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Review Article

Dentistry Section

A Review of Polymer Crown Materials: Biomechanical and Material Science

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ABSTRACT

The conventional full coverage crown comes with complications such as material biomechanical complication, non- aesthetic appearance and the unpredictable longevity intraorally. Technology such as 3-dimensional printing accelerates the development of the polymer such as PEEK (Polyetheretherketone) in dentistry. Stress distribution analysis, specifically Finite Element Analysis (FEA) is one of the assessment methods to determine the suitability of the material used intraorally. The present paper focuses on the history and current usage of polymer in dentistry, potential role of polymer in full coverage crown fabrication and relevant investigations including FEA as investigation for in vitro assessment.

Keywords: Finite element analysis, Fixed prosthodontics, Full coverage crown, Polymers, Stress analysis

INTRODUCTION

1. Full Coverage Crown on Posterior Teeth

There are many reasons for placement and construction of dental crowns, which includes post root canal therapy, extensive caries and tooth fracture. The mechanical properties of a material to be selected as a dental crown should have adequate fracture resistance, compression strength, tensile strength and fatigue strength. It should closely resemble enamel and dentine's coefficient of thermal expansion and thermal conductivity capability while having pleasing, non-degradable aesthetic properties over the time. It needs to be biocompatible and should be harmless to dental soft and hard tissues [1].

Materials and technique: Historical, current perspectives and the future

The use of ceramics with refractory technique in modern dentistry started with the fabrication of porcelain denture since 17th century [2]. The original purpose of porcelain was to produce artificial teeth and their usage extended to include veneers, crowns, inlays, onlays and others. The first commercialised ceramics in dentistry was the feldspathic dental porcelain in Europe [1]. Now-a-days, the common group of material used for the construction of posterior full coverage fixed dental prosthesis are full metal crown, metal ceramic crown, feldspathic/ silica ceramic, Leucit /Lithium disilicate glass reinforced, densely sintered alumina and zirconia. Currently, there is no sole metal/ceramic system and material recommended for all clinical purposes as it depends on the clinician to choose them based on the treatment plan and aesthetic need [3]. Computer Aided Design/ Manufacturing (CAD/CAM) for fabrication of dental prostheses are widely used now due of its practicality, cost-effectiveness, quality assurance, ability to minimise the quantity of the work force and helps in introduction and testing of a new materials [4].

Clinical performance

Sailer I et al., investigated the 5-years success rate of metal ceramic single crown and full porcelain single crown with the different materials and it had shown almost comparable results, apart from feldspathic/ silica-based porcelain crown. The placement of a crown on the posterior teeth also produced near similarity in survival rate between the metal ceramic crown and full porcelain crown (reinforced glass ceramic, glass infiltrated ceramic, densely sintered alumina and densely sintered zirconia) which ranges from 87.8 to 97%. Although the high success rate ensures a predictable and good prognosis of a full coverage crown, complications can happen during and after the construction of it. Biological complications such as caries, loss of vitality, fracture on abutment teeth and biomechanical complications such as ceramic chipping, loss of retention (particularly in densely sintered zirconia) and framework fracture has been highlighted as common complication in a systematic review [5].

A brief insight on material performance in fabrication of Fixed Partial Dentures (FPDs) will be useful. Pjetursson BE et al., had assessed the biomechanical and aesthetic aspects of ceramic based FDPs, namely metal-ceramic based, reinforced glass ceramic based, infiltrated alumina based, and densely sintered zirconia based FDPs. A total of 40 studies were included in their assessment. The annual failure rate of the material varied from 1.15 percent to 2.97 percent in which the metal ceramic crown had the lowest score while the glass infiltrated alumina scored the highest. This mean the metal ceramic FDPs has the highest survival rate (94.4%) and the glass infiltrated alumina has the lowest survival rate (86.2%). From the biological complication aspects, sintered zirconia is deemed to have a higher risk to develop secondary caries. Periodontal complications are more likely to happen to a tooth restored with the glass infiltrated alumina FDPs and reinforces glass ceramic FDPs. Biomechanical complications are more frequently detected in all ceramic based FDPs. The fracture of the framework are most likely to happen to glass infiltrated FDPs and reinforced glass FDPs. Densely sintered zirconia has complications in other aspects such as delamination of ceramic, marginal discolouration and debonded restorations. Even though technologies were focused on this material for improvement, further complications are still occurring. Further investigations are needed to form a novel material with fewer complications [6].

