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CHAPTER 1

AN EXAMINATION OF ARTIFICIAL INTELLIGENCE USE IN DENTISTRY

Suzan CANGÜL

Özkan ADIGÜZEL

AN EXAMINATION OF ARTIFICIAL INTELLIGENCE USE IN DENTISTRY

Accessibility to technology has become extremely easy with the use of tablets, smartphones and other mobile devices, and this has caused a change in the cultural structure of society. Terms such as "digital transformations" and "digitalised workflow" are markers of living within technology. Together with these developments, artificial intelligencce (AI) has started to occupy a greater place in daily life (Joda et al., 2020).

AI is the ability of a machine to mimic human intelligence, identify objects and words, and to undertake complex tasks such as solving problems and making decisions (Lin, Huang, and Huang, 2017; Lee, Kim, Jeong & Choi, 2018). AI enables computerised models to perform a task rationally. It is examined in three forms; machine learning, representative learning, and deep learning (Şener & Şen, 2022).

According to Barr and Feigenbaum, AI is a computer system designed to associate human behaviours with intelligence, which exhibits language understanding, learning, reasoning, problem-solving, and many other features. There are many sub-categories related to areas of AI. These are formed from machine learning and deep learning, cognitive calculation, natural language processing, robotics, specialist systems and fuzzy logic (Barr, Feigenbaum, and Cohen, 1981). AI models predict future events from exisiting observation clusters (Schwendicke, Samek, & Krois, 2020).

In the 1950s, Alan Turing and John McCarthy laid the foundations of AI, defined as computerised synthetic human cognitive function (Heo et al., 2021). Despite the long time since first emergence, developments entered periods of stagnation in 1973-1980 and 1987-1993. At the end of the 1990s, AI started to come to the fore again with Deep Blue beating the world chess champion, Gary Kasparov (Campbell, Hoane Jr & Hsu, 2002). In the recent stage of technological advancement, AI is used in healthcare in diagnosis and results evaluation, which has increased the success of treatment outcomes of healthcare professionals.

AI systems, which are defined as a set of procedures to perform a certain task, have historically followed hand-prepared rules to be able to reach a solution. According to the area of each procedure to be applied, specialists and engineers make manual adjustments down to the finest details. For example, a system designed to be able to differentiate abnormally coloured nodes on medical imaging must have recorded potential tumour sizes and healthy tissue colours to be able to do this (Mueller & Massaron, 2021).

The route to understanding AI is through thoroughly learning concepts such as machine learning, neural networks, and deep learning. The term "machine learning", first used by Simon Cowell in 1959, predicts the outcome based on data clusters provided with the help of algorithms such as synthetic neural networks (Bowing et al., 2006). The basis of AI is formed of algorithms created from certain repetitions to easily solve a mathematical problem. These algorithms examine a lots of manually entered data and are trained to then provide a correct response by fully conceptualising these (Akdoğan & Özdemir, 2024). The learned information is then applied to new cases encountered. As a result, the main advantage of machine learning is that it increases learning levels using an extensive database formed from new images and further develops newly designed AI models (Albayrak, Özdemir, Us, & Yüzbaşıoğlu, 2021).

Deep learning, which uses multi-layered artificial neural networks, is a sub-branch of machine learning. These neural networks are formed of an input, an output, and intermediate hidden layers. At this point, the system not only learns a design but attempts to learn designs which can be combined and added to each other (Nguyen, Larrivée, Lee, Bilaniuk & Durand, 2021). This system, which is used in image analysis, is used especially in dental radiology. It has high accuracy rates in the identification of dental caries. Analysis of radiographic images greatly facilitates diagnosis for dental practitioners (Chen, Stanley, and Att, 2020). An increase in the rate of clinical accuracy also accelerates the treatment process.

As multi-layered artificial neural networks are produced from very large data clusters, this renders them very productive. It has been shown that AI models which can be trained with hundreds of thousands of clinical cases can produce more successful results than specialists. In dentistry, benefit has often been gained from newly established convolutional neural network (CNN) models (Saglam et al., 2021).

In the field of dentistry, AI is used in disease diagnosis and treatment planning, in the determination of small details which would not be visible to the naked eye in imaging methods, and as virtual assistance (Türk Akbulut, 2025). Taking more objective and correct decisions, especially in clinical procedures, helps to make objective evaluations and save time by supporting the workload. Developments in analytical methods and the ease of access to all types of health-related data are a marker that AI will become indispensable in healthcare in particular (Jiang et al., 2017).

Artificial Intelligence Applications in Oral and Maxillofacial Surgery

Robotic applications are at the forefront of AI in oral and maxillofacial surgery. However, high costs and difficulties in application constitute problems in this subject (Bas et al., 2012). Of the surgical procedures performed, extraction of the third molar tooth is one of the most frequently performed procedures.

Determination of anatomic location markings is of the greatest importance in preserving the anatommic structures and shortening the operation time. AI algorithms provide this determination (Widmann, 2017).

AI is used in the prediction of both oedema and the risk of complications that may develop after tooth extraction and the degree of difficulty of treatment. Zhang et al. found that an AI model developed for this purpose had 98% accuracy in rspect of facial oedema occurring after extraction of mandibular 3rd molar teeth (Zhang, Li, Li & Li, 2018). Orhan et al. used AI in the determination of the relationship of 3rd molar teeth with anatomic structures, and accurate results were obtained at the rate of 86.2% (Orhan et al., 2021). In addition, AI deep learning models have predicted extraction difficulty at an accuracy rate of 67%, and the complication risk and difficulty of treatment at 80% (Wei, Peng, Li & Wang, 2018; Yüce & Taşsöker, 2023)

Early diagnosis is of great importance in the diagnosis of oral cancers, but there are generally few early stage diagnoses. Using AI, Rosma et al. reported an accuracy rate of 59.9% for the possibility of intra-oral cancer development, which was consistent with specialist views (Rosma, Sameem, Basir, Mazlipah, & Norzaidi, 2010). It has been predicted that AI will reduce morbidity and mortality rates, especially in regions where healthcare services are insufficient (Ilhan, Lin, Guneri, & Wilder-Smith, 2020).

AI is used in implant treatment planning, determining bone quality, bone height, surrounding anatomic formations, the diagnois of tempero-mandibular joint diseases, and determination of the inferior alveolar nerve branch (Sağlam et al, 2021). Early and correct diagnosis of diseases will be facilitated with the development of these systems.

Artificial Intelligence Applications in Endodontics

Radiographs and their interpretation are of great importance to endodontists in respect of treatment planning. Multi-layer CNNs facilitate the analysis of x-ray images using AI.

Another feature of AI is that it can identify morphological abnormalities and discover new canals which are often encountered in endodontics. Using a CNN method, Lahoud et al. (Lahoud et al., 2021) made 3-dimensional tooth segmentation automatically. To investigate whether or not AI was as effective as a human, 433 CBCT radiographic segmentations were examined and it was concluded that AI was as good as a human operator in respect of performance and was much better in terms of speed.

AI provides dentists with clear informationn about which treatments are necessary. In the scope of areas of use in endodontics, subjects have been examined including being of assistance in diagnosis, determination of root fractures and periapical lesions, correct calculation of canal length, determination of the location of root canal entry, and evaluation of pain after treatment (Güneç, 2023).

Of these, programs that can provide diagnostic support are the area in which AI can provide the best results. A correct diagnosis allows the practitioner to overcome many problems that can occur at the stage of treatment planning. In addition, clear observation of the root canal anatomy is extremely important for treatment success, so 2 and 3-dimensional radiographic systems are used for this purpose. However, in some difficult root canal entries, the use of AI is required to facilitate the procedure. In studies by Choi et al. using AI to determine root canal entries, sensitivity values of 94% were obtained (Choi et al., 2019). That AI also predicts C-shaped canals, seen especially in mandibular second molars at an accuracy rate of 95%, significantly alleviates the severity of treatment. Therefore, it is expected to increase the success rates of endodontic treatments (Yüce & Taşsöker, 2023).

Acccuracy rates of 78% have been reported with CBCT imaging used in the determination of root fractures, while in evaluations using AI, Fukuda et al. found this rate to be 93% (Fukuda et al., 2020). Thus it will be possible to avoid the extraction of healthy teeth and unnecessary interventions to teeth that cannot be treated (Akdoğan & Özdemir, 2024).

Although it provides many advantages, the use of dental volumetric tomography (DVT) is limited to cases where it will affect treatment planning and prognosis because of the high radiation exposure for patients compared to 2-D imaging (Low, Dula, Bürgin & von Arx, 2008). In the future, together with the development of 3D imaging systems which will reduce the radiation dose, studies coud be conducted to investigate how effective segmentation methods are in respect of healing after treatment (Şener & Gürses, 2023)

Artificial Intelligence Applications in Pediatric Dentistry

When the areas of use of AI in dentistry are examined, it can be seen that pedodonti is the area of least use. But in the future, this area has the potential for applications that will change many things. This design model will be able to facilitate paediatric dentistry in the future in terms of aesthetics and time-saving (Kurup, Sodhi, & Sangeetha, 2020).

Previous studies have reported that AI could play a role in pedodontic applications without injections for provide pain control, predict the size of unerupted premolar and molar teeth in the mixed dentition period, and in early orthodontic applications with specific instruments prepared with AI (Baliga, 2019).

Another area of use in pediatric dentistry is that extra teeth can be overlooked when the dentist is not sufficiently experienced. With the help of deep learning models, AI facilitates the screening of extra teeth in these cases. Thus, AI is important in the diagnosis of mesiodens (Fisher-Owens et al., 2007).

Clinical and radiological examinations are used in chronological age evaluations of children and adolescents. However, these methods may not always provide correct results. Although clinical evaluation can be performed quickly, there is a high probability of incorrect results. Therefore, AI neural modelling used for this purpose is an important option for dentists as it is accurate and reliable (Tuzoff et al., 2019).

Taking the oral dental health and treatment requirements of children into consideration, AI algorithms are expected to be helpful in the preparation of remedial programs. There is also a need for the development of AI for education programs for the parents and paediatric patients (Jung & Kim, 2016).

Artificial Intelligence Applications in the Treatment of Prosthodontics Teeth

Computer-assisted design (CAD) and computer-assisted manufacture (CAM) applications are frequently used in the field of prosthetics. AI has been combined with CAD/CAM to further improve patient applications. AI CAD/CAM eliminates deficiencies in data collection and manufacturing, and minimises the probability of errors that could occur (Tandon, Rajawat & Banerjee, 2020). For the dentist to be able to design aesthetics completely in the best way and to be able to motivate the patient, post-treatment face profiles should be simulated. Virtual reality simulation (VRS) technology is used for this purpose.

AI, which has replaced traditional prosthesis moulding methods, is used in many areas such as digital smile design, removable and fixed prosthesis planning, and colour selection. Especially in terms of providing the desired aesthetics, colour selection is extremely important. Compared to the visual method, the use of AI in this area provides more successful results (Schwendicke et al., 2020). Previous studies with measurements and calculations made in the face region have shown that aesthetic expectations can be met at a high rate (Vera, Corchado, Redondo, Sedano & Garcia, 2013). The reliability of AI algorithms with efficacy proven at a certain rate will be able to be further proved with future studies.

To facilitate the image integration process in the digital smile design technique, a system has been formed which automatically combines facial and intra-oral images using AI (Li et al., 2020).

Artificial Intelligence Applications in Periodontology

As in the other areas of dentistry, the use of AI in periodontology has increased. Alveolar bone loss and changes in bone density can be determined with AI. It has also started to take an important place in the evaluation of the prognosis of teeeth that are periodontally unhealthy, in implants and surrounding tissues, and in the diagnosis of halitosis. In the future, different parameters should be added to AI applications that are used to help clinicians in addition to radiography when there is intense patient traffic. This is because the mobility status of the teeth, smoking status plaque control, and pocket depth are markers used in the diagnosis of periodontal diseases (Atalay, Balcı & Toygar, 2023).

Wth the development of regional CNNs in AI applications, diagnosis can be made more easily with fewer data. Lee et al. used CNNs in the determination of teeth with a poor prognosis because of periodontal problems, and reported an accuracy rate of 78.9% (Lee et al., 2018). In another study, three periodontologists examined 100 radiographs in respect of periodontology and found that this application could determine teeth with a poor prognosis at the rate of 81% (Thanathornwong & Suebnukarn, 2020). Alveolar bone loss was evaluated with AI on periapical radiographs in another study, and no significant difference was determined between the AI model and dentists (Cha, Yoon, Yeo, Huh & Han, 2021). Krois et al. compared the evaluations of periodontal bone loss of CNNs and 6 dentists and the results showed that the CNNs had a higher rate of accuracy (Krois et al., 2019). AI is also used in implant planning, and measuring bone loss around the implant and the severity of peri-implantitis

(Cha et al., 2021). Researchers have reported that AI-assisted studies by dentists would be of great help.

