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"A COMPREHENSIVE REVIEW OF CAD/CAM TECHNOLOGIES IN FIXED DENTAL PROSTHESES: DESIGN PARAMETERS, MATERIALS, ADAPTATION, AND CLINICAL PERFORMANCE "

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ABSTRACT

The rapid evolution of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies has significantly transformed the field of prosthodontics, particularly in the fabrication of fixed dental prostheses (FDPs). This review presents a comprehensive analysis of the role of CAD/CAM systems in the design, manufacturing, and clinical performance of fixed dental crowns, with emphasis on material selection, geometric design parameters, adaptation quality, and long-term surface integrity. The limitations of conventional fabrication methods and the advantages offered by digital workflows are critically discussed. Key design parameters influencing prosthesis success including finish line geometry, convergence angle, and cement layer thickness are examined in relation to marginal and internal adaptation. The review also highlights the mechanical and surface characteristics of contemporary ceramic materials, particularly lithium disilicate glass-ceramics, under simulated oral conditions such as thermal fluctuations, pH cycling, and mechanical loading. Surface roughness, hardness, and corrosion-related degradation are discussed as indicators of long-term clinical durability. Recent advances in evaluation techniques, including micro-computed tomography, are reviewed for their effectiveness in non-destructive assessment of crown adaptation. The study consolidates current knowledge, identifies existing research gaps, and underscores the need for standardized CAD/CAM protocols to enhance the reliability, longevity, and clinical success of fixed dental prostheses.

Key Words: CAD/CAM dentistry; Fixed dental prosthesis; Dental crown; Lithium disilicate; Marginal adaptation; Surface roughness; Micro-hardness; Ageing behavior; Prosthodontics.

I. INTRODUCTION

Medical prosthesis is a bionic aid that replaces a body part lost due to trauma, disease, or congenital defects. It is an artificial organ implanted and defined according to the patient's needs and anatomy for both functional and aesthetic purposes. Medical prostheses serve a variety of functions and have a broad range of applications. The prostheses, such as a shoulder, femur, maxilla, kneecap, or some other joints are implanted for functional purposes, while prostheses like maxillofacial, auricular, and limbs, are generally implanted only for aesthetic issues. Out of these medical prosthesis products, dental prostheses are being restored for both functional and aesthetic reasons. In today's scenario, the demand

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for restoration of dental prosthesis is growing in human life irrespective of its cost of restoration. Therefore, the field of Prosthodontics, which is concerned with the design, manufacturing, and fitting of dental prostheses, is the highly rated area in medical sector for research and development [1].

Over the years, conventional production method has been employed by means of lost wax casting process to shape the metal into the desired prosthesis. Using conventional method, only simple prosthetic shapes could be possible to fabricate, and desirable accuracy could not be achieved. Moreover, such method is prone to a variety of subjective errors. The use of Computer-Aided Designing and Manufacturing (CAD/CAM) in dentistry has provided advanced modeling, state-of-the-art materials, and machining. CAD/CAM systems have been used in prosthetic dentistry work on reverse engineering principle; the process starts from 3D digitization of prepared tooth to CAD modeling and finally manufacturing on a CAM unit. Implementations of such types of manufacturing methods have resulted in significant advancement in prosthetic dentistry [2].

CAD/CAM is being utilized for production of medical prosthesis products to eliminate the human errors involved in conventional production process. It helps to fabricate customized prosthesis products with high accuracy and in less time. In addition, implementing CAD/CAM provides the scope to include non-metallic bio- materials e.g. ceramics and possibility of additive manufacturing for fabrication of medical prostheses. CAD/CAM provides rooms to manufacture custom-made optimal dental restorations with minimum discrepancies. Virtual CAD modeling of the prosthesis is also possible using the scanned data of the body part to be restored. Further, manufacturing simulation can be accomplished for intricate prosthetic shape using CAD modeling data through CAM technique.