2. Polymer Crown

Material and Technique

Polymer is a well-structured chain of molecule consisting of monomers that are linked to each other. The process of forming the polymer is called polymerization, in which monomers bond to adjacent neighboring monomers. The process is produced with the addition of polymerization and the condensation of polymerization. Polymers can be adjusted to fulfill certain required properties by the researchers. The adjustments are made by forming cross-linking thermosetting process, blending process, copolymerization and addition of plasticizers [1].

Acrylic resin was the first successful form of dental polymer introduced in the market with the advantages of being simple to manipulate, with uncomplicated manufacturing and aesthetically pleasing. Nevertheless, it also has several disadvantages like excessive polymerization shrinkage, less resistance to intraoral environment, poor adhesion to tooth structures and at times, discolouration of the tooth [7].

Currently, dental polymers in prosthodontics and restorative dentistry are more diversely used. It is used in denture fabrication and repair in the form of denture bases {Poly(methyl metacrylate)}, soft lining material and production of artificial teeth. It is also widely used as impression material in the form of hydrocolloids, elastomeric materials, polysulphide, polyether and polyvinylsiloxane. Resin composites, bonding agents and sealers are dental polymers that are important components in restorative dentistry [8].

The term *temporary/transitional/provisional restoration* has been used regularly and interchangeably in prosthodontics literature. However, temporary restoration may not be well suited according to some authors as it might resemble the nature of short-lived, an interim restoration with limited functions. It should be sharing the same properties as the permanent restoration; however it can be more desirable in term of long-term aesthetics, color stability and its longevity [9]. A provisional crown is the crown provided between the tooth preparation and issue stage of the indirect, permanent prosthesis to the patient. This crown is provided on an interim basis and is expected to last in expected time span. A longer usage of this crown will cause risks of pulpal degeneration and dentin hypersensitivity. It will provide an excellent platform to start, especially in cases where there is a need to alter the vertical dimension, develop new occlusal scheme, change the shape, contour and aesthetic component of the tooth and even gives the operator and patient a chance to assess the newly restored dentition through a prototyping try-in intraorally [9-11].

Ideal properties of provisional restoration should include excellent durability of the material and good marginal adaptation to prevent microleakage. Besides, it should also exhibit proper resistance and retention form and be able to allow normal physiological mastication process to occur, while being suitable and stable aesthetically. It should also have suitable thermal conductivity thus protecting the pulp. Other factors like being cost effective, low incidence of hypersensitivity reaction, easy retrievability and recementation, biocompatible, to allow appropriate oral hygiene practice by patient, and reasonable working properties by the operator are also important aspects of the provisional restoration [9].

The materials commonly used for provisional restoration are Poly(methyl methacrylate) (PMMA) (Duralay®, Unifast SC®, Jet®), Poly(ethyl methacrylate) (PEMA) (Snap®, Trim®, Splintline®), Bis-acryl composite Auto & Dual-polymerized (Protemp®, Quicktemp®, Luxatemp®), Urethane dimethacrylate (light cured) (Triad®), composite resin and preformed material (polycarbonate resin and full metal) [9]. A provisional restoration can be made by either using direct or indirect method. It is well established that PMMA was considered inferior in marginal strength, flexural strength and fracture resistance with risks of causing pulpal inflammation until ethyl methacrylate was introduced. This successfully addressed the problems, thus making it a better alternative for short-term provisional restoration [9,12-14].

Resin composite that can be used for a provisional restoration is divided into 3 groups namely the auto-polymerized, dual-polymerized and polymerization by light cured system. They have been proven as a superior material for provisional restoration compared to the methacrylate group as numerous authors proved that the material answered the issues arising from the lack of ideal physical and mechanical properties [12]. Laboratory studies shows that dual-polymerized group had better mechanical properties and this was proven again in randomised clinical trial comparing these 3 groups. It showed that the light-cure and dual-cure were superior in mechanical properties compared to auto-polymerized group despite poor scoring in handling properties [15,16]. For repair, the strength dropped significantly (85%) after adjustments were made, showing that it might be better to fabricate new provisional restorations if any complications occurred [13].

