldissara S, & Scotti R. (1998). Reliability of tactile perception using sharp and dull explorers in marginal opening identification. *International Journal of Prosthodontics, 11* (6), 591-594.

Berg N, & Dérand T. (1997). A 5-year evaluation of ceramic inlays (Cerec). *Swedish Dental Journal, 21* (4), 121-127.

Bernhart J, Brauning A, Altenburger M, & Wrbas K. (2010). Cerec 3D Endocrowns—Two-year clinical examination of CAD/CAM crowns for restoring endodontically treated molars. *International Journal of Computerized Dentistry, 13* (2), 141-145.

Beuer F, Schweiger J, & Edelhoof, D. (2008). Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *British Dental Journal, 204* (9), 505-511.

Beuer F, Gernet W, Edelhoff D, & Naumann M. (2010). Prospective study of zirconia-based restorations: 3-year clinical results. *Quintessence International, 41* (8), 631-637.

Bindl A, & Mörmann W. (1999). Clinical evaluation of adhesively-placed Cerec endo-crowns after 2 years—preliminary results. *Journal of Adhesive Dentistry, 1* (3), 255-265.

Bindl A, & Mörmann W. (2002). An up to 5-year clinical evaluation of posterior In-Ceram CAD/CAM core crowns. *International Journal of Prosthodontics, 15* (5)*,* 451-456.

Bindl A, & Mörmann W. (2004). Survival rate of mono-ceramic and ceramic –core CAD/CAM-generated anterior crowns over 2-5 years. *European Journal of Oral Sciences, 112* (2)*,* 197-204.

Bindl A, & Mörmann W. (2005). Survival of ceramic computer-aided design/manufacturing crowns bonded to preparations with reduced macroretention geometry. *International Journal of Prosthodontics, 18* (3)*,* 219-224.

Cehreli M, Kökat A, & Akça K. (2009). CAD/CAM zirconia vs. slip-cast glass-infiltrated alumina/zirconia all-ceramic crowns: 2 year results of a randomized controlled clinical trial. *Journal of Applied Oral Sciences 17* (1), 49-55.

Christensen G. (2008). In-office CAD/CAM milling of restorations: The future? *Journal of the American Dental Association, 139* (1), 83-85.

Cohen P. (1992). Meta-analysis: Application to clinical dentistry and dental education. *Journal of Dental Education, 56* (3), 172-175.

Craig, R., & Powers, J. (2002). *Restorative Dental Materials* (11^{th} ed.). St. Louis, MO: Mosby.

Crispin B, Hewlett E, & Seghi R. (1991). Relative color stability of ceramic stains subjected to glazing temperatures. *Journal of Prosthetic Dentistry, 66* (1), 20-23.

Dennissen H, Dozic A, van der Zel J, van Waas M. (2000). Marginal fit and short-term clinical performance of porcelain-veneered CICERO, CEREC and Procera onlays. *The Journal of Prosthetic Dentistry, 84* (5)*,* 506-513.

Encke B, Heydecke G, Wolkewitz M, & Strub J. (2009). Results of a prospective randomized controlled trial of posterior ZrSiO(4)-ceramic crowns. *Journal of Oral Rehabilitation, 36* (3), 226-235.

Estafan D, Dussetschleger F, Agosta C, & Reich C. (2003). Scanning electron microscope evaluation of CEREC II and CEREC III inlays. *General Dentistry, 51* (5), 450-454.

Fasbinder D. (2002). Restorative material options for CAD/CAM restorations. *Compendium of Continuing Education in Dentistry, 23* (10), 911-922.

Fasbinder D, Dennison J, Heys D, & Neiva G. (2010). A clinical evaluation of chairside lithium disilicate CAD/CAM crowns—A two year report. *Journal of the American Dental Association, 141* (Suppl 2), 10s-14s.

Fasbinder D. (2012). Chairside CAD/CAM: An overview of restorative material options. *Compendium of Continuing Education in Dentistry, 33* (1), 50-58.

Federlin M, Männer T, Hiller K, Schmidt S, & Gottfried S. (2006). Two-year clinical performance of cast gold versus ceramic partial crowns. *Clinical Oral Investigations, 10* (2), 126-133.

Freedman M, Quinn F, & O'Sullivan M. (2007). Single unit CAD/CAM restorations: a literature review. *Journal of the Irish Dental Association, 53* (1), 38-45.

Gladys S, Van Meerbeek B, Inokoshi S, Willems G, Bream M, Lambrechts P, & Vanherle G. (1995). Clinical and semiquantitative marginal analysis of four tooth-coloured inlay systems at 3 years. *Journal of Dentistry, 23* (6), 329-338.

Glass G. (1976). Primary, secondary and meta-analysis of research. *Educational Research, 5*, 3-8.