The preservation of oral hygiene is an extremely important subject in the field of periodontology. The primary activity for this is effective tooth brushing. An in-vitro study found that tooth brushing with an AI-based robotic system provided results as good as with manual brushing (Ahmad et al., 2021).

Artificial Intelligence Applications in Orthodontics

There is a very extensive area of use for AI in orthodontics. For good orthodontic treatment, there must first be correct diagnosis and treatment planning. Together with the development of AI systems, it is predicted that there will also be developments in evaluations such as orthodontic treatment planning, digital measurements, radiographic analyses, facial appearance after orthognatic surgery, and treatment requirements. It is extremely important that these systems themselves are not seen as competition for clinicians but as support. It is an application that will save time by shortening the working time (Akar & Şirin, 2023).

There are AI-supported patient monitoring applications that provide remote observation of malocclusion treatment in orthodontics. These applications allow patients who live far away or who have a very busy life to be followed up without visiting the clinician. Patients first scan the teeth and the images are sent to the clinician by telephone. Then, using AI programs orthodontists give feedback and problems that could develop in the future can be overcome (Caruso et al., 2021; Sosiawan et al., 2022).

Othodontics requires cephalometric analyses to be performed reliably on a computer. To eliminate human error and to complete the procedures to be performed in the shortest time, researchers plan to produce more technological programs in which the points required for the analyses to be performed would be determined by the computer. AI development has contributed to the realisation of this plan. This has been done using programs such as AudaxCeph, OrthoDx, WebCeph, WeDoCeph, and CareStream Imaging. Thus, the marking of cephalometric points and analysis calculations have been performed automatically (Hezenci & Bulut, 2024)

In addition to these applications, 3D CBCT craniofacial images have been of use for AI to automatically identify and classify skeletal malocclusion. Kim et al. recommended a deep learning system to determine the best treatment method for patients (Monill-González, Rovira-Calatayud, d’Oliveira & Ustrell-Torrent, 2021).

Another point is that bone age estimation can be performed quickly with the use of AI, especially in children and adolescents (Kim et al., 2021). AI is also useful in smile aesthetics, the evaluation of patient co-operation, and classification of orthodontic photographs (Türk Akbulut, 2025). AI has emerged as a technology that significantly lightens the workload of clinicians in diagnosis and treatment.

Artificial Intelligence Applications in Restorative Dentistry

The aesthetic expectations of patients have led to continuous advances in restorative dental treatment. Areas of use of AI have also started to increase with the development of technology. To be able to use these systems in the most effective way, there should be systematic categorisation of AI performance and limitations. AI is used especially in the determination of dental caries and tooth fractures, in establishing the limits of preparation, and in predicting restoration failure (Hung et al., 2020).

The number of publications related to AI in restorative dentistry has shown a great increase in the last two years compared to previously (Revilla-Leon et al., 2022). In a review that examined 29 studies in which dental caries were determined with AI, the correct diagnosis rates were found to be 76%-88.3%. The reason that AI is important in the determination of caries is that it is rapid and reliable. Determination of caries at the early stage allows the treatment to be less invasive, thereby reducing the workload and directing the clinician to other aspects of patient care. The potential benefit to clinicians on this subject is very high (Azhari, Helal, Sabri & Abduljawad, 2023).

In another study, it was attempted to find the preparation lines with AI technology and the accuracy rate was reported to vary betweeen 90.6% and 97.4% (Alqutaibi & Aboalrejal, 2023).

Artificial Intelligence Applications in Oral and Maxillofacial Radiology

The first use of AI in dentistry was in 1991 by Mol et al. with the determination of periapical bone lesions on dental radiographs (Mol & Van der Stelt, 2002).

Two-dimensional, three-dimensional, and advanced imaging techniques are used in the field of dentistry radiology. The data obtained from these methods constitutes a great resource for AI (Leite et al., 2021). The more widespread use of CBCT has led to an increase in studies related to the development of AI models. Long-term studies have shown increased interest in AI in dentomaxillofacial radiology (Hung et al., 2020).

AI has great potential for the determination and identification of anatomic structures. The use of this method, which has shown sensitivity of 95.8% -99.45% in the determination of teeth on periapical radiographs, is not limited to this alone but has also shown 75.5%-93.3% accuracy in the diagnosis of dental caries. In the determination of vertical root fractures and extra roots on panoramic radiographs, AI has shown 86.9% accuracy and 98.9% sensitivity (Grischke, Johannsmeier, Eich, Griga & Haddadin, 2020). This increases the diagnostic success of clinicians (Nguyen et al., 2021). In addition, AI has been successfully used in many other areas such as root morphology, pulp calcification, follow-up of growth development, evaluation of bone quality, classification of maxillofacial cysts and tumours, and the diagnosis of periodontitis and osteoporosis (Yüce and Taşsöker, 2023).

Conclusion

Significant advances have been continuously recorded in the use of AI in dentistry. Increased use of patient data will provide an acceleration in research in the areas of AI, machine learning, and neural networks. In the future, AI technology will be able to provide more definitive results in the diagnosis, classification, and treatment of diseases. Therefore, the evaluation and results of clinical performance of AI models should be supported with further studies. With greater and more accurate use of AI, digital techniques will replace traditional techniques in the future and this will provide greater access for patients.

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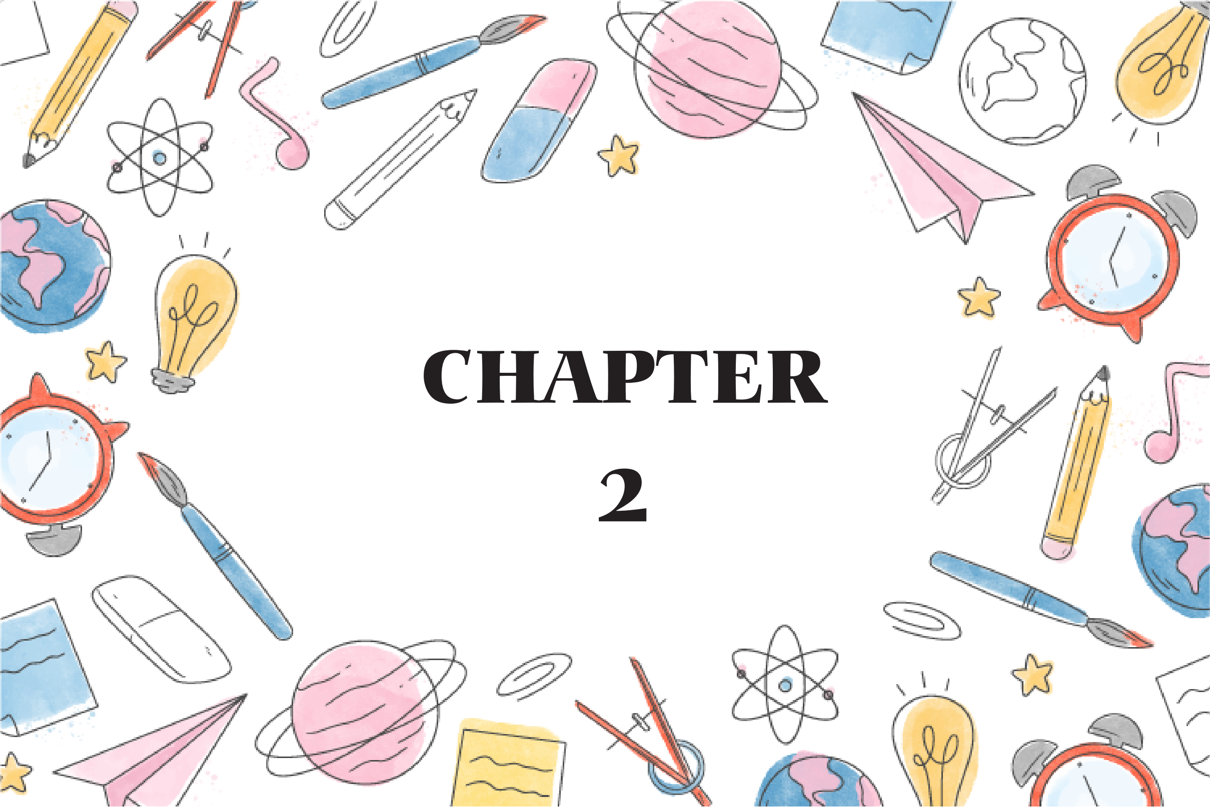

CHAPTER 2

PERI-IMPLANT DISEASES AND TREATMENTS

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1.INTRODUCTION

Dental implants are nowadays a widely preferred treatment method due to their functional and aesthetic advantages in the compensation of missing teeth. However, the long-term success of implants is not only limited to the success in the surgical and prosthetic stages, but is also closely related to the biological compatibility with the surrounding tissues and the continuity of health. Peri-implant diseases are clinical pictures resulting from inflammatory processes occurring in the hard and soft tissues around the implant. These diseases, which are generally associated with microbial plaque, can be analysed under 2 main headings: peri-implant mucositis and peri-implantitis. Peri-mucositis is reversible and limited to soft tissue and peri-implantitis is characterised by progressive bone loss. In this study, the definition and history of dental implant, differences and similarities with a natural tooth, imaging methods, indications and contraindications of dental implant treatment, complications that may be encountered, peri-implant tissue diseases, diagnosis, risk factors, microbiology and treatment methods are discussed (Berglundh et al., 2018).

2.DENTAL IMPLANTS

2.1 Similarities and Differences between a Natural Tooth and an Implant

Although implant is the most preferred treatment for the replacement of missing teeth today, the biggest reason for the failure of this treatment is the absence of the periodontium consisting of alveolar bone, gingiva, periodontal ligament and cementum, which is present in an anatomical tooth and provides support to the tooth.

Galgali et al. In 1961, in a study on cadavers, they reported that there was 1.04 mm thick connective tissue above the alveolar bone and 0.97 mm thick junctional epithelium above it. These two structures are expressed as biological width with an average thickness of 2 mm (Galgali & Gontiya, 2011). The biological width is a critical agent that ensures the healthy retention of teeth in the mouth and the protection of tissues (Rajendran et al., 2014). Since the biological width around implants is increased compared to teeth, a greater sulcular depth is observed around an implant compared to an anatomical tooth.

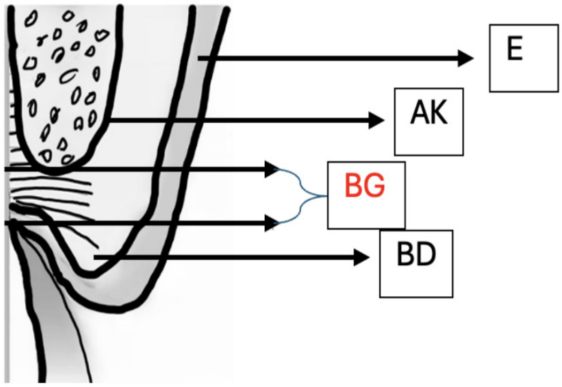

FIG.1: *Elements of Biological Width AK: Alveolar bone, E: Epithelium, BD: Connective tissue, BG: Biological width (Cochran et al., 1997)*

The connective tissue in a natural tooth has more mechanical resistance than the connective tissue around the implant. The number of vessels providing nutrition is higher in a natural tooth compared to the implant root. This is because the flap opened and bone tissue removed during the placement of the implant into the bone leads to a decrease in the number of vessels. When exposed to bacterial infections , the possibility of tissue damage is higher in implants. In the probing method used to detect an inflammatory condition, bleeding is more easily observed in an anatomical tooth, while bleeding around the implant is less likely to be observed.

The gingival groove fluid is richer in the number and type of complement system mediators than the peri-implant groove fluid. Therefore, a natural tooth responds more rapidly to a possible inflammatory situation (Hatpoğlu & Programme, n.d.). In addition, the fact that the implant does not contain periodontal ligaments causes the stress on the tooth to be concentrated on the bone and consequently bone loss. In other words, the incidence of peri-implantitis around the implant is higher than the incidence of periodontitis in a natural tooth.

2.2 Imaging in Dental Implantology

The gold standard imaging method generally preferred in implantology is cone beam computed tomography (CIBT/CBCT). Due to its disadvantages such as longer irradiation time, thicker sections, higher radiation dose, conventional CT/CT (computed tomography) has been replaced by cone beam computed tomography (CIBT/CBCT), which allows examination of a larger scale with less radiation dose and cost. Periapical radiographs and panoramic radiographs can also be utilised. Periapical radiographs allow accurate measurements in a limited area with low radiation dose and low cost. Panoramic radiographs help to start planning in the right direction and to understand the relationship of the maxilla and mandible with the surrounding tissues. However, it should be kept in mind that these imaging modalities are two-dimensional and may mislead the physician unless three-dimensional imaging is available. In addition to these imaging modalities, occlusal, bite-wing, cephalometric and magnetic resonance imaging (MR) imaging can be used as conventional imaging modalities and advanced imaging modalities, respectively.