Although alloy and porcelain have been proven to be good materials for single and multiple permanent fixed prostheses, they still have disadvantages in terms of aesthetic, biological complications, biomechanical complications and required heavy preparation [5,6]. As such, composite crowns were investigated to be an alternative material to be used as a permanent restoration. In-vitro study showed that it had sufficient fracture resistance properties for posterior teeth with ample occlusal preparation (1.3 mm) and all around chamfer preparation (0.5 mm) which was considered more conservative [17,18]. The results from a study showed that although a 5-year survival rate was as high as 88.5 percent, the material still suffered from problems such as plaque retention which cause gingivitis [19]. In addition, previous studies showed that it also had a significantly wear rate worse than metal ceramic even though it had been reinforced with glass-fibre network [20]. Other complications such as delamination, loose crowns and the need for root canal therapy were also proven in the study [21]. The authors concluded that the material was only suitable for long term provisional restoration purposes.

Polyether Ether Ketone (PEEK) is a semicrystallized thermosoftening polymer network derived from the Polyaryletherketone (PAEK) group. It is widely used in the medical field where it has been discovered as an excellent option to titanium in orthopaedics [22]. In dentistry, the research and application of PEEK is extensive, including being used as a dental implant, provisional abutment, obturator, denture base, clasp for dentures and others due to its good biological, mechanical, aesthetic and handling properties [23-28]. Laboratory studies evaluating the mechanical properties had been promising as it shows the fracture resistance of this material is comparable to that of zirconia and performed better than lithium disilicate in multi-unit fixed prosthesis [28]. PEEK surface modification achieved with acid etching and abrasion is required to improve bonding with the dental luting cement [28-32]. The introduction of Barium containing glass filler to the material also showed similar result [33]. The promising potential of this material warrants more studies to be carried out with more systematic and detailed clinical trials which is currently lacking.

STRESS DISTRIBUTION THROUGH THE RESTORED TOOTH-CROWN COMPLEX AS A DETERMINANT OF CLINICAL PERFORMANCE

1. The Importance of Stress within the Tooth-crown Complex and the Clinical Implications

Studies on ceramic dental material show that although the survival rate for both materials is at an acceptable rate, they still suffer from multiple reasons of failure, namely the ceramic fractures and framework fractures [5,6]. This need to be addressed as it will be beneficial for long term prognosis of the restored tooth.

Rekow E et al., highlighted 2 main determinants that can play critical roles in ensuring the success and predictability in long term prognosis, which are clinician and patient based. The clinician will influence the prognosis with factors such as the amount of tooth preparation and reduction, amount of area covered by cement space, the type of material and luting cement selected for the restoration and the addition of core buildup and/or root canal treated teeth. The patient dependent factor includes the location of the tooth (incisor/molar/etc.,), remaining tooth structures, geometrical calculation of dentition and occlusal force [34].

Masticatory performance can be defined as the ability of a person to achieve satisfactory disintegration of food consumed. The experiment to test this performance is often based on the ability of the participants to disintegrate the tested food within a predetermined number/cycle of mastication. There are many ways for the assessment of the performance, including patient-based questionnaires and self-assessment, evaluation on the food particle (colour etc.,) and food fragmentation sieving method. The factors involved in masticatory performance include presence and condition of post canine tooth, occluding units of tooth, bite force, malocclusion, sensory innervation, tongue motor function, movement of masticatory muscles, salivary flow rate and others. The two most important components for masticatory performance are the bite force and numbers of preserved dentition which exist intraorally [35,36].

It was further explained that the maximum bite force exhibited can influence the masticatory performance in a positive way. There is evidence that mention, that the higher maximum occlusal force produced, the higher masticatory efficacy is achieved [37]. The highest occlusal force in normal dentition involves the posterior region namely the premolar and molar teeth [38-40]. The recorded maximum bite force is around 300-500 Newton (N) and the calculation of occlusal forces in the molar area involves an estimated 300-600(N) unilaterally in normal patients with natural dentition [41,42].