Granell-Ruiz M, Fons-Font A, Labaig-Rueda C, Martinez-Gonzalez A, Roman-Rodriquez J, Sola-Ruiz F. (2010). A clinical longitudinal study 323 porcelain laminate veneers. Period of study from 3 to 11 years. *Medicina Oral Patologia Oral Cirugia Bucal*, *15* (3), e531-e537.

Griggs J. (2007). Recent advances in materials for all-ceramic restorations. *Dental Clinics of North America, 51* (3), 713-732.

Guess P, Strub J, Steinhart N, Wolkewitz M, & Stappert F. (2009). All-ceramic partial coverage restorations—midterm results of a 5-year prospective clinical splitmouth study. *Journal of Dentistry, 37* (8), 627-637.

Hehn S. (2001). The evolution of a chairside CAD/CAM system for dental restorations. *Compendium, 22* (6), 4-6.

Heymann H, Bayne S, Sturdevant J, Wilder A, & Roberson T. (1996). The clinical performance of CAD-CAM—generated ceramic inlays: A four year study. *Journal of the American Dental Association, 127* (8), 1171-1181.

Higgins JP, Thompson SG. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine, 21* (11), 1539-1558.

Higgins JP, Thompson SG, Deeks JJ, & Altman DG. (2003). Measuring inconsistency in meta-analyses. *British Medical Journal, 327* (7414), 557-560.

Inokoshi S, Van Meerbeek B, Willems G, Lambrechts P, Braem M, &Vanherle G. (1992). Marginal accuracy of CAD/CAM inlays made with the original and the updated software. *Journal of Dentistry, 20* (3), 171-177.

Isenberg B, Essig M, & Leinfelder K. (1992). Three-year clinical evaluation of CAD/CAM restorations. *Journal of Esthetic Dentistry, 4* (5), 173-176.

Jahangiri L, Wahlers C, & Hittelman E. 2005. Assessment of sensitivity and specificity of clinical evaluation of cast restoration marginal accuracy compared to stereomicroscopy. *Journal of Prosthetic Dentistry, 93* (2), 138-142.

Keshvad A, Hooshmand T, Asefzadeh F, Khalilinejad F, Alihemmati M, & Van Noort R. (2011). Marginal gap, internal fit, and fracture load of leucite-reinforced ceramic inlays fabricated by CEREC inLab and hot-pressed techniques. *Journal of Prosthodontics, 20* (7)*,* 535-540.

Kunzelman K, Jelen B, Mehl A, & Hickel R. (2001). Wear evaluation of MZ100 compared to ceramic CAD/CAM materials. *International Journal of Computerized Dentistry, 4* (3), 171-184.

Lee K, Park C, Kim K, & Kwon T. (2008). Marginal and internal fit of all-ceramic crowns fabricated with two different CAD/CAM systems. *Dental Materials Journal, 27* (3), 422-426.

Liu P, & Essig M. (2008). A panorama of dental CAD/CAM restorative systems. *Compendium of Continuing Education in Dentistry*, *29* (8), 482-493.

Magne P, & Belser U. (1997). Esthetic improvements and in vitro testing of In-Ceram Alumina and Spinell ceramic. *International Journal of Prosthodontics, 10* (5)*,* 459-466.

Martin N & Jedynakiewicz N. (1999). Clinical performance of CEREC ceramic inlays: a systematic review. *Dental Materials 15* (1), 54-61.

Masek R. (1999). Reproducing natural color effects on milled ceramic restorations. *International Journal of Computerized Dentistry, 2* (3), 209-217.

Masek R. (2001). Achieving high-level aesthetics with CEREC. *Compendium of Continuing Education in Dentistry, 22* (6), 19-26.

Miyazaki T, & Hotta Y. (2011). CAD/CAM systems available for the fabrication of crown and bridge restorations. *Australian Dental Journal, 56* (1 Suppl), 97-106.

Miyazaki T, Hotta Y, Kunii J, Kuriyama S & Tamaki Y. (2009). A review of dental CAD/CAM status and future perspectives from 20 years of experience. *Dental Materials Journal, 28* (1), 44-56.

Molin M, & Karlsson S. (2000). A randomized 5-year clinical evaluation of 3 ceramic inlay systems. *The International Journal of Prosthodontics, 13* (3), 194-200.

Mörmann W, & Krejci I. (1992). Computer-designed inlays after 5 years *in situ.* Clinical performance and scanning electron microscope evaluation. *Quintessence International, 23* (2)*,* 109-115.

Mörmann W. & Bindl A. (2000). The Cerec 3—A quantum leap for computer-aided restorations: Initial clinical results. *Quintessence International*, *31* (10), 699-712.

Mörmann W. (2004). The origin of the Cerec method: A personal review of the first 5 years. *The International Journal of Computerized Dentistry, 7* (1), 11-24.

O'Neal S, Miracle R, & Leinfelder K. (1993). Evaluating interfacial gap for esthetic inlays. *Journal of the American Dental Association, 124* (12)*,* 48-54.