2.3 Indications and Contraindications of Dental Implant Treatment

An ideal planning is necessary for an ideal implant. Before the surgical operation of the implant, the patient should be examined in detail from all angles, and the number and material of the implant should be determined by considering the anatomical and social conditions of the patient. Each patient should be evaluated individually and treatment planning should be personalised. Damage to neighbouring anatomical structures during the manipulation of the implant may result in a decrease in the patient's quality of life or even death. Some structures that should be considered during the operation are as follows:

- -Maxillary sinus
- Nasopalatine duct
- Canalis sinuosus
- Posterior superior alveolar artery and nerve
- Mental foramen
- Incisive canal
- Lingual foramen
- Lingual channel

Dental implants are preferred according to various clinical conditions in patients with missing teeth.

- In **single** tooth deficiencies, the missing tooth can be replaced with implants without interfering with neighbouring teeth.
- In cases of partial edentulism, implants offer both functional and aesthetic advantages in fixed prosthesis construction.

In complete edentulism, implant-supported overdentures can be used to increase the stabilisation of total dentures.

Implants can also act as a support element to improve prosthetic retention.

Implants are also effective in preventing advanced bone loss by contributing to the preservation of bone in resorbed alveolar crests (Özcan et al., 2015).

Implant applications may not be appropriate in all cases. Therefore, systemic and local factors should be meticulously evaluated.

Systemic contraindications are mainly the following:

- Uncontrolled diabetes may adversely affect the osseointegration process of the implant by slowing wound healing.
- Serious psychological disorders may negatively affect the patient's compliance with the treatment process and oral hygiene and may reduce success (Büyükakyüz & Darwısh, 2013).
- Immunosuppressive diseases and treatments may decrease the success of the implant by increasing the risk of infection (Kürkçüoğlu et al., 2010).
- Patients with coagulopathy (bleeding disorders) have a high risk of complications during surgery.
- In individuals undergoing active cancer treatment, chemotherapy and radiotherapy may inhibit implant healing.

Local Contraindications can be listed as follows:

- Inadequate bone volume may be insufficient to provide primary stability of the implant and may require grafting.
- Parafunctional habits such as bruxism (clenching) can lead to mechanical complications by placing excessive load on implant and prosthetic components (Kürkçüoğlu et al., 2010).
- Active periodontal disease is a risk factor for peri-implant tissues; it should be controlled before treatment.
- Smoking increases the failure rate by delaying the fusion of the implant with bone (osseointegration) (Özcan et al., 2015).
- Poor oral hygiene increases the risk of peri-implantitis and can lead to implant failure.

2.4 Complications that may be encountered in Dental Implantology

According to the timing, it is classified into three groups as perioperative, early postoperative and late postoperative.

2.4.1 Perioperative Complications

Complications that may occur in the perioperative period include conditions that occur during surgical intervention. One of the most common problems is excessive bleeding or haematoma formation due to damage to vascular structures. If important structures such as the inferior alveolar nerve or the mental nerve in the posterior region of the mandible are damaged, the patient may develop temporary or permanent sensory loss. In the maxillary region, perforation of the sinus membrane is an important complication that may cause sinusitis in the future. In addition, failure to ensure primary stability of the implant in patients with insufficient bone quality and volume is another problem that may be encountered during surgery (Reasons for Early and Late Loss in Dental Implants, n.d.)

2.4.2 Early Postoperative Complications

Early postoperative complications usually occur in the first weeks following the operation. In this period, infection is one of the most serious problems that may threaten the integrity of the implant. This risk increases if proper sterilisation is not provided or if the patient's systemic condition is predisposed to infection. Postoperative pain and oedema is usually a physiological process; however, in extreme or prolonged cases, a pathological condition should be suspected. However, problems such as premature opening of the sutures or inadequate closure of the wound site can also be seen during this period. In cases where stabilisation is not adequate, the implant may become mobile, resulting in early loss of the implant (URVASIZOĞLU & TÜREN, 2019).

2.4.3 Late Postoperative Complications

Late postoperative complications are observed in the long term after implant placement and completion of prosthetic superstructures. Mechanical complications such as loosening of the prosthetic screw and fracture of the prosthetic materials may occur over time. Metal fatigue that may occur in the implant material during prolonged function may cause fracture of the implant body, although this is rare. In addition, failure to provide adequate soft tissue support or bone resorption, especially in implants in the aesthetic area, may cause the patient's aesthetic expectations not to be met (Reasons for Early and Late Loss in Dental Implants, n.d.).

The most important late postoperative complications are peri-implant mucositis, peri-implantitis and implant loss.

3. PERI-IMPLANT TISSUE DISEASES

Dental implants, which are placed in appropriate places in the mouth to restore the function of lost teeth, are a treatment method that has been used for a long time from past to present.(Amarnath et al., 2011; Listgarten et al., 1992; Stellingsma et al, 2004) Although dental implants offer many advantages in terms of both aesthetics and function, they also bring some disadvantages. Although they create a new retention area for microorganisms in the oral microbiota, this situation may lead to the development of inflammatory responses in the peri-implant tissues and cause the emergence of peri-implant diseases.(Lindhe & Meyle, 2008)

The combined use of clinical and radiographic examinations is necessary to assess the condition of the peri-implant tissues. Thus, clinical and radiographic findings provide a reference for diagnosis. In the 2017 World Periodontology Workshop, peri-implant diseases and conditions were grouped under 4 main headings. These topics are peri-implant health, peri-implant mucositis, peri-implantitis, peri-implantitis, peri-implant hard and soft tissue deficiencies. Each title is examined in detail within the framework of definitions, diagnostic criteria, parameters used and etiological factors.(Papapanou et al., 2018)

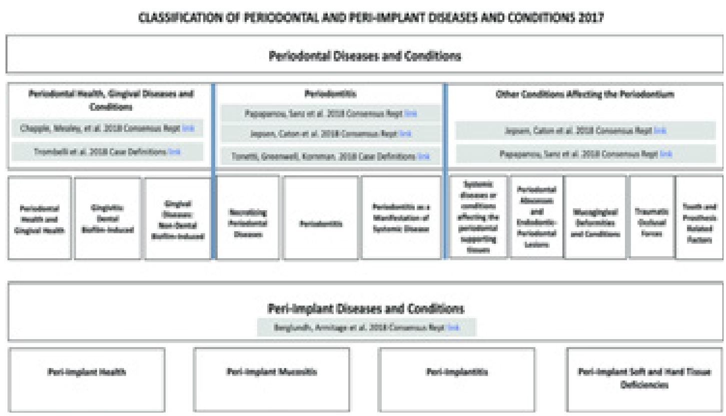

TABLE 1: *Table of the classification of periodontal and peri-implant diseases and conditions accepted at the World Periodontology Workshop in 2017 (G. Caton et al., 2018)*

3.1 Peri-Implant Health

Peri-implant health is the ability of the soft tissue called mucosa and hard tissue structures called bone around the dental implant to continue their functions without any signs of inflammation (Araujo & Lindhe, 2018). Although this is considered to be the main criterion for the long-term success of the implant, there should be no bleeding, swelling, suppuration or bone loss in the peri-implant area for the tissue to be clinically characterised as healthy.

Based on the 2017 World Workshop on Periodontology definition of peri-implant health, the following items are required for diagnosis (Araujo & Lindhe, 2018):

1. Absence of signs of soft tissue inflammation in the peri-implant area such as redness, swelling and bleeding at probing,
2. No increase in probing depths around the implant compared to previous examinations,
3. No bone loss and stable peri-implant area when compared with the initial bone level on radiographic examinations,

PHOTO 1. *Healthy peri-implant mucosa in the implant-supported crown of the upper right first premolar (Heitz-Mayfield, 2024)*

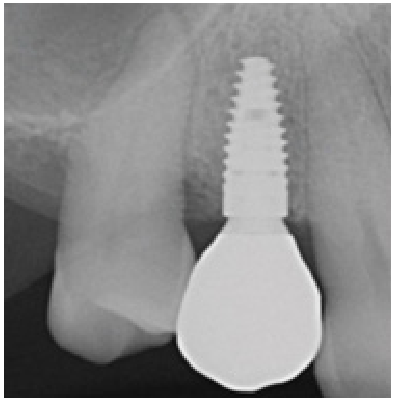

PHOTO 2. *Periapical radiograph showing marginal bone levels after remodelling without loss of supporting bone (Heitz-Mayfield, 2024)*

3.2 Peri-Implantitis

Peri-implantitis is the progressive destruction of alveolar bone accompanied by inflammation and/or BOP. It can be compared with historical data to determine changes in the bone level of the implant. For the diagnosis of peri-implantitis when historical data are not available, the presence of probing haemorrhage and/or suppuration, a probing pocket depth of 6 mm or greater, and bone loss from the most coronal to the apical aspect of the implant of 3 mm or greater are evaluated.(Renvert et al., 2018)

PHOTO 3. *Implant peri-implantitis in the upper lateral incisor region, deep peri-implant probing depth >6 mm, redness, swelling, bleeding and presence of suppuration during probing(Heitz-Mayfield, 2024)*

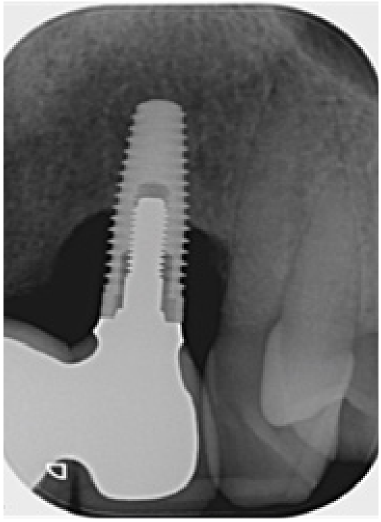

PHOTO 4. *Periapical radiograph showing marginal bone loss >3 mm apical to the most coronal part of the endosseous portion of the implant (Heitz-Mayfield, 2024)*

3.3 Peri-Implant Mucositis

Peri-implant nucositis is an inflammatory condition that develops in the soft tissues surrounding a functioning implant. There are visual signs of inflammation and/or bleeding on probing, but no bone loss.(Heitz-Mayfield & Salvi, 2018a)

2018 World Periodontology Workshop criteria for the diagnosis of peri-implant mucositis:

1. Signs of soft tissue inflammation in the peri-implant area, characterised by the observation of bleeding and/or suppuration on light probing during clinical examination,
2. No change in bone level on radiographic examination,
3. Increased probing depth is required compared to previous examinations without bone loss.

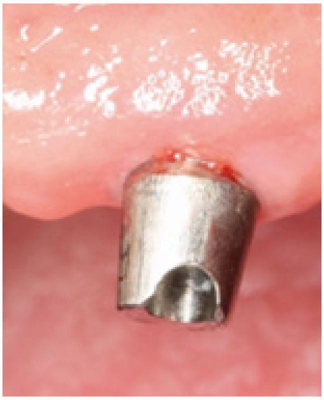

PHOTO 5. *Peri-implant mucositis with inflammation and haemorrhage on light examination(Heitz-Mayfield, 2024)*

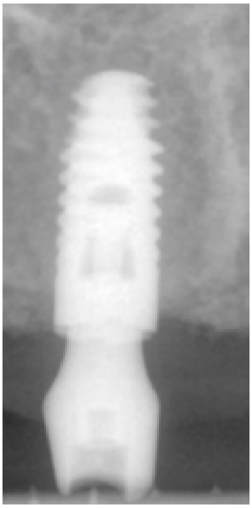

PHOTO 6. *Periapical radiograph showing no loss of supporting bone (Heitz-Mayfield, 2024)*

3.4 Hard and Soft Tissue Deficiencies

Hard tissue deficiencies in the peri-implant region can be explained as tooth loss before implant placement, trauma from tooth extraction, periodontitis, endodontic infections, systemic diseases, sinus-related bone height in the posterior maxilla, or bone loss after implant placement due to implant malposition, excessive load, soft tissue thickness and systemic diseases again. Hard tissue deficiencies in these scenarios threaten the stability of the implant by weakening the bone support around the implant. Soft tissue deficiencies can occur due to tooth loss before implant placement, periodontal diseases, systemic diseases or buccal bone deficiency, papillary height, keratinized tissue, migration of teeth after implant placement. Treatment options may include surgical and non-surgical methods for tissue regeneration and reconstruction. Therefore, early diagnosis and appropriate management of peri-implant tissue loss is critical to ensure the long-term success of the implant (Hämmerle & Tarnow, 2018).