II. CONVENTIONAL AND CAD/CAM METHODS

Implementation of CAD/CAM has been benefited the clinical dentistry by reducing the chair time, eliminating the provisional appointments and impression method, and improving technical communication between dentist and laboratory technician. In addition to clinical benefits, CAD/CAM dentistry has benefited patients by providing a variety of aesthetic metal-free dental materials, elements the long casting process, and improves implant techniques. Despite of above benefits, dental CAD/CAM systems have some limitations such as high initial investment cost of restoration, need of skilled dental practitioners, and challenges in intra oral digital scanning process due presence of soft tissues and moistures [3].

Although CAD/CAM is being successfully implemented in medical prostheses for last few years, therefore, recent advancements in this technology can be further implemented not only to produce high quality prostheses but for clinical research and development also.

III. DENTAL PROSTHESIS: AN INTRODUCTION

Dental Prosthesis is an area concerned with the assessment, recovery preparation, rehabilitation and preservation of functional ability, convenience, appearance and fitness of patients with pathological problems associated with damaged or defective teeth and/or maxillofacial tissues using biocompatible replacements. The main purpose of dental prosthesis is to restore oral function, particularly masticatory features which depend on the how well occlusal surfaces (Figure 1a) of opposite teeth contacts. Hence, to create effective and suitable occlusal contacts (Figure 1b), the customized geometry of dental prostheses is required. Dental prostheses can be classified into two types based on the restoration process: (i) Removable Dental Prostheses, (ii) Fixed Dental Prostheses [4].

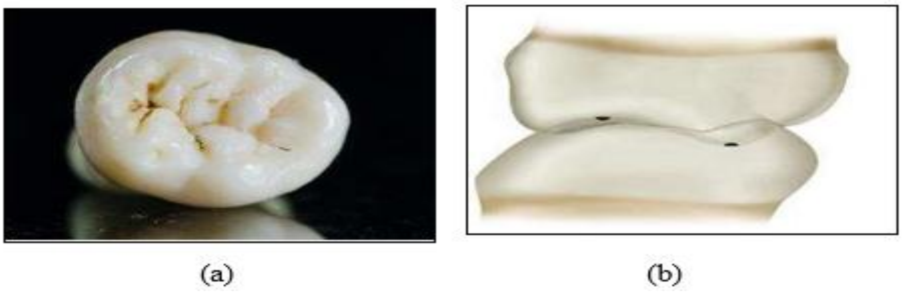

Figure 1. (a) Occlusal surface (b) Occlusal contact of opposite teeth

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(a) (b)

Figure 2. Classification of Removable Dental Prostheses (a) Partial unit (inlays & onlays restorations) prostheses (b) Single unit (Crown restoration) prosthesis

Removable Dental Prosthesis is all forms of dentures produced in the clinical laboratory at different levels of damaged teeth. These can be quickly separated from the patient's mouth for washing and reinserted without the use of cement. Most of the time, they are intended to replace multiple missing teeth rather than just one or two, as bridges do, or even more teeth in edentulous patients. Removable, partial and complete denture prostheses are common examples as shown in Figure 2 [5].

Fixed Dental Prosthesis is also produced in the laboratory for partial damaged and complete missing teeth, but these are cemented to the teeth prepared by the dentist and patients can not remove it for cleaning or other purpose. Generally, fixed prostheses are recommended for partial, single, and small unit (two or three) restoration such as inlays, onlays, veneers, crown, and bridge restoration [6].

IV. CAD/CAM in FDC Prosthesis

Recently, CAD/CAM has been implemented in several dental restoration areas such as inlays/onlays, complete denture, bridge restoration, and crown restoration etc. A restoration of the crown is a way of having a dental crown put on top of and around a badly or partialy injured tooth. The crown restoration process includes the development of the crown by the dental lab. A dentist removes the affected parts of the tooth a couple of days later and prepares it for a new cap or crown.