2. Different Methods on Analysing the Stress Distribution

One of the earliest equipment used to measure stress/strain relationship of the material tested is strain gauge unit historically. Photoelasticy has been known as a reliable method in assessing stress/strain and has been proven successful in evaluating the stress generated in dental structures and materials since late 1940's [43]. It is based on the principle of the defragmentation of light wave. Although the 2-dimensional photoelasticity is well known for its easiness, the 3-dimensional approach has been suggested to be used in the field of dentistry due to variation of anatomy and configuration aspect [44]. A better understanding in cavity designs and preparations by direct and indirect restorations has been achieved with the use of this technique previously [45,46]. An earlier study done by using the 2-dimensional approach drew several key points in crown fabrication of the posterior teeth. Craig RG et al., detected the highest compression and tensile stress area on the prepared lower molar, and thus highlighted several important points on how to prevent the failure of restorations, including the importance of contact points, avoidance of grooves construction and suitable shoulder finish line [47]. A 3-dimensional photoelasticity study on the full posterior crown later revealed that the minimum amount of shear stress can be achieved by producing the chamfer finish line [48].

A Finite Element Analysis (FEA)

- **The basis, historical perspectives and current development**

FEA is an algorithm study to calculate the nature and behaviour of the material and can be used to predict the performance of the material upon application of physical load on it. It is based on a complex mathematical equation which calculates and combines the small equation and fragmentation of the subject, then connect it to become a much larger field to represent the whole subject. The relevant field that uses this method includes mechanical engineering, automotive, biomedical, aerospace and many more [49]. The FEA research was developed earlier by using 1-dimensional and 2-dimensional method to answer the question raised in the field of aeronautic, structural engineering and others. Its purpose was mainly to answer the problems of heat propagation, stress and strain relationship of material, deformation of subjects, structural investigations of building construction and others. The research about this field was focused on the work of Clough and Wilson from the University of Berkeley [49]. Now, it has become one of the main knowledges in engineering with the help of the advancement of the super computer and modernised state-of-the-art development tools in the form of software.

The advantages of the FEA is mainly thorough the applicability of this method to be used on material or subjects that have variation in terms of shape, volume, structure and other aspects. The heterogeneity of the subjects with complex geometric does not limit the method in analysing the behaviour of the material upon application of any form of stimuli on it. This can be achieved by the usage of new non-linear, 3-dimensional approach of this method. The calculation is very specific and highly accurate, too. The varying effect of complicated stimuli such as temperature changes, fluid dynamic and heat transfer and propagation also can be applied.

However, this method is time consuming as the researchers needs to spend vast amount of time in the laboratory to recreate the model that can replicate as close as possible to the exact subject. This method requires suitable processing equipment as well, since it involves the usage of a supercomputer and specific software for example CATIA and CASTOR [50].

- **Full coverage crown and its principles**

Due to the increasing demand for more aesthetic and metal free restoration, the all ceramic crown had been used extensively for the FEA study to maximise their capability and potential. In the earlier key study by Hojjatie B and Anusavice KJ, the investigation of the influence of directional simulated force to the amount of stress generated within the tooth crown complex by using 3 dimensional FEA was looked. The study concluded that the directions of load were more important than other aspects, for example tooth reduction and occlusal thickness for crown fabrication. The limitations of the study were that the materials used were considered homogenous, so it did not reflect the variation in the shape and contour of the crown. Other aspects such as periodontal ligament effect and cement interface were not validated. The crown also had no veneering porcelain and it was assumed that the fabrication of the crown is perfect without any processing defect, too [51].

Imanishi A et al., studied stress distribution on all ceramic crown for posterior dentition. In this study, the horizontal loading force produced the highest stress at occlusal and cervico-buccal area while the vertical and 45 degrees loading were less than that, which is the same finding mentioned previously. This proves that the fabrication of the crown needs more attention on the occluding point and cervical area regardless of the layering technique. This is more significant especially to the patient that suffers from parafunctional habit such as bruxism so as to prevent tooth-crown complex fail catastrophically [52].