3.5 Microbiology and Pathology of Peri-Implant Diseases

In the aetiology of peri-implant diseases, the effect of pathogenic bacteria is quite evident. From a microbiological perspective, these bacteria are usually microorganisms associated with periodontal diseases such as gingivitis and periodontitis, but they form biofilms by settling in the retention areas in the relevant areas due to the characteristics of both natural tooth and implant surfaces. The bacterial biofilm exerts an effect on the immune system and thus causes the onset of the inflammatory process as a result of a disturbed balance between bacterial activity and the host immune response. The biofilm around the peri-implant, which is usually composed of gram-negative and anaerobic bacteria, is similar to the microbiological community seen in individuals with advanced periodontitis (Mombelli & Décaillet, 2011).The main microorganisms are Porphyromanas gingivalis, Fusobacterium nucleatum, Prevotella intermedia, Treponema denticola, Streptococcus species and Actinobacillus actinomycetemcomitans (De Boever & De Boever, 2006; Fürst et al, 2007; Hultin et al., 2002; Mombelli & Mericske-ster, 1990; Socransky et al., 1998; Socransky & Haffajee, 2005; Van Winkelhoff & Wolf, 2000)

1. **Porphyromonas gingivalis** is an anaerobic, gram (-), rod-shaped bacterium and has an important role in the aetiology of periodontal disease. Increased serum antibody levels against P.gingivalis are observed in individuals with periodontal disease. At the same time, P.gingivalis is a pathogen that can invade cells. It causes chemokine paralysis by inhibiting chemokines such as IL-8. It can stimulate Toll-like receptors (TLR-2, TLR-4, TLR-9) and exhibit TLR-4 agonist or antagonist behaviour depending on the amount of iron in the environment. It modulates immune cells by producing protease enzymes known as gingipains, suppresses the immune system and accelerates tissue destruction. In addition, virulence factors such as lipopolysaccharide, fimbriae, capsule, alpha haemolysin, collagenase, short chain fatty acids are present.
2. **Fusobacterium nucleatum** is a gram (-), anaerobic pathogen also found in normal oral flora. It plays a key role as a bridge between

initial colonisation and subsequent secondary colonisation. Toxic metabolites act as virulence factors.

3. **Prevotella intermedia** is an anaerobic, gram (-), black pigmented bacterium with proinflammatory effects due to virulence factors such as cysteine protease and adhesins. Compared to P.gingivalis, it has less virulence and proteolytic effect. Hydrolases, haemolysin, lipopolysaccharide, cysteine protease, interpain A are virulence factors of this bacterium.
4. **Treponema denticola** is one of the red complex bacteria and is an obligate anaerobic, gram (-) motile and proteolytic spirochete.
5. **Actinobacillus actinomycetemcomitans** is a facultative anaerobic, gram (-), non-spore, immobile member of the Pasteurellaceae family. In addition to having the ability to invade cells, an increase in Aa levels was observed in pathological areas. It has virulence factors such as endotoxin, leukotoxin, bacteriocin, collagenase, protease, immunosuppressive and chemotactic inhibition factors.

Overall, the qualitative structure of the biofilm microflora involved in the aetiology of peri-implantitis is remarkably similar to the microbial composition seen in periodontitis cases. This similarity suggests that individuals with active periodontal disease are at higher risk for the development of peri-implantitis (Heitz-Mayfield & Lang, 2010).

3.6 Risk Factors in Peri-Implant Diseases

Risk factors that are effective in the occurrence of peri-implant diseases can be analysed in 3 main categories: patient-related, dental implant-related and physician-related. Each category has different levels of impact on peri-implant health and proper management of these risk factors is of great importance to increase implant success and ensure that patients have a complication-free treatment process.

3.6.1. Patient Factors

3.6.1.1 Inadequate Oral Hygiene

Poor or inadequate oral hygiene leads to the accumulation of oral microbial plaque and consequently to the development of inflammation in peri-implant tissues. This process may be limited to reversible inflammatory reactions in the early period or may result in an irreversible scenario (Renvert & Quirynen, 2015) without intervention (Tecco et al., 2018).

3.6.1.2. Cigarette Use

Smoking is one of the main risk factors for peri-implant diseases and negatively affects the host response, leading to more aggressive tissue destruction. This leads to a disturbance in the balance between host response and bacterial status. This disruption may be related to changes in the microbial composition of the subgingival dental plaque, an increase in the number and virulence of pathogenic microorganisms, impairments in the host immune response, or a combination of both mechanisms. In smokers, periodontal pathogens can colonise more easily and periodontal destruction is higher as a result. Despite this, clinical signs of inflammation are observed less in smokers. Smoking has no microbiological effect on plaque accumulation, but it has the effect of increasing the complexity of microbiota and pathogen colonisation in the pocket. As a result of smoking, neutrophil chemotaxis, phagocytosis and oxidative properties change and PGE2 production from monocytes increases in response to lipopolysaccharide. As a result, implant success decreases and the risk of peri-implantitis increases with smoking.(Ataoglu et al., 2002; Attard & Zarb, 2002; Keenan & Veitz-Keenan, 2016; Mumcu, 2018; Roos-Jansåker et al., 2006; Weyant, 2025)

3.6.1.3. Alcohol Use

Alcohol use may adversely affect the healing process of oral tissues after implant applications (Schuckit, 1979)(Walker & Shand, 1972) through systemic effects such as effects on the liver, vitamin K and disruption of coagulation metabolism by suppressing prothrombin synthesis.

3.6.1.4. Excessive Occlusal Forces and Parafunctional Habits of the Patient

Such habits can lead to stress accumulation in the peri-implant bone tissue, triggering marginal bone loss and jeopardising osseointegration (B. R. Chrcanovic et al., 2015).

3.6.1.5. Genetic Polymorphism

The immune response of the host is shaped by the release of inflammatory markers against microbial attack. The most prominent proinflammatory cytokine is interleukin-1 (Dinarello, 1994), with increased levels of markers observed in peri-implant diseases (Salcetti et al., 2025).

3.6.1.6. Periodontitis History

The risk of peri-implantitis is increased in individuals with a history of periodontal disease due to bacterial colonisation and common predisposing factors such as genetic predisposition, poor oral hygiene and systemic conditions.(Daubert et al., 2015; Ferreira et al., 2006; Renvert & Polyzois, 2015)

3.6.1.7. Diabetes

Diabetes mellitus is an important systemic disease that affects the severity and spread of periodontal diseases. Periodontal destruction is more pronounced and severe in individuals with inadequate glycaemic control. In diabetic conditions, an increase in advanced glycation products (AGEs) is observed. This increase triggers the release of oxygen products and pro-inflammatory mediators. AGEs also increase the adhesion and chemotaxis of inflammatory cells to periodontal tissues, leading to deepening of inflammation. Furthermore, AGEs induce apoptosis (programmed cell death) in fibroblast and osteoblast cells, leading to structural deterioration and bone destruction in periodontal tissues.(Daubert et al., 2015; Ferreira et al., 2006; Variola et al., 2011)

3.6.1.8 Bone Quality and Quantity

D1 Bone is the bone type that supports the implant the most and the bone-implant contact is maximum. In this bone type, the least stress is transmitted to the implant apical, but its nutrition is poor and regeneration ability is low. More heat is released during milling and strains are observed. Shorter implants and long crowns may be preferred for D1 bone. D2 bone is the gold standard for implant surgery. The cortical part provides stabilisation and the spongiosis part prevents heat. Osseointegration is more predictable. For D3 and D4, the use of large diameter implants, increased groove depth, wider groove spacing and increased number of implants gain importance. D4 bone in the posterior region of the maxilla may be difficult to place an implant and therefore has a high chance of failure. As a result, the type of bone in the area to be implanted should always be considered by the physician in terms of future complications.(B. Chrcanovic et al., 2017)

3.6.1.9. Soft Tissue and Vascularisation

Soft tissue thickness, the presence of keratinized mucosa and the amount of vascularisation in the region are among the important risk factors for the occurrence of peri-implant diseases. In areas with insufficient keratinized mucosa, oral hygiene becomes very difficult and this situation triggers inflammatory processes by facilitating plaque accumulation (Wennström et al., 1994). Inadequate vascularisation around the implant may adversely affect tissue healing and lead to a more aggressive inflammatory process (Schropp & Isidor, 2008). Therefore, these criteria should be evaluated in detail during the planning of implant surgery and supportive therapies should be used if necessary.

3.6.2 Physician Factors

Risk factors for peri-implant diseases include the planning and execution stages of surgical procedures, such as the correct position, number and angle of implants, factors related to implant supported prosthetic rehabilitation and the experience of the physician (Tolman & Laney, 1993; Watanabe et al., 2002).

3.6.3 Implant Factors

Especially under this heading, factors related to the implant surface are analysed. Roughening of implant surfaces to accelerate osteointegration and strengthen the bone-implant connection is a frequently used method. However, some studies have shown that implants with greater roughness increase the likelihood of developing peri-implantitis compared to less rough surfaces due to increased retention areas, and it has been suggested that the reason for the increase may be related to biofilm accumulation (Lang & Berglundh, 2011) (Marrone et al., 2013) (Marrone et al., 2013).

3.7 Diagnosis of Peri-Implantitis and Peri-Implant Mucositis

The symptoms of peri-implant diseases are similar to periodontal diseases that develop around natural teeth. (Bal & Dişçioğlu, 2012)

In the diagnosis of peri-implant diseases; the presence of bleeding during probing, radiographic detection of bone loss, mobility of the implant, whether the patient has risk factors that predispose to peri-implant diseases and intraoral clinical evaluation are taken into consideration. In addition, the presence of suppuration, bacterial evaluation of peri-implant groove fluid and saliva, and microbiota examination can also be utilised (Bal & Dişçioğlu, 2012).

The periodontal probe is the main instrument used in the diagnosis of periodontal diseases. In the case of peri-implant health, pocket depth is not available for probing (Berglundh et al., 2018).

PHOTO 7. *Periodontalprobing using a Williams14W probe] (Al Shayeb et al., 2014)*

One of the most important parameters utilised in the diagnosis of peri-implant diseases is radiographic findings. In a healthy implant, the bone level is located at the neck of the implant. Radiographs with peri-implant diseases include bone loss. These radiographs showing bone loss are not only helpful in diagnosis but also one of the most important criteria guiding the treatment in the future. (Heitz-Mayfield, 2024)

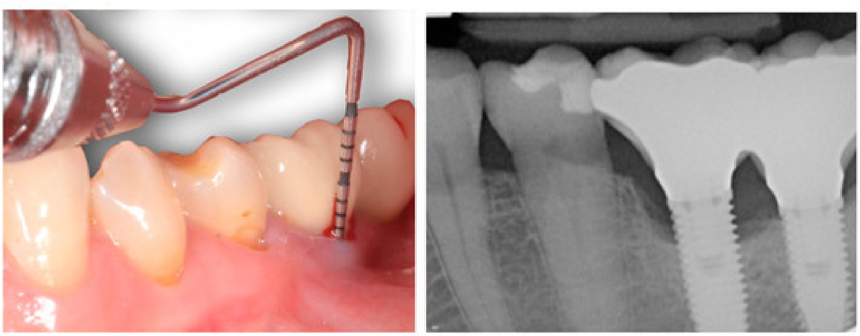

PHOTO 8. *Clinical and radiological image of a peri-implantitis patient (Monje et al., 2019)*

Factors such as having a history of periodontitis, the presence of systemic diseases that delay healing such as diabetes, and being predisposed to the disease as a result of genetic variation are criteria that the physician should consider during the diagnosis of peri-implant diseases. Alcohol and smoking, poor oral hygiene indicated by excessive plaque accumulation, and parafunctional habits such as clenching teeth and nail biting, which indirectly lead to bone loss, are among the findings that guide the physician during diagnosis. In addition, the degree of mobility of the implant can be examined by manual method in the examination (Renvert & Quirynen, 2015).

3.7.1 Diagnosis of Peri-Implantitis

In cases of peri-implantitis, marginal bone loss, pocket depths exceeding 3 mm and loss of attachment are observed, similar to chronic periodontitis. Peri-implantitis is characterised by a pathological pocket formed due to bone loss. Clinical signs of peri-implantitis include bleeding during probing and increased probing pocket depth. However, the definitive diagnosis should be based on the evaluation of these clinical findings together with radiographic data. In the presence of peri-implantitis, in addition to the inflamed appearance of the mucosa, mucosal recession may be observed (Berglundh et al., 2018).

In the presence of peri-implantitis, radiographs show irregular and progressive marginal bone loss around the implant. This loss usually exhibits a circular (circumferential) pattern and progresses to deeper parts of the implant in later stages.(Berglundh et al., 2018)

3.7.2 Diagnosis of Peri-Implant Mucositis

The main criterion for the diagnosis of peri-implant mucositis is the presence of bleeding during probing. It is also characterised by a hyperemic gingiva. In the presence of perimucositis, bleeding on probing is almost always observed. On clinical observation, a healthy peri-implant mucosa is matt, firm in texture and pink in colour; it does not bleed on probing. A mucosa with peri-implant mucositis is hyperemic, oedematous and swollen on clinical observation. In some cases, it may show suppuration (Heitz-Mayfield & Salvi, 2018b).