V. Characteristics of FDC Prosthesis

Excellent aesthetics, good adaptation, and improved mechanical properties are the primary criteria for efficient FDC prosthesis restoration. The aesthetic dental material obscures the identity of restorations and improves the patient’s confidence, while adaptation and mechanical strength are responsible for longevity and clinical success of the restoration. In general, adaptation is explained in terms of marginal discrepancy (MD), absolute marginal discrepancy (AMD), and internal discrepancy (ID) [7]. Holmes et al [25] described different types of measurements between the casting surface and tooth in order to determine and identify the MD in a systematic manner. The AMD is the angular combination of MD and extension flaws. The ID is the errors in the prescribed allowances between tooth preparation and inner surface of crown restoration. Poor adaptation creates high plaque accumulation and exposes the cemented region to the oral environment, which increases micro-leakage and leads to periodontal diseases. Finally, restoration loss of its mechanical stability and failures occur [8-10]. Because of their low crack tolerance, dental restorations fail in functional mode. As a result, interim restorations should have sufficient mechanical strength to resist the forces experienced during their clinical service. The mechanical performance of the crown restoration is often affected by how well the structures are bonded for stress distribution in the assembly, as uniform interface stress throughout the assembly is a key factor in restoring functional longevity.

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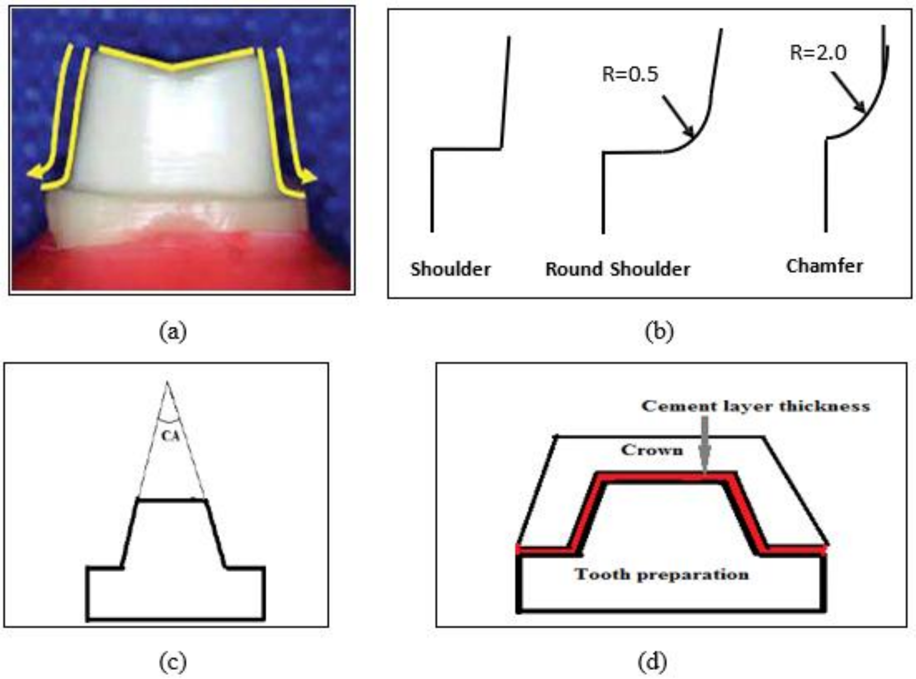

Figure 3 Fixed Dental Crown restoration process designing parameters (a) Tooth Preparation (b) Finish Lines (c) Convergence Angle (d) Cement Layer Thickness

Various studies have investigated that some factors that influence the Adaptation of the all-ceramic crown restoration. These factors are defined as finish line (FL) design, veneering firing cycles, angle of preparation or convergence angle (CA), cement layer thickness (CLT), type of cementation, and material used reportedly influence the marginal discrepancy of complete crown restoration [11-14]. The FL, CA, and CLT are designing process parameters and can be controlled during tooth preparation and crown designing processes.

Mechanical strength is another important factor that influences the clinical performance of dental crown restoration. Dental restorations fail in functional services due to their poor fracture resistance. Hence, in order to endure the forces faced during their clinical operation, the interim restorations should have adequate mechanical ability. The mechanical performance of the crown restoration also relies on how well the materials are bonded for stress delivery across the assembly; as a uniform contact stress in the assembly acts as a primary consideration in restoring functional durability. Clinical durability depends on deep, reliable bonding as well as compatibility between composite materials fabrication yield strength [15-18].