Jager N et al., assessed the CAD-CAM produced full ceramic crown and the author tried to distinguish between the effect of the crown preparation principles and luting cement's interface on stress analysis of the tooth crown complex. The study measured 3 related stress involved, which are the occlusal simulated forces (665N), forces separated by different layers of material due to the difference in thermal of coefficient expansion and stress developed by cement polymerization during the setting phase. The author found that primarily no relation of stress distribution with different occlusal thickness within the tooth crown complex was evident. He also found that in the posterior crown, chamfer with collar finish line is better tolerated than chamfer with knife edge finish line. The uniform distribution and consistent thickness of the luting cement were needed to avoid shear stress overloading and coefficiency of the thermal expansion between two different ceramics during veneering porcelain should not produce too much difference to prevent tensile stress from developing rapidly. The study concluded that the zirconia core performed better than alumina and gold. He derived a conclusion that if the construction of the dental core is a must, the core must be selected based on suitable properties and must complement the properties of materials used in the veneering process. A selection of higher strength and more rigid dental core does not necessarily reduce the unnecessary stress exerted on the crowned tooth [53,54]. Rafferty BT et al., concluded that the most important factors that can increase the stress within the tooth crown complex were the increasing thickness of the luting cement and horizontal direction of the biting force. He suggested that multiple factors needed to be considered in the fabrication of the posterior crown construction if the aim was to reduce the highest stress. This way the experiment could be translated and applied in daily life [55].

- **Methods used in current FEA in restorative dentistry**

The FEA study requires the development of a tooth model before it can be assessed. The reproduction of a model that can mimic a real normal human tooth with regard to simulated oral structures (periodontal ligament) and environment (normal physiological mastication) is extremely challenging. The method used previously involved digitization of the human teeth for remodeling which has several disadvantage including high complexity of recreation modelling with various factors to be considered, time consuming and even easier modification done to the model might introduce errors. Magne P recommended the use of the multiple step approach that were meticulously designed to reduce the risk error. He recommended the use of a micro computerise scan (Micro-CT scan) and an interactive Medical Image Central System (MIMICS) with REMESH module for the imaging, scanning and development of the mesh network. Then the refinement of the Mesh Network will be done using specialised software (MAGICS 9.0) to ensure the suitability of the shape and angle of the mesh network to the tooth. The final step is to upload the established model with the refine mesh network to be uploaded into a specific FEA software. The advantages of this approach are: generally quicker and less time consuming, highly accurate for example of anatomy reproduction in remodelling, flexibility in adjusting the model according to the specific test that will be used and more convenient. However, the researcher must have a proper access to the specific devices such as micro-CT scan and the specific software with proper training and calibration [56].

- **Review of FEA study with full coverage (all ceramic and polymer) crown**

Full metal crown had been associated with durability and longevity intraorally. An FEA analysis study showed that the stress distribution on Stainless Steel Crown (SSC) can withstand normal functional masticatory forces even with minimal residual tooth structure left [57]. On a monolithic dental ceramic crown, the stress distribution needs to be analysed systematically to prevent fracture under normal simulated physiological mastication due to ceramic brittleness. High flexural, shear and tensile stress were detected on the wall and the margin of completely bonded monolithic ceramic crown [58]. The cusp angle also plays a pivotal role in which the high inclination of all ceramic crown will generate highest stress compared to middle and low incline crown [59]. Multiple studies comparing the stress distribution between all ceramic crown and polymer-ceramic crown, the result showed almost comparable result. The CAD-CAM polymer-ceramic crown blocks can withstand normal simulated physiological mastication without conventional complication associated with all ceramic crown and thus can be suggested as an alternative [60,61].

CONCLUSION

Polymer-ceramic derived crown had been proven as an alternative to conventional all ceramic crown. The novel monolithic polymer crown with the example of PEEK material shows promising potential of being used as the new material for fixed prosthesis, as it is predicted to fulfil the functional demand to be used as a crown material especially on the posterior tooth. After all, a robust laboratory investigation such as FEA followed by clinical trial is required to ensure a smooth transition of the material from the laboratory, in-vitro data to be used and applied in our daily dental practice.

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