3.8 Treatment of Peri-Implant Mucositis and Peri-Implantitis

3.8.1 Treatment of Peri-Implant Mucositis

Peri-implant mucositis is characterised by inflammation around the gingiva. In this disease, there is no bone loss and it is usually caused by bacterial accumulation around the implant. For this reason, treatment is usually simpler and successful results can be achieved if intervened early. The treatment process should start with improved oral hygiene and professional cleaning.

3.8.1.1 Oral Hygiene Improvement

Oral hygiene is a fundamental factor in the treatment of peri-implant diseases. Inadequate hygiene leads to plaque accumulation and thus inflammation. (Elemek, Agrali, et al., 2017) Furthermore, the use of chlorhexidine-containing mouthwashes controls inflammation by reducing the bacterial load.

3.8.1.2 Scaling and Root Planning

Bacterial plaque around the implant is one of the main causes of peri-implant diseases. Scaling and root planing are mechanical cleaning methods frequently used in the treatment of peri-implant diseases. (Berberoglu et al., 2015) Furthermore, smoothing the implant surface promotes healing by reducing bacterial accumulation.(Elemek, Agrali, et al., 2017)

3.8.1.3 Antibiotic Therapy

Antibiotic therapy is usually used locally or systemically in the treatment of peri-implant mucositis. Topical chlorhexidine or antibacterial gels may help treatment. Systemic antibiotics are effective in controlling bacterial infection before the disease progresses to advanced stages. Antibiotics such as amoxicillin and clindamycin show activity against microorganisms.(Alassy et al., 2021)

3.8.2 Treatment of Peri-Implantitis

Peri-implantitis is a more advanced disease characterised by inflammation and bone loss in the tissues around the implant. This disease requires more complex treatment approaches and can lead to implant loss if left untreated. The treatment of peri-implantitis is mainly based on two main modalities: surgical treatment and non-surgical treatment. A successful treatment process relies on an appropriate balance between non-surgical approaches and surgical interventions. This balance is critical to increase the effectiveness of the treatment process and to ensure the long-term success of the implant. In the management of peri-implant diseases, non-surgical methods may be effective in controlling the disease without progression in the initial stage; in advanced stages, surgical interventions may be required.(Esen, 2025)

3.8.2.1 Non-Surgical Treatment Approaches

Non-surgical treatments are usually preferred in the early stages of the disease and include mechanical debridement, use of antimicrobial agents and laser applications. Mechanical debridement involves the removal of biofilm and plaque deposits on the implant surface with specialised instruments. In addition, irrigations with antimicrobial agents such as chlorhexidine may be helpful in infection control. Diode laser applications are also used for disinfection of peri-implant tissues.

3.8.2.2 Surgical Treatment Approaches

Surgical treatment methods are applied in cases with severe bone loss. These methods include resective and regenerative procedures. While resective surgery aims to remove infected tissues and clean the implant surface, regenerative surgery aims to regenerate lost bone tissue. It has been reported to give more successful results when combined with mechanical debridement and antimicrobial applications.(AKKALE et al., 2023; Elemek, Ağralı, et al., 2017)

3.8.3 Current Treatment Approaches

3.8.3.1 Biological Agents

Biological agents are used in dentistry to accelerate the healing of the operation site and to support tissue regeneration during and after treatment. For this purpose, PRF (Platelet Rich Fibrin) and PRP (Platelet Rich Plasma) agents are used in periodontology. These platelet-rich plasmas are obtained by taking a blood sample from the patient and applied to the tissue around the implant (Taşkaldıran et al., 2011).

3.8.3.2 Diode Lasers

Diode laser is a type of laser called “soft tissue laser”, which works with light energy converted into heat. It accelerates healing and reduces the risk of inflammation by providing antibacterial effect and tissue biostimulation. It also increases physician and patient comfort by helping to control bleeding. It helps tissue moulding by working minimally invasively. Studies show that diode laser provides improvement in parameters such as gingival index, plaque score, bleeding on probing, especially when used in addition to non-surgical periodontal treatment. However, it may not be sufficient alone in advanced cases such as the treatment of bone defects (Crispino, 2015).

4.CONCLUSION

In this study, peri-implant diseases, especially peri-implantitis and peri-implant mucositis, which are increasingly encountered with the increasing use of dental implants, are discussed. Peri-implantitis is a condition that occurs as a result of inflammatory processes in the soft and hard tissues around the implant and is characterised by progressive bone loss. This inflammation, which starts as peri-implant mucositis in the early period, turns into peri-implantitis when not treated appropriately and may cause serious tissue damage that may lead to loss of the implant.

In this study, the diagnostic criteria, microbiological basis and risk factors of peri-implantitis were evaluated and the importance of regular follow-up, patient education and oral hygiene in the prevention and management of the disease was emphasised. When the treatment approaches are analysed, it is seen that non-surgical methods (mechanical debridement, antimicrobial irrigation, laser treatments, etc.) can be effective in the early stages, but surgical procedures (resective and regenerative) are inevitable in advanced cases.

Clinical studies in the literature show that successful peri-implantitis treatment is possible with patient-specific planning, accurate diagnosis, selection of the appropriate treatment modality and post-treatment supportive care practices. In this context, multidisciplinary approach and individualised protocols in the treatment of peri-implant diseases are among the main factors determining the long-term success of the implant.

Consequently, maintaining the health of peri-implant tissues is possible through a comprehensive and continuous care process that focuses not only on treatment but also on disease prevention. This thesis aims to contribute to the understanding of peri-implant diseases and to determine effective treatment approaches.

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CHAPTER 3

CHEMICAL CONSTITUENTS OF THE RESIN COMPOSITE MATRIX: FOCUS ON MONOMERS AND PHOTOINITIATORS

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Materials that contain both organic and inorganic components are known as composites. Resin composites have been developed as an alternative to amalgam and have been used in restorative dentistry for many years (Willems, Lambrechts, Braem & Vanherle, 1993).

An ideal restorative material should possess the following characteristics: resistance to mechanical stress, excellent adaptation to cavity walls, low thermal conductivity, minimal porosity, and biocompatibility with living tissues. Additionally, it should be easy to manipulate and apply, exhibit aesthetic harmony—particularly in anterior restorations—and provide radiopacity for diagnostic visibility. Furthermore, it should not undergo dimensional or morphological changes in the oral environment, be cost-effective, have an extended shelf life, be compatible with enamel and dentin bonding systems, and allow for high-quality, long-lasting finishing and polishing procedures (Hickel et al., 2007).

Resin composites, which are tooth-coloured and aesthetic restorative materials, have been shown to bond to dental tissues, reduce marginal leakage, and are suitable for conservative cavity preparations by supporting the remaining tooth structure after caries removal. Furthermore, the completion of composite restorations can be accomplished within a single appointment. They are more cost-effective in comparison to porcelain and gold restorations, do not contain mercury, and exhibit low thermal conductivity (Dayangaç, 2000).

Despite these advantages, composite resins also have certain limitations. Their application is not simple; they require technical precision and clinical experience. They have a high coefficient of thermal expansion, low modulus of elasticity, questionable biocompatibility, and exhibit polymerization shrinkage. Moreover, they have lower wear resistance in areas of high occlusal stress and limited longevity (Dayangaç, 2000).

Over the years, numerous studies have been conducted to overcome these disadvantages and to enhance the mechanical and chemical properties of composite resins. With advances in technology, new materials have been developed to address these challenges.

Resin composites are composed of three primary structural components:

I. Organic Matrix

The most commonly utilised monomers for the matrix are bisphenol A (Bis-GMA), ethoxylated bisphenol A glycol dimethacrylate (Bis-EMA), triethylene glycol dimethacrylate (TEGDMA), hydroxyethyl methacrylate (HEMA) and urethane dimethacrylate (UDMA). (Pratap, Gupta, Bhardwaj

& Nag,2019). The other components of the matrix are stabilisers to maximise storage stability and an initiator system for free radical polymerisation (Peutzfeldt,1997).

II. Inorganic Fillers:

The inorganic component of composite resins consists of filler particles with various shapes and sizes, such as quartz, borosilicate glass, lithium aluminum silicate, strontium, barium, zinc and yttrium glasses, and barium aluminum silicate. These fillers are dispersed throughout the resin matrix to improve mechanical and optical properties (Çelik, 2017).

The material's mechanical properties, particularly its strength and abrasion resistance, are attributed to the inorganic fillers. Based on particle size, fillers can be categorised as macrofill, microfill, hybrid, minifill, microhybrid and nanofill. Filler particle sizes range from 5 nm to 50 µm. (Pratap et al, 2019). The categorization in question was created by Lutz and Phillips; however, due to its subsequent development, nanofills were not included in the categorization from the outset. A more thorough classification was developed by Willems et al. in 1993. This classification is based on factors such as surface roughness, Young's modulus, and the size of the major particles. The advent of nanotechnology has enabled dental manufacturers to formulate high-loaded composites with loadings of up to 79.5%. These nanoparticles have been demonstrated to enhance the quality of the fillings, reducing their roughness and increasing their smoothness. Furthermore, they have been shown to retard the biodegradation of the material over time, whilst also mitigating bacterial penetration, colour changes, curing shrinkage, and marginal leakage (García, Lozano, Vila, Escribano, & Galve, 2006). Dental composites characteristically comprise glass, quartz, and fused silica as fillers (Peutzfeldt,1997).

III. Coupling Agents:

The interface between the organic matrix and inorganic fillers is mediated by coupling agents, typically organosilicon compounds known as *silanes*.[1] These agents promote chemical bonding between the two phases, enhancing the mechanical integrity of the composite. Zirconate and titanate are other coupling agents used (Pratap et al., 2019; Willems et al., 1993).

The objective of the present chapter is to provide an overview of the chemical components of the resin composite matrix, specifically monomers and photoinitiator systems, and to assess their influence on the material's physical, mechanical, and clinical behavior based on current scientific evidence.

Monomers

Triethylene glycol dimethacrylate (TEGDMA), urethane dimethacrylate (UDMA), and bisphenol A-glycidyl methacrylate (BisGMA) are common component monomers that make up the matrix. Despite being derived from this group of methacrylate monomers, there are also other proprietary modified versions of these monomers (Peutzfeldt,1997).

Bis-GMA (bisphenol A diglycidyl ether) is a diester derived from methacrylic acid and bisphenol A diglycidyl ether (Peutzfeldt,1997). Bis-GMA has two polymerizable groups and tends to form a cross-linked polymer (Yoshinaga, Yoshihara, & Yoshida, 2021). However, the use of Bis-GMA poses a problem due to the endocrine-disrupting effect of bisphenol A, one of its basic products (Tarumi, Imazato, Narimatsu, Matsuo & Ebisu, 2000; Van Landuyt et al., 2011).

UDMA was developed as a substitute monomer due to its superior properties over BisGMA, including higher toughness, higher filler loading, and lower viscosity. The combination of 2-hydroxyethyl and 2,4,4-trimethylhexamethylene diisocyanate results in the formation of UDMA (Kerby, Knobloch, Schricker & Gregg, 2009).

The dimethacrylate monomer TEGDMA is predominantly employed in dentistry; however, it is also utilised in fuel-resistant metal components, industrial sealants, photopolymers, anaerobic adhesives, and ultraviolet-cured coatings. In the manufacture of other compounds, TEGDMA also serves as an intermediate compound (Meyer, 2010). Furthermore, given the high viscosity of Bis-GMA, it is imperative to incorporate a low-viscosity monomer such as triethylene glycol dimethacrylate (TEGDMA) within composite resins. However, it has been demonstrated that excessive addition of TEGDMA to the resin composition can result in increased polymerization shrinkage and water absorption, as well as a weakening of mechanical properties (Gonçalves, Azevedo, Ferracane & Braga, 2011).

The chemical reaction between methacrylic acid and ethylene oxide results in the production of hydroxyethyl methacrylate (HEMA). In addition to its use in the manufacture of photosensitive chemicals, adhesives, coating additives, thermosetting paints, sealants and personal care items, HEMA is utilised in the production of dental adhesives. It has been established that other methacrylate esters are also produced using HEMA as an intermediate (Mulligan, Hatton & Martin, 2022).

Recent advancements in monomer chemistry have focused on modifying widely used methacrylate-based systems—particularly Bis-GMA and UDMA—to obtain monomers with lower viscosity. Examples include hydroxyl-free Bis-GMA, aliphatic UEDMA, aromatic urethane dimethacrylates, and other methacrylate derivatives (Moszner, Fischer, Angermann, & Rheinberger, 2008).