In order to prove the mechanical strength and reliability of dental materials during performance in the oral cavity, in vitro testing is essential. Conventional lab test analysis can provide material Strength details, predict the probability of failure, or equate material types, the longevity and success of dental restorations during function is still insufficient to estimate. Many difficult conditions, such as temperature, acidic or basic pH and cyclic loading, are found in the oral condition accompanying dental restorations. A significant parameter related to the mechanical strength and rigidity of the dental crown restoration is fracture strength in compression. To provide marginal consistency of crown restorations would be a complex clinical issue, disclosing edge chipping failures on preparation and marginal dental restoration fracture. CAD-CAM dental prostheses like ceramics are typically brittle materials. Awareness of the parameters for chipping such materials is critical in terms of resistance, or to evaluate failure conduct during clinical intervention [19].

Generally, all dental ceramics perform good resistance to chemical actions on the outer surface, but it varies with their materialistic properties like composition, microstructure and chemical character. Along with materialistic constituents, the chemical longevity of dental glass-ceramics may also be affected by some external ingredients like the pH of erosive agent, the duration of exposure, and the surrounding temperatures [40, 41]. A dental restoration has been performed in the oral environment comprises various challenging factors like basic or acidic pH, thermal and stress

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fluctuations [20-22]. Furthermore, the oral environment has remained one of the causes of physicochemical transformation, and temperature fluctuations in the oral environment are the root cause of the decay of glass-ceramic dental restorations. The oral saliva has a buffering capacity that can neutralize the pH of the oral domain to a certain degree. However, scarcity of inertness of ceramics, especially glass-ceramics towards acidic and basic pH of oral fluids and foods, causes corrosion and dissolution of dental restoration.

Corrosion is a persistent process that remains unnoticed in the initial phase and becomes apparent after a long duration. Although, any of the failure testing methods, either fractography, Finite Element Method (FEM) or laboratory test valid in clinic sense, has never demonstrated the failure of dental restoration due to corrosive damage but it can integrate the stresses induced during the mastication process, propagates the flaws, and provides the conditions for staining. The coarseness developed due to corrosion damages the surface of adjacent tooth [23]. Furthermore, the rate of abrasion from the surface of ceramic dental restoration depends on the quality of surface finishing as well as on resistance to the oral environment by the ceramic material used in fabrication of that dental restoration. The highly finished surface shows a lower rate of corrosion than irregular; hence the surface of restoration must be fine and polished. Experimentally, parameter corrosion is represented by surface roughness.

Clinically, hardness is another surface characteristic that determines the chemical durability of dental restoration material. The insusceptibility to localized plastic deformation due to scratches, flaws, wear, and stress developed during functional exercises can also be determined by surface hardness of the monolithic dental ceramic restorations. Although dental ceramics exhibit exemplary surface hardness, it can be affected by temperature fluctuations and pH of surrounding medium, wherein cyclic pH degrades the surface relatively more than that of static pH. Furthermore, increases in surface roughness of dental ceramic restorations due to temperature and pH cycles negatively affect their hardness.

VI. Conclusion

This review highlights the significant impact of CAD/CAM technologies on the advancement of fixed dental prosthesis fabrication. Digital workflows have addressed many limitations associated with conventional manufacturing methods by improving accuracy, repeatability, and customization of dental restorations. The literature consistently demonstrates that CAD/CAM-fabricated fixed dental crowns exhibit superior marginal and internal adaptation when critical design parameters are appropriately controlled. Finish line configuration, convergence angle, and cement layer thickness are identified as dominant factors influencing adaptation quality and long-term clinical success. Material selection, particularly the use of lithium disilicate glass-ceramics, provides favorable aesthetics and mechanical properties; however, surface degradation due to thermal and pH fluctuations remains a concern for long-term durability. Increases in surface roughness and reductions in hardness over time indicate the importance of surface finishing and environmental resistance.

Advanced evaluation techniques such as micro-CT and SR-µ-CT have emerged as reliable tools for non-destructive, three-dimensional assessment of crown adaptation, offering deeper insight into prosthesis performance. Despite substantial progress, variations in study methodologies and design protocols limit direct comparison across investigations. Future research should focus on standardizing CAD/CAM design parameters, ageing protocols, and evaluation techniques to further optimize clinical outcomes and enhance the longevity of fixed dental prostheses.

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