Otto T, & Schneider D. (2008). Long-term clinical results of chairside Cerec CAD/CAM inlays and onlays: A case series. *The International Journal of Prosthodontics, 21* (1), 53-59.

Pallesen U, & van Dijken J. (2000). An 8-year evaluation of sintered ceramic and glass ceramic inlays processed by the Cerec CAD/CAM system. *European Journal of Oral Sciences, 108* (3), 239-246.

Posselt A, & Kerschbaum T. (2003). Longevity of 2328 chairside Cerec inlays and onlays. *International Journal of Computerized Dentistry, 6* (3), 231-248.

Poticny D, & Klim J. (2010). CAD/CAM in-office technology : Innovations after 25 years for predictable, esthetic outcomes. *Journal of the American Dental Association, 141* (2 Suppl), 5-9.

Puri S. (2012). The state of the digital dentistry in 2012. *Dentaltown*, December 2012.

Reich S, Wichmann M, Rinne H, & Shortall A. (2004). Clinical performance of large, all-ceramic CAD/CAM-generated restorations after three years—A pilot study. *Journal of the American Dental Association*, *135* (5), 605-612.

Reich S, Fischer S, Sobotta B, Klapper H, & Gozdowski S. (2010). A preliminary study on the short-term efficacy of chairside computer-aided design/computer-aided manufacturing-generated posterior lithium disilicate crowns. *The International Journal of Prosthodontics, 23* (3), 214-216.

Reiss B, & Walther W. (2000). Clinical long-term results and 10 – year Kaplan-Meier analysis of Cerec restorations. *International Journal of Computerized Dentistry, 3* (1), 9-23.

Rekow E. (1992). A review of the developments in dental CAD/CAM systems. *Current Opinion in Dentistry, 2* (June), 25-33.

Roberson T, Heymann H, & Swift E, Eds. (2002). *Sturdevant's Art and Science of Operative Dentistry (*4th ed). St. Louis, MO: Mosby.

Sjögren G. (1995). Marginal and internal fit of four different types of ceramic inlays after luting. *Acta Odontologica Scandinavica, 53* (1), 24-28.

Sjögren G, Molin M, & van Dijken J. (2004). A 10-year prospective evaluation of CAD/CAM-manufactured (Cerec) ceramic inlays cemented with a chemically cured or dual-cured resin composite. *The International Journal of Prosthodontics, 17* (2), 241-246.

Sturdevant J, Bayne S, & Heymann H. (1999). Margina gap size of ceramic inlays using second-generation CAD/CAM equipment. *Journal of Esthetic Dentistry, 11* (4), 206-214.

Tan P, Gratton D, & Diaz-Arnold A. (2008). An in-vitro comparison of vertical marginal gaps of CAD/CAM titanium and conventional cast restorations. *Journal of Prosthodontics, 17* (5), 378-383.

Thordrup M, Isidor F, & Hörsted-Bindslev P. (1999). A 3-year study of inlays milled from machinable ceramic blocks representing 2 different inlay systems. *Quintessence International, 30* (12), 829-836.

Thordrup M, Isidor F, & Hörsted-Bindslev P. (2006). A prospective clinical study of indirect and direct composite and ceramic inlays: Ten-year results. *Quintessence International, 37* (2), 139-144.

Tsitrou E, & van Noort R. (2008). Minimal preparation designs for the single posterior indirect prostheses with the use of the Cerec system. *International Journal of Computerized Dentistry, 11* (3-4), 227-240.

Tsotsos S. (2001). Single-appointment, all-ceramic anterior restorations. *International Journal of Computerized Dentistry, 4* (4), 263-272.

Vanoorbeek S, Vandamme K, Lijnen I, & Neart I. (2010). Computer-aided designed/computer-assisted manufactured composite resin versus ceramic single-tooth restorations: a 3-year clinical study. *International Journal of Prosthodontics, 23* (3), 223-230.

Wiedhahn K, Kerschbaum T, & Fasbinder D. (2005). Clinical long-term results with 617 Cerec veneers: A nine-year report. *International Journal of Computerized Dentistry, 8* (3), 233-246.

Wittneben J, Wright R, Weber H, & Gallucci G. (2009). A systematic review of the clinical performance of CAD/CAM single-tooth restorations. *International Journal of Prosthodontics, 22* (5), 466-471.

Wrbas K, Hein N, Fabian J, Jörg M, & Hellwig E. (2007). Two-year clinical evaluation of Cerec 3D ceramic inlays inserted by undergraduate dental students. *Quintessence International, 38* (7), 575-581.

Young J, & Altschuler, B. (1977). Laser holography in dentistry. *Journal of Prosthetic Dentistry, 38* (2), 216-225.

Zimmer S, Gohlich O, Ruttermann S, Lang H, Raab W, & Barthel C. (2008). Long-term survival of Cerec restorations: A 10-year study. *Operative Dentistry, 33* (5), 484-487.