In addition, ring-opening monomers such as spiro-orthocarbonates have been incorporated into composite resins to reduce or eliminate polymerization shrinkage. High molecular weight monomers like dimer acid-based dimethacrylates, TCD-urethane, and organically modified ceramics have also been developed with the same goal. (Trujillo-Lemon, Lu, Tanaka & Stansbury, 2006).

Furthermore, dimer acid-based dimethacrylates offer higher molecular weight and lower viscosity compared to conventional Bis-GMA and UDMA monomers. These materials demonstrate a higher degree of conversion, along with lower polymerization shrinkage, water sorption, and elastic modulus (Trujillo-Lemon et al., 2006). Similarly, TCD-urethane-based monomers are known for their low shrinkage behavior (Kurokawa et al., 2007).

The degradation of the polymeric component of contemporary composite dental restorative materials not only compromises the longevity of the restoration, but also has cellular consequences due to the compounds that can leach from these materials. Consequently, new-generation composite resins must be designed to have a longer lifespan, and any compounds released from these materials must not have a toxic effect on cells (Van der Laan et al., 2019).

The process of RBC biodegradation is accelerated by a number of factors. Firstly, the hydrolysis of ester linkages in common dental resin monomers, such as BisGMA, TEGDMA, and UDMA, is catalysed by host salivary hydrolases and esterases. Secondly, the elevation of cariogenic bacterial pathogenicity also accelerates the process. As a consequence of the resin matrix's subsequent breakdown, there is an increased water sorption in the material. This, in turn, leads to more hydrolysis, degradation, and monomer release (Stewart & Finer, 2019).

Yoshinaga et al. (2021) developed dental acrylic monomers with the objective of obtaining hardened products with good mechanical properties. In this study, five urethane acrylic monomers were synthesised as methacrylic monomer substituents with a view to replacing Bis-GMA and UDMA. In the present study, the mechanical properties of a cured resin containing the urethane diacrylates TMXDI-HEA, TMXDI HPA, XDI-HPA, and NBDI-HEA were examined and compared to those of UDMA. The results demonstrated that the cured resin exhibited higher mechanical properties than UDMA. Whilst the elevated toxicity of acrylate monomers in comparison to methacrylate monomers is a cause for concern, the utilisation of these urethane acrylates, particularly in hybrid resin blocks, may be a more suitable option due to their enhanced mechanical properties and the fact that curing outside the mouth reduces monomer toxicity (Yoshinaga et al., 2021).

In a study conducted by Barszczewska-Rybarek et al., new urethane-dimethacrylate monomers were synthesized from 1,3-bis(1-isocyanato-1-methylethyl)benzene (MEBDI) and oligethylene glycols containing one to three oxethylene groups. The combination of MEBDI-based urethane-dimethacrylates with TEGDMA resulted in copolymers with high monomer conversion, low polymerization shrinkage, low water absorption and solubility, and good mechanical properties (Barszczewska-Rybarek, Chrószcz & Chladek, 2020).

Van der Laaan et al. developed simultaneous thiolene-based polymerization and allyl sulfide-based chain transfer reactions to obtain cross-linked polymeric resins exhibiting low shrinkage stress and obtained new prototype composites. 15 While glass, which is biologically inert, has traditionally been used as a filler in composite resins, many of the prototype composites have been supplemented with fluorapatite (FA) crystals, which resemble enamel crystals and are bioactive. In all prototype composite resins, an increase in hardness was observed compared to BisGMA/TEGDMA-based composites when using BisGMA/TEGDMA+glass-filled prototype composites. The other mechanical properties of prototype composites filled with glass alone were comparable to those of BisGMA/TEGDMA-based composites. The addition of FA to the composite resin weakened the mechanical properties of the prototype and the BisGMA/TEGDMA composite (Van der Laan et al., 2019)

Polymerization of Resin Matrix

Polymerization is the chemical process through which monomeric units react to form long-chain polymer structures. (Pratap et al., 2019). This process proceeds through three principal stages: initiation, propagation, and termination. The generation of free radicals—crucial intermediates for chain growth—is primarily facilitated by photoinitiators (Garcia et al., 2006). These radicals may also be produced via thermal, photochemical, or redox mechanisms (Van Landuyt et al., 2007). Accordingly, resin composite materials can be classified as light-cured, chemically cured, or dual-cured, depending on the curing mechanism employed (Kinomoto, Torii, Takeshige, & Ebisu, 1999).

In chemically initiated systems, polymerization is triggered by a reaction between an organic peroxide (contained in the base paste) and an organic amine (contained in the catalyst paste) (Sakaguchi, 2012). Although chemically and light-activated resins share many compositional similarities, their primary distinction lies in the nature of their initiator systems. In chemically cured composites, benzoyl peroxide acts as the initiator and is combined with an aromatic tertiary amine. Nevertheless, chemical-cure composites present several limitations, including color instability, difficulty in achieving homogenous mixing, increased porosity, inaccurate component ratios, prolonged setting times, and restricted working times. Despite these drawbacks, they offer notable advantages such as ease of application, elimination of light-curing devices, and the ability to cure in areas inaccessible to light (Garcia et al., 2006). In light-curing systems, exposure to blue light activates the photoinitiator system, triggering electron transfer between the initiator and a co-initiator. This leads to hydrogen abstraction, resulting in the generation of free radicals. The co-initiator is converted into an amino alkyl radical, while the initiator becomes a ketyl radical. As the terminal electron from the alkene group traverses the monomer, the molecule transitions into a radical state. The combination of these radicals initiates a chain reaction, which continues until terminated by interaction with another monomer (Kowalska, Sokolowski, & Bociong, 2021).

It is important to note that not all monomers undergo polymerization; some remain unreacted. The degree of conversion (DC) is defined as the ratio of polymerized monomers to the total number of monomers present in the resin matrix (Pratap et al., 2019). This is a crucial factor that affects the biological and physical characteristics of dental resin. As a consequence of the uncured molecules permeating the surrounding tissues, the material's biocompatibility is exacerbated by the low conversion (Brandt, Schneider, Frollini, Correr-Sobrinho, & Sinhoreti, 2010; Schroeder & Vallo, 2007).

Photoinitiators

There are two types of photoinitiator:

Type-1. Benzoyl peroxide (BPO) and trimethylbenzoyl-diphenylphosphine oxide (TPO) (Santini, Miletic, Swift & Bradley, 2012).

Type-2. Camphorquinone (CQ). Phenanthrenequinone (PQ), benzophenone (BP) and 1-phenyl-1,2-propanedione (PPD) (Pratap et al., 2019).

This distinction arises from the different ways in which these photoinitiators produce free radicals, a process which is explained in more detail in the following sections. Both type-1 photosensitizers and type-2 initiators can start the polymerisation process via C-cleavage or H-abstraction. A photoinitiator and a tertiary amine or electron donor comprise the photoinitiation system (Pratap, 2019). This photoinitiator system is stable at room temperature when the oligomer is present, as long as the composite is not exposed to light (Sakaguchi & Powers, 2012).

Type-1 Photoinitiators

Type-1 photoinitiators absorb high-intensity violet light, which excites the singlet state and causes photochemical cleavage of carbon-phosphorus bonds. The chemical in these photosensitizers breaks down into two radicals via an alpha-cleavage photoinitiation mechanism. Trimethylbenzoyl and diphenylphosphinoyl radicals are produced when trimethylbenzoyl-diphenylphosphine oxide rapidly cleaves from its triplet excited state. Although they have varying rate constants, these radicals can initiate polymerisation (Ikemura, & Endo, 2010). Monoacylphosphine oxide (MAPO), bisacylphosphine oxide (BAPO) and TPO are examples of type-1 photoinitiators (Lima et al., 2019; Pratap et al., 2019). Type-1 photoinitiators enhance the characteristics of the material. Their low-energy bonds facilitate photopolymerisation using shorter-wavelength, higher-energy photons of violet light, and their homolytic cleavage produces more active radicals. Type-1 photosensitizers have a larger molar absorptivity and therefore improve cure efficiency. These initiators also improve tissue colour matching due to their shorter wavelength absorption range, resulting in low pigmentation. A further benefit is the reduction in the elution of leftover monomers, which increases the resin's crosslink density (Meereis et al., 2014).

Type-2 Photoinitiators

The absorption band of type-2 photoinitiators, such as CQ, PQ, and BP with co-initiators, is located between 400 and 490 nm. As a consequence of the bimolecular reaction, the initiation is frequently characterised by a slower rate of reaction in comparison to that of photoinitiation instigated by type-1 sensitizers (Yoshida & Meng, 2014). The initiation of polymerisation is catalysed by observable blue light photons. The majority of CQ's co-initiators are aromatic tertiary amines. It is evident that achieving a high degree of conversion is contingent upon the accurate and precise measurement of the concentration of CQ and co-initiators. The carbonyl group of CQ transitions into a triplet state by excitation into a singlet state upon exposure to blue light, thereby initiating the polymerization process (Pratap et al., 2019).

The type, concentration and structure of the co-initiator all significantly impact radical formation (Lima et al, 2019). Due to their superior optical absorption characteristics in the near-visible wavelength range, this form of photoinitiator is preferable to the type-1 Photoinitiators (Lalevée, & Fouassier, 2018).

Camphorquinone

Camphorquinone and co-initiators are the most widely used photoinitiating systems in dental composites. Dart and Nemcek created it in 1971 (Kowalska et al, 2021). CQ is a type-2 photoinitiator and an alpha-diketone. Visible light with wavelengths between 360 and 510 nm is absorbed by this photoinitiator (Van Landuyt, et al, 2007). According to some publications, the absorbance maximum is 468 nm (Pratap et al, 2019; Dressano, et al 2016), however it may also be found at 469 nm (Lima et al, 2019), 467 nm (Park, Chae & Rawls, 1999), and 474 nm (Van Landuyt, et al, 2007). These variations, known as solvatochromic shift, arise because CQ may dissolve in different resins, such as TEGDMA or HEMA (Pratap et al, 2019). CQ is a powder with a strong yellow hue that gives the uncured composite a yellow tint (Rueggeberg, Giannini, Arrais & Price, 2017). Because of the yellowish staining, which may cause issues with color matching (Neumann, Miranda Jr, Schmitt, Rueggeberg & Correa, 2005; Meereis et al, 2016), less photoinitiator was used, which altered the material's final qualities. The co-initiator that causes the staining oxidizes with time, changing the dental resin's color (Almeida et al., 2020).

Camphorquinone (CQ) concentrations in dental resins typically range from 0.17% to 1.03% by weight of the resinous portion (Taira et al., 1987). However, Shintani et al. (1985) demonstrated that the actual CQ content in dental composites lies between 0.03% and 0.09% by weight. These discrepancies arise from the use of different amine co-initiators (Musanje, Ferracane & Sakaguchi, 2009). Due to better light penetration, composites formulated with microparticle resins generally contain lower CQ levels than those with conventional filler particles (Alvim et al., 2006). Increasing the amount of CQ enhances the degree of monomer conversion and improves the mechanical properties of the composite. However, beyond an optimal concentration, no further improvement in conversion is observed (Musanje et al., 2009). Achieving this optimal CQ concentration is essential to preserve various properties of the restoration, including resistance to early wear, biocompatibility, aesthetics, and mechanical integrity. Excess unreacted CQ can impair the restoration's visual appeal and may negatively affect biocompatibility, as it can leach into saliva and oral tissues. Conversely, an insufficient CQ concentration may lead to inadequate polymerization, resulting in weakened mechanical properties (Musanje et al., 2009; Maciel et al., 2018).

Although camphorquinone can produce free radicals on its alone, it works better when co-initiators are added. To effectively excite CQ molecules, the light source's emission spectrum is essential. The half-life of the CQ triplet is around 0.05 seconds, which limits the time required to produce the triplet exciplex. Following this, the CQ triplet disintegrates into its most basic form, and no free radicals are generated (Musanje et al., 2009). The steric structure of radicals produced from amines determines the polymerization process's effectiveness (Taira et al., 1987). Aromatic tertiary amines like N, N-dimethyl-p-toluidine (DMPT), and ethyl-4-(dimethylamino) benzoate (EDMAB) are the most often utilized co-initiators (Lima et al., 2019). DMPT's very low molecular mass has led to reports that it is hazardous. EDMAB is another amine that is regarded as harmful due to its inability to polymerize with monomers. Furthermore, this amine increases intracellular glutathione and reactive oxygen species production, both of which might compromise the integrity of cellular DNA (Rueggeberg et al, 2017; Almeida et al, 2020). 2-(N,N-dimethylamino)ethyl methacrylate (DMAEMA) has the finest biocompatible qualities and does not leach (Pratap et al., 2019).

N-phenylglycine, *p*-octyloxy-phenyl-phenyl iodonium hexafluoroantimonate (OPPI), diphenyliodonium salts (DPI), and 2-ethyl-dimethyl benzoate are additional co-initiators used in camphorquinone (CQ)-based photoinitiation systems (Shin & Rawls, 2009; Meereis et al., 2014; Albuquerque et al., 2015). DPI is incorporated into CQ/amine photoinitiator systems to minimize the back electron transfer process and enhance both the degree of conversion and polymerization rate. It achieves this by reactivating dormant free radicals and replenishing the photosensitizer, thereby maximizing monomer conversion through two distinct mechanisms (Albuquerque et al., 2015). Clinically, this co-initiator offers multiple benefits: it reduces the required concentrations of amines and CQ, thereby improving the aesthetic properties of composites, and enhances curing efficiency, which can shorten clinical application time (Meereis et al., 2014). Except for the final degree of conversion, the inclusion of specific co-initiators—DPI and/or bis(4-methylphenyl)iodonium hexafluorophosphate (BPI)—in experimental Bis-GMA/TEGDMA/CQ/EDAB resin formulations results in superior mechanical properties, such as flexural strength and modulus, compared to those using only a CQ-EDAB binary system (Verzola et al., 2020). However, the addition of BPI/DPI also increases polymerization shrinkage strain and the associated strain rate (Verzola et al., 2020). Sulfinates and sulfonates, such as naphthalene sulfonates (NapTS), can serve as novel co-initiators in CQ-based systems under blue light irradiation, yielding polymers with improved bleaching performance and enhanced color stability (Kirschner et al., 2020).

The most used CQ/amine photoinitiator technique in commercial dental composites has a number of drawbacks. The restoration's yellow hue (Park et al., 1999; Dressano et al., 2016; Maciel et al., 2018) is a major drawback, because camphorquinone keeps its color after free radicals are produced (Alvim et al., 2006). Not only does CQ give dental resin its color, but high tertiary amine concentrations can cause these materials to darken with time (Moszner et al., 2007; Park et al., 1999). Because it can alter the metabolism of structural lipids, which impacts membrane integrity and permeability (Pratap et al., 2019), CQ is regarded as hazardous (Ullrich, Herzog, Liska, Burtscher, & Moszner, 2004; Dressano et al., 2016). Additionally, it has been shown that CQ has a toxic impact on pulp cells, and that this effect is correlated with the concentration of CQ in dental composite: the higher the concentration, the more cytotoxic the effect (Maciel et al., 2018). Because it produces ROS and RNS, the CQ has the potential to be genetically harmful even though it is less cytotoxic than BAPO (Wang, Xiong & Lalevée, 2018). The other issue is that there are two parts to this system, and how they interact is dependent on the medium's viscosity. The decrease of the triplet of CQ and amines in low-viscosity formulations is intimately linked to the reaction of these reagents' diffusion. However, because diffusion governs the process, bimolecular systems' reactivity is constrained in high-viscosity environments. Using polymerizable photoinitators and co-initiators, the amines are placed next to photosensitizers to lessen this impact (Ullrich et al., 2004). An oxygen-inhibited layer is also produced (Moszner et al., 2007). Other photoinitiators were taken into consideration for the creation of commercial composites as a result of these clinical issues. The impact of several photoinitiator systems (based on CQ, BAPO, or TPO) on the cytotoxicity, degree of conversion, and sorption and solubility behavior of a model adhesive resin with various photoinitiation systems was assessed by Almeida et al. (2020). Diphenyliodonium hexafluorophosphate (DPIHFP) was substituted with EDAB, BAPO, 1,3-benzodioxole (BDO), piperonyl alcohol (AP), and 1,3-diethyl-2-thiobarbituric acid (TBA) as initiators. The most cytotoxic materials were found to be groups RCQ+BDO and RCQ+AP, although experimental adhesive resins RCQ+EDAB, RCQ+EDAB+DPIHFP, RBAPO, and RTPO had comparable degrees of conversion values (over 60%) (Almeida et al., 2020).

Phenanthrenequinone

In 1999, 9,10-Phenanthrenequinone was developed as a substitute photoinitiator for CQ. It needs co-initiators like CQ and is a 2-type photoinitiator. It is intended to work with CQ and lessen yellow stains. This orange solid photoinitiator is an aromatic diketone. PQ may be less yellow than CQ and has a maximum absorbance at 420 nm. In their investigation, Albuquerque et al. (2015) contrasted the effects of CQ and PQ on the characteristics of resin-based composites. It demonstrated that compared to CQ, PQ has a larger relative photon absorption. Regardless of whether a co-initiator is included, the degree of conversion is the same for PQ and CQ. When DPI and PQ work together, the degree of conversion rises and yellow values decrease. The depth of cure of CQ-containing materials is greater than that of PQ-containing materials (Albuquerque, Bertolo, Cavalcante, Pfeifer, & Schneider, 2015).

1-phenyl-1,2 propanedione (PPD)

The photosensitizer 1-phenyl-1,2-propanedione (PPD), an alpha-diketone with a methyl and aromatic group, generates free radicals by proton transfer from an amine co-initiator (Van Landuyt et al, 2007; Rueggeberg et al, 2017). PPD is a light yellow, viscous liquid compatible with resin matrices and has a light absorbance similar to CQ (Van Landuyt et al, 2007). Used alone or with co-initiators like DPI salts or tertiary amines (Hadis, Shortall, Palin, 2012), PPD provides a comparable degree of conversion to CQ (Ikemura et al., 2010). It is less yellow, an advantage for modern esthetic materials (Park et al, 1999).

When combined with CQ, PPD enhances polymerization via dual mechanisms—photocleavage and proton abstraction—leading to higher conversion at 1:1 and 1:4 ratios. Their distinct absorbance peaks (CQ: 468 nm, PPD: 410 nm) improve light utilization and reduce yellowing. (Park et al., 1999). However, PPD has a slower polymerization rate, which may reduce crosslink density and make the material more prone to degradation (Kirschner et al., 2020).

PPD performs less efficiently under halogen lights due to mismatched absorbance but remains a viable photoinitiator for dental resins overall (Brandt, de Oliveira Tomaselli, Correr-Sobrinho & Sinhoreti, 2011).

4,6-trimethylbenzoyl-diphenylphosphine oxide (TPO)

Based on acylphosphine oxide, **2,4,6-trimethylbenzoyl-diphenylphosphine oxide (TPO)** is a type-1 photoinitiator used in products like Vit-l-escence and Tetric EvoCeram Bleach (Alsheikh, 2019; Salvador et al., 2015; Schneider et al., 2012). TPO does not require co-initiators and can be used alone or in combination with camphorquinone (CQ) (Schneider et al., 2012; Bertolo et al., 2017). Lucirin TPO eliminates the need for amines, enhancing long-term color stability (Silami et al., 2012), particularly when combined with BAPO or CQ/amine systems (Popal et al., 2018; Silami et al., 2012), likely due to its higher molar extinction coefficient (Neumann et al., 2005).

TPO has a narrow absorption range (380–425 nm), with absorption peaks reported at 400 nm and 381 nm (Miletic & Santini, 2012; Georg et al., 2007). Since most conventional curing units emit light in the 420–490 nm range and are incompatible with TPO, polywave light-curing devices are required for optimal performance (Alsheikh, 2019; Conte et al., 2017; Randolph et al., 2014; Salvador et al., 2015). These devices emit within the necessary 400–415 nm range. TPO enables bulk curing, which reduces clinical application time but may increase polymerization shrinkage stress (Schneider et al., 2012; Bertolo et al., 2017; Kinomoto et al., 1999).

Composites containing TPO show approximately 10% higher degree of conversion (DC) than CQ-based materials (Schneider et al., 2012; Randolph et al., 2014; Salvador et al., 2015; Schroeder & Vallo, 2006). Miletic and Santini (2012) reported that 0.86 wt% TPO achieved a 74% DC, compared to 68% with 0.22 wt% TPO. Furthermore, TPO allows faster polymerization with a minimum of 3-second irradiation (Ullrich et al., 2004) and exhibits higher reactivity than CQ due to its ability to generate two free radicals via α-cleavage (Popal et al., 2018; Schroeder & Vallo, 2006). The combination of TPO with amines may also reduce the oxygen inhibition layer (Wang et al., 2018).

TPO-based resins produce lower temperature rise and higher polymerization efficiency than CQ, PPD, or BAPO when halogen lights are used (Salvador et al., 2015). They also demonstrate higher surface hardness, flexural modulus, and color stability, although they exhibit similar flexural strength to CQ-based composites (Wang et al., 2018). Despite these advantages, TPO-composites present increased polymerization stress and lower depth of cure (Alsheikh, 2019; Popal et al., 2018; Randolph et al., 2014; Schroeder & Vallo, 2006; Wang et al., 2018). However, studies have reported no harmful effects on pulp tissue (Lee et al., 2015) and favorable esthetic outcomes, such as high color stability and a natural tooth appearance (Alsheikh, 2019; Conte et al., 2017; Silami et al., 2012; Ullrich et al., 2004; Wang et al., 2018; Lee et al., 2015).

Bisacylphosphine oxide (BAPO)

As a type-1 photosensitizer, bisacylphosphine oxide (BAPO) initiates the polymerization process without the need of a co-initiator. Irgacure 819 is another name for BAPO (Neumann et al, 2005). It uses a photoinitiation process of the alpha-cleavage type to generate free radicals. A violet light-emitting diode cures resin containing BAPO; the absorbance range is 365–416 nm, with a high of 400 nm (Ikemura et al, 2010), however some sources give 371 nm (Moszner et al, 2007). BAPO has a symmetrical chemical structure, is solid, and is poorly soluble in a range of monomers and oligomers (Ullrich, Ganster, Salz, Moszner & Liska, 2006). Recent research has demonstrated that polymer when BAPO is used as a photosensitizer in dental resin instead of CQ, the surface hardness is increased. According to Favarão et al, 2021) et al.'s research, BAPO exhibits the best degree of conversion when compared to TPO and CQ using distinct amine co-initiators (Neumann, 2005; Favarão et al, 2021). The absorption range makes selecting the right curing light crucial. When cured by a high-power LED light curing unit, BAPO-containing resins had a greater degree of conversion than when cured by a first-generation type LED unit (Neumann, 2005). According to TPO and CQ/amine, BAPO has the maximum flexural strength, which is another new finding (Favarão et al, 2021).When using alternative monomers, the instability does not arise, however the composite using UDMA as a matrix and BAPO as a photosensitizer has shelf-life issues (Ikemura, Ichizawa, Yoshida, Ito & Endo, 2008). On cell culture, BAPO A has a negligible genotoxic impact [50]. When BAPO is utilized, the polymer's color does not become yellow (Almeida, 2020).

The polymerization process is started by the highly reactive benzoyl and phosphonyl radicals produced by type-1 photoinitiators' rapid photolysis (Ikemura, 2010). Because BAPO contains two carbonyl groups in its composition, it generates more free radicals than TPO. BAPO is more effective than TPO because it may produce four reactive radicals from a single molecule (Arikawa, Takahashi, Kanie & Ban, 2009; Bertolo et al, 2017). Like other photosensitizers, BAPO can work in concert with CQ, but its ability to produce free radicals is the most effective [17,25]. The investigation by Wang et al. indicates that BAPO is very cytotoxic. BAPO greatly suppresses the proliferation of the cells and is very sensitive to the primary cells (Wang et al, 2018).

Novel photoinitators

In recent years, significant progress has been made in the field of acylphosphine oxide photoinitiators, with the development of new and advanced formulations. The compounds in question were specifically 9-(p-toluyl)-9-oxytho-9-phosphafuluorene (TOPF) and 9-(2,4,4,6-trimethylbenzoyl)-9-oxytho-9-phospha-fluoren (TMBOPF). In both visible and ultraviolet light, these novel photosensitizers exhibit increased photopolymerization reactivity. It has been demonstrated that their reactivity to photopolymerization is analogous to that of BAPO. As Ikemura et al. (2010) have demonstrated, the degree of yellow thick photocured coating films initiated by TMBOPF and TOPF was lower than that of traditional BAPO.

In the domain of dentistry, the novel visible light photoinitiators BTMGe and DBEGe are benzoyl germanium compounds. Approximately fifteen to twenty years ago, there was a report on the photolysis of mono-germanyl-ketones in cyclohexane solution. The reaction in question yields two radicals, namely benzoyl and germyl. Dibenzoyldiethygermane (DBDGe) and benzoyltrimethylgermane (BTMGe) are both yellow solids and liquids, respectively. The maximum extinction coefficient of DBDEGe is 418 nm, while that of BTMGe is 411 nm. (Kowalska, 2021)

The dissolution of these experimental photosensitizers is facilitated by both mono- and dimethacrylates. It has been established that these substances do not induce gene alterations and are therefore regarded as low in terms of their cytotoxic potential. In their investigation, Moszner et al. (2007) demonstrated that DBDEGe had a substantially higher absorption intensity than CQ. It has been demonstrated that, since the absorption region of DBDEGe and BTMGe is in proximity to that of CQ, these innovative photoinitiators do not require specialised light-curing equipment with a broad light spectrum. The utilisation of germanium compounds offers the distinct advantage of obviating the necessity for an amine co-initiator in order to initiate the photopolymerization process. The photocuring activity of DBDEGe is higher; its setup time is 3–5 s, whereas CQ's is 8 s. It is evident that there is a paucity of yellowing in the composites that contain the germanium photoinitiator. The network of cross-linked organic polymers was identified as the causative agent. The application of an appropriate UV-light stabiliser has been demonstrated to reduce the incidence of yellowing (Moszner et al., 2007).

Ivocerin, also known as dibenzoyl germanium, is patented and is exclusively present in a small number of products manufactured by Vivadent. Ivocerin has a maximum extinction coefficient of 418 nm (Moszner, Zeuner, Lamparth, & Fischer, 2009) and an absorption range of 390–445 nm(Alwim, 2006). While CQ-EMBO only produces one aminoalkyl radical, Ivocerin, like BTMGe and DBDGe, produces at least two radicals. Furthermore, it was demonstrated that Ivocerin had no mutagenic effects and minimal toxicity (Alkhudhairy et al, 2020).

In their study, Bouzrati-Zerelli et al. (2017) examined a novel amine-free photoinitiating method that generates germyl radicals for the polymerisation of representative methacrylate resins. It has been demonstrated that when exposed to a dental blue LED with a central wavelength of 477 nm, the CQ/R3GeH/iodonium salt combination can function as an efficient photoinitiating system for the polymerisation of methacrylate resins (Bis-GMA/TEGDMA or UDMA) in thin films or thick composites (Boeira et al., 2017).

Iodonium hexafluoroantimonate (P3C-Sb), a coumarin-based white powder used in cationic polymerization, has a maximum absorption at 347 nm, close to blue light. It works with the CQ/amine system, either alone or with tertiary amines, and can enhance the degree of conversion and polymerization kinetics. However, combining P3C-Sb with CQ or EDMAB did not significantly increase polymerization rate or conversion. So far, P3C-Sb has not been studied as a sole photoinitiator. (Al Mousawi et al., 2018). Additionally, Wang et al. (2018) proposed new photoinitiators for Bis-GMA/TEGDMA composites. Although their extracts showed low toxicity, the cytocompatibility of DTP-photopolymerized materials was lower than that of CQ-based systems.

Conclusion

In summary, the chemical composition of the resin composite matrix—particularly the nature of the organic monomers and the polymerization mechanisms—plays a critical role in determining the material's overall performance. Numerous studies have shown that these components directly affect key properties such as polymerization shrinkage, mechanical strength, wear resistance, and long-term clinical stability. Despite the widespread use and advantages of resin composites, challenges such as limited longevity, technique sensitivity, and stress-bearing limitations persist.

With continued interdisciplinary efforts and technological progress, it is expected that next-generation composite materials will significantly improve the predictability, durability, and overall success of restorative dental treatments.

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CHAPTER 4

FIBER REINFORCED COMPOSITE RESINS

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INTRODUCTION

Enhancing the mechanical performance and longevity of dental materials has long been a focal point of research in the field of dentistry. In restorative dentistry, composite resins are among the most frequently employed materials, and improving their mechanical strength and overall clinical performance remains a critical objective. One of the most effective strategies in this regard involves the modification of inorganic fillers within the resin matrix. Through the incorporation of various reinforcing agents into the polymer matrix, the physical and mechanical properties of the composite can be significantly improved. These reinforcements commonly include fibers, ceramic whiskers, nanofillers, and nanofibers (1).

Fibers have long been utilized across various industrial sectors to enhance the mechanical properties of materials. In nature, fibers exist as cellulose-based structures within the cell walls of plants and trees, where they contribute to both flexibility and mechanical strength. Fiber-reinforced materials have gained widespread application in numerous fields, including dentistry, due to their superior mechanical performance, low specific weight, optical translucency, corrosion resistance, and favorable bonding capabilities (2).

Fibers In Dentistry

Fibers were first introduced into dentistry in the 1960s with the aim of overcoming the mechanical limitations and dimensional instability of polymethyl methacrylate (PMMA) materials. During this period, efforts to develop alternatives to the restrictive properties of metal-reinforced ceramic systems also contributed to the increasing interest in fiber applications. By the 1980s, the use of fibers had expanded considerably, with various types being widely employed in prosthetic frameworks, fixed partial dentures, orthodontic retainers, and splints (3).

Fibers, which are thin, cylindrical, and flexible structures with lengths approximately 100 times their diameters, serve as effective reinforcing agents. Fiber reinforced composites (FRCs) used in dentistry share structural similarities with conventional resin composites and consist of an organic matrix and an inorganic filler phase. The organic matrix typically includes monomers such as polymethyl methacrylate (PMMA), urethane dimethacrylate (UDMA), or triethylene glycol dimethacrylate (TEGDMA). The inorganic filler phase comprises fibers of varying lengths, diameters, structures, and orientations that are incorporated into the organic matrix. These fibers are bonded to the resin structure via an adhesive interfacial layer, which plays a critical role in transferring stress from the matrix to the fibers (4).

As the reinforcing component, fibers enhance the composite's strength and stiffness, while the surrounding resin matrix stabilizes the geometry of the fibers, protects them from moisture, and maintains their position, thereby ensuring optimal load distribution and ease of application. This synergistic structure allows fibers to effectively contribute to both mechanical support and clinical workability (5).

Types of Fibers Used In Dental Applications

Carbon Fibers

Commercial production of carbon fibers began in the early 1960s with the carbonization of cotton fibers. In the field of dentistry, the commercial use of carbon fibers started in 1970, with most of these fibers being produced through the carbonization of polyacrylonitrile (PAN) (6).

The primary disadvantage of carbon fibers is their relatively low resistance to forces applied perpendicular to their longitudinal axis. To address this issue, fibers have been arranged in crosswise or vertical orientations within the matrix during the manufacturing process. Despite their limited esthetic appearance, carbon fibers have been widely used for many years in dentistry to reinforce the fracture resistance of acrylic resins, owing to their excellent physical and chemical properties as well as their biocompatibility (7).

Aramid Fibers

Aramid fibers, commercially known as "Kevlar," are low-density organic compounds. Also referred to as polyparaphenylene terephthalamide, these polymeric fibers are characterized by their high elastic modulus and low density. Due to their excellent wettability properties, aramid fibers do not require surface treatment with bonding agents. Moreover, there is no scientific evidence indicating any toxic effects. Owing to their lightweight nature and reliability, aramid fibers are widely utilized in various applications, particularly in fields where both strength and biocompatibility are essential (8).

Polyethylene Fibers

Polyethylene fiber, developed by Cappacio and Ward in 1973, possesses a naturally crystalline polymer structure. It offers several significant advantages, including its natural color, low density, high elastic modulus, excellent biocompatibility, and chemically inert, hydrophobic, and melt-resistant nature. However, despite these favorable properties, its low surface energy results in poor wettability, which is considered a major drawback. To overcome this limitation, polyethylene fibers are subjected to chemical surface treatments aimed at enhancing their wettability (9).

Polyethylene fibers can be incorporated into resin matrices in various forms, including continuous unidirectional (parallel), woven or braided, and short, randomly oriented fibers. However, it has been reported that fibers incorporated into resin without any surface treatment may act as foreign bodies rather than reinforcing agents, thereby weakening the mechanical properties of the composite. To address this issue, various techniques have been employed in the manufacturing of polyethylene fibers. These methods include chemical oxidation, plasma treatment, the use of additional acrylic monomers, and the application of chemical coating agents (3).

Glass Fibers

Glass fibers, a form of glass produced as fine filaments, are among the most commonly used fibers in both dentistry and industry. Introduced into dentistry in the early 1960s, glass fibers possess an amorphous (non-crystalline), isotropic structure arranged in a three-dimensional network. Their colorless appearance, esthetic quality, flexibility, mechanical strength, and high biocompatibility make them particularly suitable for dental applications. Additionally, glass fibers offer favorable bonding characteristics, translucency, and resistance to corrosion, all of which contribute to their clinical advantages (10).

There are several types of glass fibers, including E-glass, S-glass, C-glass, and M-glass. Among these, E-glass—also known as electrical glass—is commonly used in fiber-reinforced composites due to its low alkali content, high moisture resistance, and excellent electrical insulation properties. E-glass is based on the SiO_2–CaO–Al_2O_3–MgO system, which enables the formation of high-quality glass suitable for reinforcement purposes (11).

Factors Affecting the Mechanical and Physical Properties of FRCs

Type of Fiber

The type of fiber plays a significant role in determining its application in dental procedures. For instance, glass fibers are commonly preferred in laboratory-fabricated restorations, whereas polyethylene fibers are more frequently used in chairside prosthetic applications. Carbon and aramid fibers, on the other hand, are utilized in specific procedures such as post fabrication, where they offer notable advantages in terms of strength and performance (2).

Impregnation of Fibers with Resin

The impregnation or wetting process ensures that each individual fiber surface is fully coated with the resin matrix, which significantly contributes to the improvement of the composite's physical and mechanical properties. However, insufficient wetting of the fibers can lead to polymerization shrinkage within the resin matrix. This shrinkage may result in the formation of voids between the fibers, negatively affecting the structural integrity of the restoration and ultimately reducing its durability (12).

Volume of Fiber

Studies have shown that increasing the amount of fiber within the polymer matrix enhances the strength of the restoration. However, fiber content is defined by volume rather than weight. Even when the fiber quantity is high, a low fiber volume has been associated with lower-than-expected mechanical resistance of the restoration. This highlights the critical role of fiber volume contribution in determining the mechanical durability of fiber-reinforced composites (10).

Adhesion of Fiber to the Resin Matrix

One of the most critical factors influencing the mechanical properties of fiber-reinforced composites is the adhesion between the fibers and the resin matrix. To achieve strong bonding between polymer and glass fibers, silane coupling agents—particularly compounds such as γ-methacryloxypropyltrimethoxysilane—are commonly used. These agents promote chemical bonding at the fiber–matrix interface, thereby enhancing the mechanical strength and overall performance of the composite material (13).

Advantages and Disadvantages of FRCs

Fiber reinforced composite resins (FRCs) have emerged as esthetic, biocompatible, and metal-free alternatives in restorative dentistry. Their primary advantages include low treatment costs, chairside applicability in a single appointment, elimination of the need for laboratory procedures, and suitability for use with minimal or no tooth preparation. They are also easily repairable and particularly appropriate for pediatric patients in the growth phase as well as elderly individuals requiring provisional restorations. Furthermore, FRCs offer the ability to retain fractured segments of composite or acrylic structures and tend to cause less antagonist tooth wear compared to traditional metal-ceramic restorations (14).

However, these materials are not without limitations. Disadvantages include insufficient rigidity in multi-unit bridges, greater occlusal wear in posterior regions compared to metal frameworks, limitations in cases where moisture control is inadequate, and a lack of definitive clinical data regarding their long-term intraoral durability (15).

Short Fiber Reinforced Composite Resins

Short fiber reinforced composite resins are among the innovative materials used in modern dentistry, particularly distinguished by their high mechanical strength and crack-arresting capabilities. These composites are formulated by incorporating short glass, carbon, or ceramic fibers into a polymer matrix, significantly enhancing the material's tensile, flexural, and compressive strength compared to conventional composites. The random and homogeneous distribution of fibers facilitates the dissipation of stresses over a wider area, thereby limiting crack initiation and propagation. This structure is especially advantageous in the restoration of posterior teeth, where resistance to high occlusal forces is essential. Furthermore, short fiber-reinforced composites possess an elastic modulus similar to that of dentin, which plays a crucial role in achieving biomechanically compatible stress distribution within the tooth structure during function (16).

In clinical practice, the application range of these materials is broad, encompassing various indications from the restoration of posterior teeth to serving as a core build-up in endodontically treated teeth. Due to their ability to arrest crack propagation, these composite resins contribute to extending the longevity of restorations, making them a favorable option in treatments aimed at long-term clinical success. However, their esthetic performance may be limited in anterior regions because of the visibility of the fiber content. Therefore, when using these materials, it is essential to carefully balance esthetic demands with mechanical strength requirements during clinical application (17).

CONCLUSION

Fiber reinforced composite resins constitute a significant advancement in restorative dentistry, offering improved mechanical performance, effective stress distribution, and enhanced resistance to fracture propagation. Their utility is particularly evident in posterior restorations and endodontically treated teeth, where functional demands are high. Despite their esthetic limitations in the anterior region due to fiber visibility, careful case selection and adherence to clinical protocols can mitigate these concerns. As material science continues to evolve, fiber reinforced composites are expected to play an increasingly prominent role as reliable, conservative, and biologically compatible alternatives to traditional restorative materials.

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